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Strontium-isotopic ratios of dated corals have been obtained from submerged reefs formed during Quaternary glacial periods off the Hawaiian islands. These data, combined with data from deep-sea sediments, tightly constrain the secular variation of marine $^{87}Sr/^{86}Sr$ for the past 800,000 yr. Although long-term trends are apparent, no significant (>0.02‰), rapid (<100,000 yr) excursions in $^{87}Sr/^{86}Sr$ were resolved nor did we observe any samples with $^{87}Sr/^{86}Sr$ greater than that of modern seawater. Strontium in mollusks from elevated marine terraces formed during interglacial periods on the southern California coast show resolvable and consistent variations in $^{87}Sr/^{86}Sr$ which, when compared to the trend of Quaternary marine $^{87}Sr/^{86}Sr$, can be used to infer uplift rates and define approximate ages for the higher terraces. The Sr-isotope age estimates indicate that uplift rates vary among crustal blocks and were not necessarily constant with time. No contrast in Sr-isotopic ratios between similar-age Hawaiian and California fossils was observed, confirming that any change in marine $^{87}Sr/^{86}Sr$ from glacial to interglacial periods must be small. A realistic appraisal of the potential of Sr-isotope stratigraphy for chronometric applications in the Quaternary suggests that the technique will be limited to relatively coarse distinctions in age.

INTRODUCTION

Recent studies have shown that the secular variation of seawater $^{87}Sr/^{86}Sr$ is a powerful tool for dating late Tertiary marine carbonates (Koepnick *et al.*, 1985; DePaolo and Ingram, 1985; DePaolo, 1986; Hess *et al.*, 1986; Ludwig *et al.*, 1988; McKenzie *et al.*, 1988; Hodell *et al.*, 1989, 1990; Capo and DePaolo, 1990). The geochronometric utility of the technique arises from the nearly monotonic increase in marine-carbonate $^{87}Sr/^{86}Sr$ with decreasing age for the past 35 myr. Thus any time period in this range is characterized by a unique $^{87}Sr/^{86}Sr$ value (at least to a resolution of ~2 myr or coarser). The use of Sr-isotope stratigraphy in the Quaternary, however, is inherently limited by the fact that in this relatively short time interval the total variation of marine $^{87}Sr/^{86}Sr$ is only about 0.14‰ (Capo and DePaolo, 1990), so that the precision of isotopic measurements must be correspondingly high. Balancing the stringent demands on analytical capability, however, is the relative ease with which suitable carbonate fossils can be obtained. We report here an attempt to (1) define better the marine Sr-isotope record for the late Quaternary, (2) use Sr-isotope stratigraphy to constrain relative and absolute ages of Quaternary marine terraces formed during interglacial periods in southern California, and (3) test for the presence of a glacial–interglacial oscillatory signal superimposed on the longer-term Sr-isotope trend for the Quaternary.

SAMPLE LOCALITIES AND THEIR GEOLOGIC SETTING

Submerged Terraces off the Hawaiian Islands

Six prominent marine terraces are pre-

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served at 150 to 1340 m depth on a broad submerged platform to the northwest of the island of Hawaii. These terraces are coral reefs which formed during times when reef growth on the subsiding volcanic platform was able to match glacial–eustatic changes in sea level (Moore and Fornari, 1984; Szabo and Moore, 1986; Moore and Campbell, 1987; Ludwig *et al.*, 1991). Growth of each reef terminated when it could not match the rapid sea-level rise caused by melting of the ice sheets. Mass-spectrometric $^{234}U/^{238}U$ dates for the six terraces to the northwest of Hawaii have recently been determined (Ludwig *et al.*, 1991) and confirm a long-term, approximately constant subsidence rate of about 2.6 mm/yr over the past 500,000 yr or so (Fig. 1). Together with a $^{234}U/^{238}U$ date for a deeper terrace east of Maui (Moore *et al.*, 1990), these results show that terraces were formed during glacial periods ranging in age from 15,000 to at least 750,000 yr. Because these corals have been directly and reliably

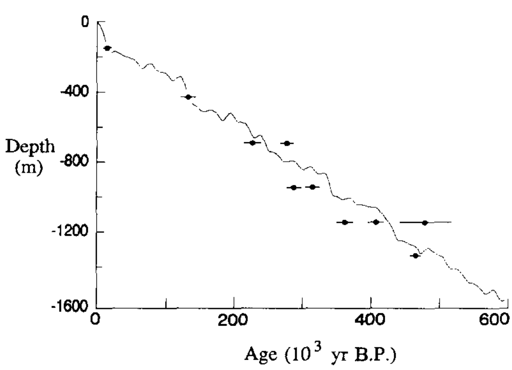

FIG. 1. Age–depth relation of coral samples from submerged Hawaiian terraces (Ludwig *et al.*, 1991). Because neither precise sample depths nor a detailed knowledge of how the samples relate to the reef morphology are known, depths shown are the average depths to the tops of the reef faces, as estimated from the depth of the slope break for each reef, from the best-available bathymetry (Moore and Clague, 1987; Ludwig *et al.*, 1991). Dots indicate $^{234}U/^{238}U$ ages and their present-day depths; horizontal lines through dots show uncertainty in $^{234}U/^{238}U$ age. Irregular curve, for comparison, shows estimated depths of past sea-level stands assuming a constant crustal subsidence rate of 2.6 mm/yr and global sea-level variations derived from the oxygen-isotope record of deep-sea sediment.

dated, they comprise a uniquely well-constrained sample suite for defining the secular marine $^{87}Sr/^{86}Sr$ trend.

Elevated Terraces in and near Southern California

Erosional marine terraces are formed by wave action during periods when a coastline remains stable relative to sea level for thousands of years. On uplifting coasts, such relative stability requires that the rate of eustatic sea-level rise nearly matches the rate of tectonic uplift. If coastal uplift is long sustained, it must eventually surpass the limited range over which sea level can vary, so that any terrace that was being cut will rise beyond the reach of the sea. Repeated oscillations of sea level will produce a series of terraces whose ages are roughly proportional to their elevation (Fig. 2).

Flights of such terraces are well preserved at several localities along the southern California coast and offshore islands, particularly on uplifted, fault-bounded crustal blocks (Fig. 3; Woodring *et al.*, 1946; Vedder and Norris, 1963; Muhs, 1983). On San Nicolas Island (SNI), 14 terraces are recognized as high as 274 m (Fig. 4). The second terrace is reliably dated ($^{230}Th/^{234}U$ on coral) at about 120,000 yr (Muhs *et al.*, 1987), but the higher terraces are either undated or only approximately dated with the less reliable amino acid and uranium-trend methods (Wehmiller and Belknap, 1978; Muhs, 1985; Muhs *et al.*,

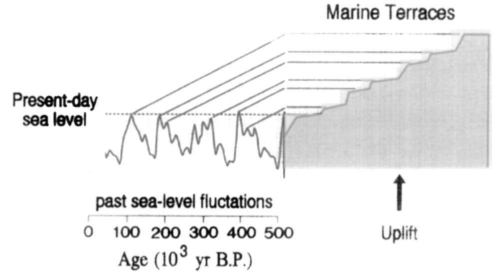

FIG. 2. Schematic diagram showing formation of marine terraces in a region of long-term uplift. Only some of the possible terrace-formation times are shown on diagram. Modified from Lajoie (1986).

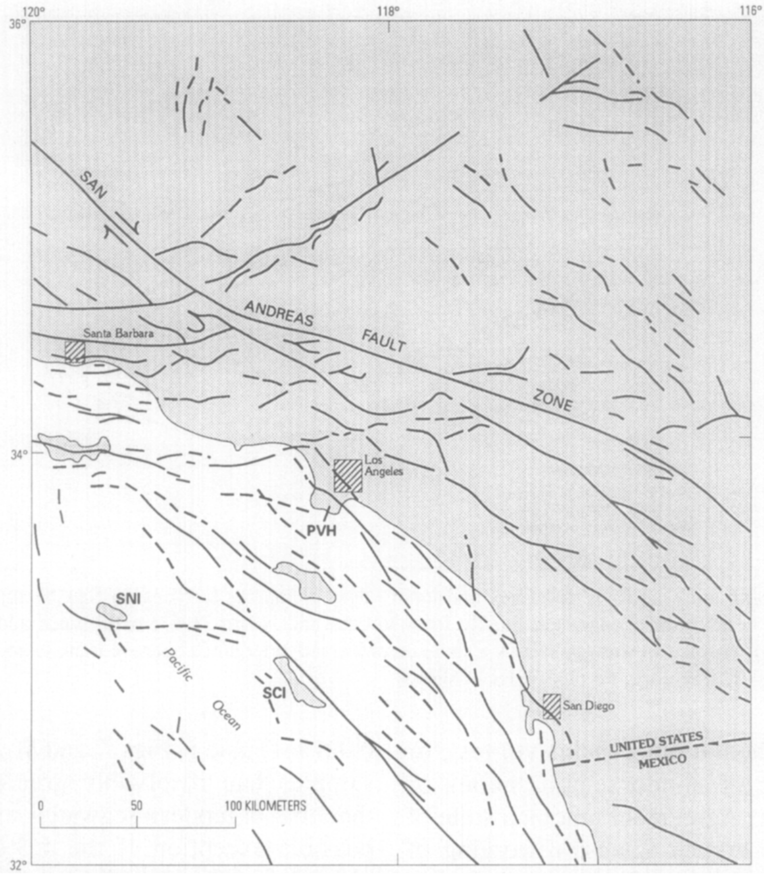

FIG. 3. Map of part of southern California and continental borderland showing study areas and major faults. SNI, San Nicolas Island; SCI, San Clemente Island; PVH, Palos Verdes Hills. Location of faults from Legg *et al.* (1988).

1989). On the northern part of San Clemente Island (SCI), at least 12 terraces are recognized (Fig. 5). The second terrace is similar in elevation and ^{230}Th/^{234}U age (125,000 yr) to the second terrace on SNI (Muhs and Szabo, 1982). The higher terraces on SCI, like those on SNI, have not been reliably dated (Muhs, 1983). On the Palos Verdes Hills (PVH), 13 terraces have been recognized (Fig. 6; Woodring *et al.*, 1946). Based on both aminostratigraphy and oxygen-isotope stratigraphy, corals from the second PVH terrace have an age of about 125,000 yr (Muhs *et al.*, in press).

Uplift rates calculated from the elevation of the 120,000- to 125,000-yr terraces on SNI and SCI are similar—about 0.22 mm/yr. The uplift rate calculated from the height of the 125,000-yr terrace at PVH is somewhat higher, about 0.32 mm/yr. These uplift rates are typical for areas in California and Baja California that are dominated by strike-slip faults (Kern, 1977; Lajoie *et al.*, 1979; Rockwell *et al.*, 1989; Muhs *et al.*, 1990). Well-preserved bivalve and gastropod fossils are fairly abundant in California marine terrace deposits, so that we were able to analyze at least five different individual fossils from each of most terraces in order to test for the presence of both nonmarine Sr and diagenetic alteration of the primary Sr-isotope ratios. Either of these effects would probably vary in degree from one sample to another, so that agreement of isotopic ratios within a suite of samples from a single terrace should be a

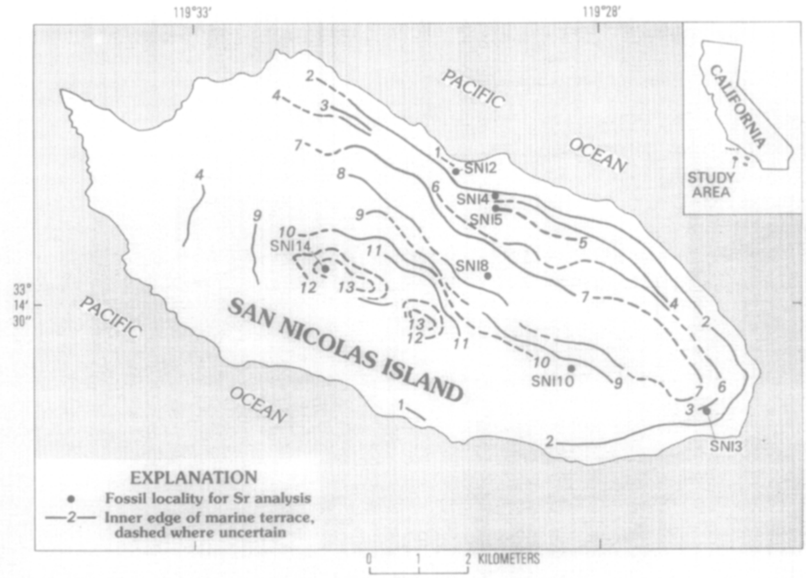

FIG. 4. Map showing fossil localities and inner edges of marine terraces on San Nicolas Island, California. Terrace inner edges are mostly from Vedder and Norris (1963) with minor additions by Muhs (1985). Terrace 14 was apparently a shoal before island emergence because there is no paleo-sea cliff backing it; therefore, no inner edge is shown.

sensitive (although not conclusive) test for the presence of noncontemporaneous or nonmarine Sr. Agreement among a suite of samples also argues against reworking of older fossils into younger terrace deposits.

SR-ISOTOPE RATIOS OF SAMPLES FROM QUATERNARY MARINE TERRACES

To normalize for interlaboratory bias and intralaboratory drift, we present our Sr-isotopic data in terms of δ^{87}Sr, defined as the difference between a sample's ^{87}Sr/^{86}Sr and that of modern seawater, in parts per thousand (analogous to δ^{18}O).

Hawaiian Terraces

Our sample of modern coral from Hawaii is indistinguishable in ^{87}Sr/^{86}Sr from modern marine carbonate (difference = -0.005 ± 0.017‰; Table 1), indicating the lack of any significant component of basalt-derived Sr in the coastal sea water. Samples from the Quaternary reefs show little change in ^{87}Sr/^{86}Sr from 15,000 to ~460,000 yr, with a total range in measured ^{87}Sr/^{86}Sr of only 0.021‰ (Table 1, Figs. 7 and 8). None of the samples had resolvably greater ^{87}Sr/^{86}Sr than that of modern seawater, and, with the possible exception of the 463,000-yr sample, none of the Hawaiian samples deviates from a trend of monotonically decreasing ^{87}Sr/^{86}Sr with age (about 0.007‰ per 100,000 yr over the past 750,000 yr) and with terrace depth.

Compared with the data reported by Capo and DePaolo (1990) from deep-sea cores DSDP-590B and V28-328[1], the Hawaiian data agree within error limits with two exceptions: their ~300,000-yr (Site 590B) sample and their 120,000-yr Hawaiian terrace sample. We can account for neither discrepancy, but point out that the Sr-isotope data presented here (for Hawaii plus two 120,000- to 125,000-yr California terraces) comprise a much more densely sampled suite, with good internal consistency.

[1] Although there are other careful studies with data from Pleistocene marine samples, none are of sufficient precision to address the very small Sr-isotopic variations discussed here.

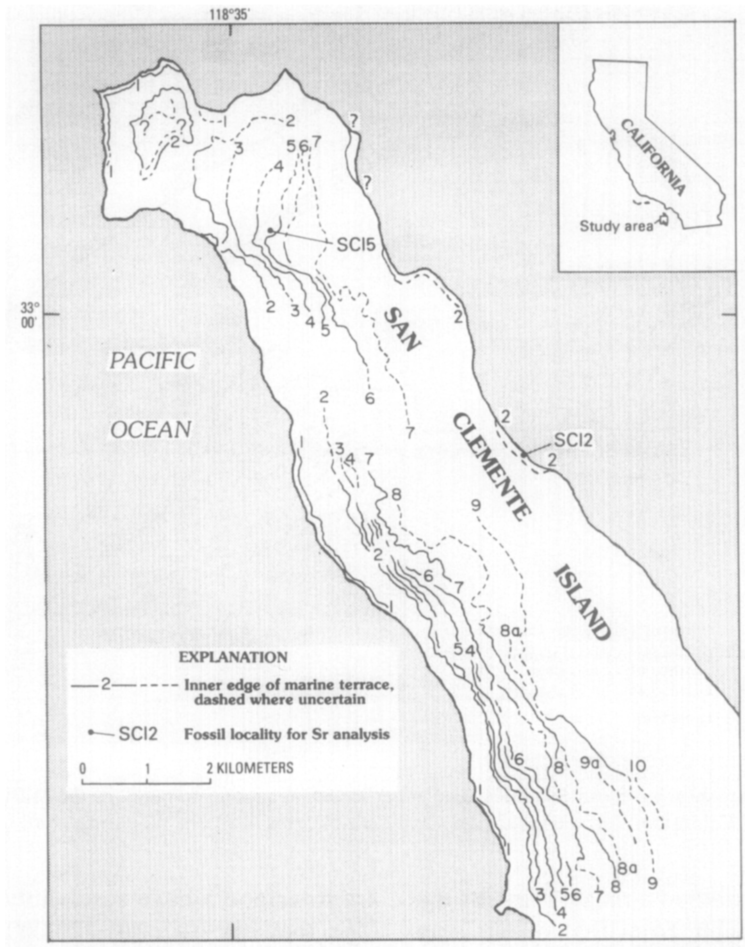

FIG. 5. Map showing fossil localities and inner edges of marine terraces on San Clemente Island. Terrace inner edges are from Muhs (1983).

With the exceptions noted above, the Hawaiian-coral data and Capo and DePaolo's data from the two DSDP sites (Capo and DePaolo, 1990) can be pooled to provide relatively tight limits on the form of the marine Sr-isotopic curve for the past 800,000 yr or so (Fig. 8). Note, however, the great contrast in the detail of information preserved in the oxygen-isotopic record of marine carbonates (Fig. 8) compared to the Sr-isotopic record.

Southern California Terraces

Sr-isotopic ratios of samples from terraces on SNI, SCI, and PVH are given in Table 2 and shown as a function of terrace elevation in Figure 9. These data include replicate analyses for different samples of shells for each of these terraces to test for the possibility of significant diagenetic alteration of the primary Sr-isotope composition of the samples. However, in no case was there an analytically resolvable difference between the $^{87}Sr/^{86}Sr$ of an individual fossil from a particular terrace with that of the weighted mean for all individuals from that terrace, so that we are reasonably confident that neither diagenetic alteration of the $^{87}Sr/^{86}Sr$ ratios nor fossil reworking has affected our data.

As with the case of the modern Hawaiian coral, a shell collected from the present-day

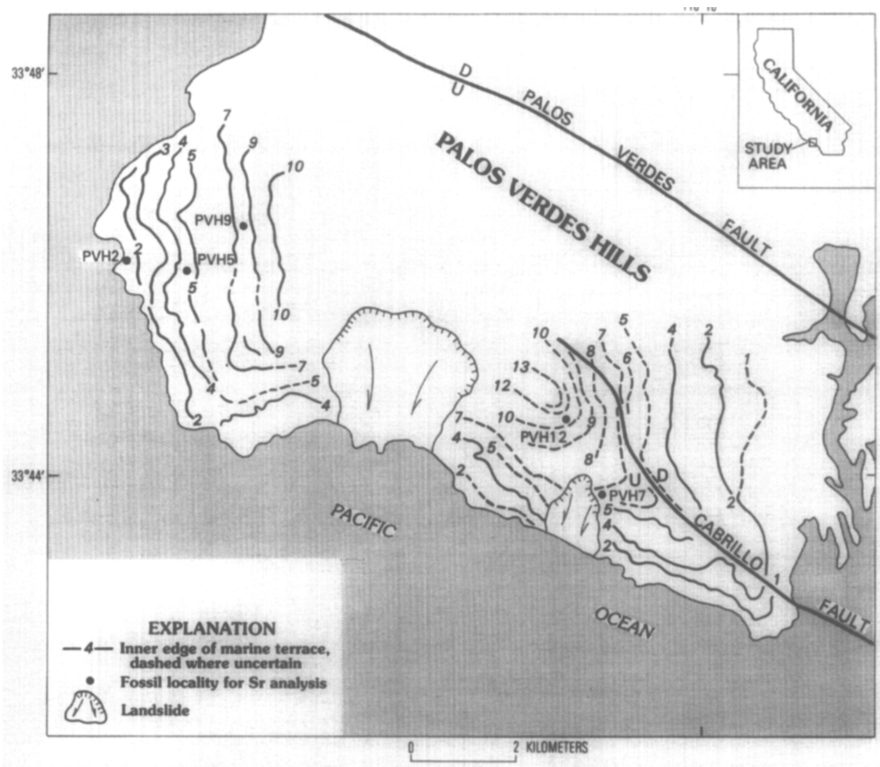

FIG. 6. Map showing fossil localities, and inner edges of marine terraces in the western Palos Verdes Hills, California. Terrace inner edges and fault margins are from Woodring *et al.* (1946).

beach on SNI yielded a mean $^{87}Sr/^{86}Sr$ that is indistinguishable from that of our standard of modern marine Sr (difference = +0.0025 ± 0.0057‰; Table 2). This agreement at a very high level of precision shows that the ocean near SNI is indeed isotopically representative of the global marine system, and that there is no significant component of continentally derived Sr. Samples from the older SNI terraces show a monotonic, near-linear decrease in $^{87}Sr/^{86}Sr$ for successively higher terraces from terrace 2 through terrace 5 (Table 2, Fig. 9). Terraces 8, 10, and 14, although having analytically distinct $^{87}Sr/^{86}Sr$ values, do not show a consistent trend with elevation; both terraces 8 and 14 have significantly higher $^{87}Sr/^{86}Sr$ than terrace 10.

Sr-isotope ratios for the two sampled terraces on SCI overlap the SNI trend within analytical uncertainty, such that fossils from terrace 5 have resolvably lower $^{87}Sr/^{86}Sr$ than the second (120,000 yr) terrace (Table 2, Fig. 9). Samples from PVH, however, define a divergent trend compared to those from SNI—successively higher terraces have progressively lower $^{87}Sr/^{86}Sr$, defining a monotonic, near-linear trend with terrace elevation. The differences between $^{87}Sr/^{86}Sr$ of adjacent terraces are so small (typically <0.01‰) that they cannot be analytically resolved, but a trend of decreasing $^{87}Sr/^{86}Sr$ with terrace elevation is apparent.

The most straightforward interpretation of these data is that the 46- to 370-m terraces on PVH correspond to the somewhat lower terraces on SCI and SNI. This conclusion is consistent with the greater late Quaternary uplift rate inferred for PVH compared to that of SNI and SCI, as estimated from the height of the dated 120,000-

TABLE 1. SR-ISOTOPE DATA FOR SUBMERGED TERRACES OFF HAWAII AND MAUI

Sample no.	Collected depth (m)[a]	Projected depth (m)[b]	δ^{87}Sr (‰)[c]	Number of analyses/ samples[d]	Age[e] (10^3 yr)
21	beach	—	−0.005 ± 17	4/2	0
3/4	−20	−150	−0.016 ± 17	2/1	14 ± 1
17	−219	−150	−0.017 ± 17	2/1	15 ± 1
16	−160	−430	−0.018 ± 17	2/1	133 ± 10
5/6	−835	−693	−0.020 ± 17	2/1	225 ± 12
9	−835	−693	−0.031 ± 12	1/1	226 ± 13
22	−750	−693	−0.028 ± 17	2/1	276 ± 9
18	−980	−945	−0.032 ± 17	2/1	314 ± 10
23	−960	−945	−0.030 ± 17	4/2	287 ± 10
14	−1060 to −1222	−1146	−0.017 ± 17	4/2	406 ± 12
19	−1130	−1146	−0.037 ± 23	2/1	360 ± 12
24	−1110	−1146	−0.044 ± 11	2/1	475 ± 38
20	−1405	−1336	−0.022 ± 10	4/3	463 ± 8
13	−1600	−1600	−0.053 ± 17	3/2	750 ± 13

[a] Estimated from 3.5 kHz echo records at time of strong jerks from dredge for dredge samples, and from depth of top of reef face for loose samples collected by submersibles (Ludwig *et al.*, 1991).

[b] Depth of top of reef face as estimated from depth of average slope break (onset of abrupt slope steepening) for the reef, from the best available bathymetry between 19°58′ and 20°06′ North latitude (Moore and Clague, 1987; Ludwig *et al.*, 1991).

[c] δ^{87}Sr is the permil difference between the ^{87}Sr/^{86}Sr of the sample and that of present-day marine Sr, as represented by our modern marine-carbonate standard EN-1 (Ludwig *et al.*, 1988); e.g., $\delta^{87}\text{Sr} = 1000[(^{87}\text{Sr}/^{86}\text{Sr})_{\text{sample}}/(^{87}\text{Sr}/^{86}\text{Sr})_{\text{MSW}} - 1]$, where MSW = modern seawater. Value given is the weighted mean of the number of analyses given in the next column to right, with 95% confidence limit uncertainties of the least-significant digits.

[d] First number is the number of mass-spectrometric analyses; second number is the number of samples actually dissolved and purified.

[e] From mass-spectrometric ^{234}U/^{238}U analyses. Details of dates and sample locations are given in Moore *et al.* (1990) for sample 13, and in Ludwig *et al.* (1991) for all others.

125,000 yr terraces (Muhs and Szabo, 1982; Muhs and Rosholt, 1984; Muhs *et al.*, 1987, in press). A detailed correlation using only the terrace ^{87}Sr/^{86}Sr values is very difficult to make, however, because of the analytically distinct reversals in the trend of ^{87}Sr/^{86}Sr versus elevation for SNI terraces 8 (183 m) and 14 (274 m).

Southern California Terraces: Corespondence with the Marine Sr-Isotope Record

The simplest approach to comparing the Sr-isotope record of the California terraces is to use the elevations and ^{230}Th/^{234}U ages of the lower terraces to calculate uplift rates, then to use these uplift rates to estimate ages for the higher terraces. For the 120,000- to 125,000-yr terraces at SNI, SCI, and PVH, we have assumed a paleo-sea level of +6 m (Bloom *et al.*, 1974). The resulting Sr-isotopic trends for SCI and PVH are in reasonable agreement with the marine Sr-isotope trend (Fig. 10A). However, ^{87}Sr/^{86}Sr values for the highest (and therefore oldest) terraces on SNI diverge significantly from the marine ^{87}Sr/^{86}Sr trend (Fig. 10A). To bring the SNI Sr-isotopic trend into reasonable visual agreement with the marine trend, a pre-120,000-yr uplift rate about 45% greater than the post-120,000-yr rate (i.e., 0.32 rather than 0.22 mm/yr) is required (Fig. 10B). This uplift rate yields ages for SNI terraces 5, 8, 10,

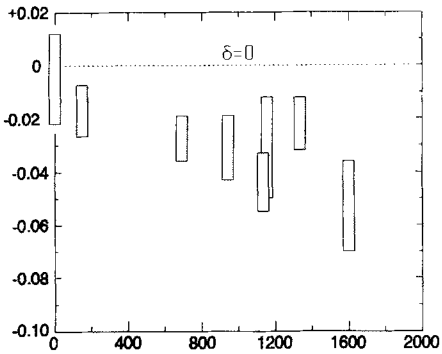

FIG. 7. Variation in weighted-mean $\delta^{87}Sr$ of coral samples from submerged Hawaiian terraces as a function of terrace depth. Vertical dimension of boxes indicates analytical uncertainty of the weighted-mean value for each terrace, except for the −1146-m terrace. Sample 24 from the −1146-m terrace disagrees with the other two −1146-m samples slightly beyond error, and so is shown as a slightly offset and overlapping with the mean of the other two −1146-m samples.

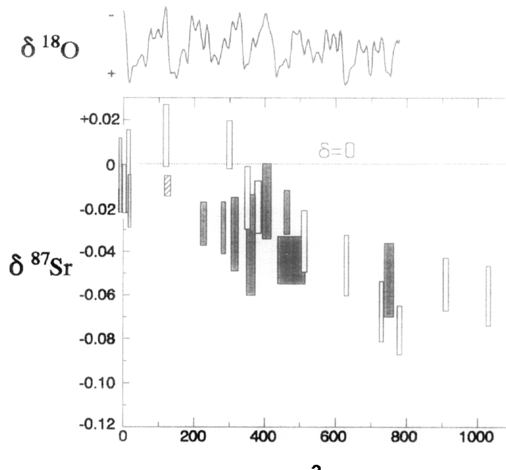

FIG. 8. Variation in $\delta^{87}Sr$ of samples from submerged Hawaiian terraces (shaded boxes) as a function of age, together with data from deep-sea sediment carbonates (open boxes; Capo and DePaolo, 1990). Zero-age sample offset slightly to left for clarity. Data pooled (weighted means) for samples with analytically indistinguishable ages and $\delta^{87}Sr$ (uncertainties in the precise relation of individual samples to location within the reef make the $^{234}U/^{238}U$ age a better pooling criteria than reef depth; Ludwig *et al.*, 1991); box with diagonal lines at 125,000 yr is weighted mean for the 133,000-yr Hawaiian sample plus the two 120,000- to 125,000-yr California terrace samples. Vertical dimension of all boxes indicates analytical uncertainty in $\delta^{87}Sr$. (To permit direct comparison between data sets, uncertainties for the data of Capo and DePaolo (1990) were assigned on the basis of the average 12×10^{-6} per analysis 95% confidence limit reproducibility that we calculate for replicate analyses given in that paper.) Width of shaded boxes indicates analytical uncertainty in age. Top curve shows secular variation in $\delta^{18}O$ of deep-sea sediment (Imbrie *et al.*, 1984).

and 14 of 410,000, 610,000, 790,000 and 900,000 yr, respectively.

These age estimates for the SNI terraces differ from those of previous investigators. Age estimates based on uranium-trend dating for terraces 5 and 8 (Muhs *et al.*, 1989) are older than our Sr-isotope/uplift-rate estimates, and age estimates for terraces 5 and 10 based on nonlinear amino-acid racemization kinetics (Wehmiller and Belknap, 1978) are much younger. The age estimates from amino-acid racemization also require that pre-late Quaternary uplift rates were higher than the uplift rate for the last 125,000 yr, decreasing by at least a factor of 2 from the middle to the late Quaternary. If uplift of SNI is the result of a vertical component of movement along the fault that borders the southwest side of the island, then both our data and those of Wehmiller and Belknap (1978) imply that this vertical component of movement was greater before 125,000 yr ago. For PVH, the Sr-isotopic method lacks the precision to address differences in uplift rates before the late Quaternary compared to uplift rates in the past 125,000 yr. An uplift rate of ~0.32 mm/yr is a reasonable *minimum* estimate of the rate of vertical movement of the Palos Verdes fault. Holocene rates of vertical movement on the Palos Verdes fault are estimated to be of the same magnitude, ranging from 0.1 to 0.4 mm/yr (Fischer *et al.*, 1987).

IS THERE A GLACIAL–INTERGLACIAL CONTRAST IN MARINE $^{87}SR/^{86}SR$?

Regardless of assumed uplift rates, there is no apparent contrast in the Sr-isotopic record of samples from the California terraces of interglacial age compared to that of the Hawaiian terraces of glacial age. This assertion is best documented for the well-dated samples (terrace 2 on SNI and SCI, and sample 16 off Hawaii) that should straddle the glacial–interglacial transition at ~120,000–130,000 yr. For this time period, the maximum difference between glacial and interglacial marine $^{87}Sr/^{86}Sr$ is between −0.0265 and +0.0095‰ (pooling the SNI and SCI data and taking into account analytical errors). Although the ages of the higher California terraces are much less certain, the consistency of their Sr-isotopic ratios with those of the Hawaiian terrace samples in the same general age range also indicates that any glacial–interglacial contrast in the marine Sr-isotopic record must be small, and does not encompass Sr-isotopic ratios greater than that of modern seawater. These observations are consistent with modeling of the Sr-isotope budget of the oceans, which shows that abrupt (<100,000 yr) variations of more than about 0.05‰ are unlikely because of the large damping effect exerted by the long residence time of Sr in the oceans (Hodell *et al.*, 1990).

USING THE MARINE $^{87}SR/^{86}SR$ TREND FOR QUATERNARY GEOCHRONOMETRY

The ideal time period for the application of Sr-isotope stratigraphy to geochronometry is at a geologic time interval wherein the marine $^{87}Sr/^{86}Sr$ was changing rapidly and monotonically. For marine carbonates of late Tertiary age, these conditions are essentially met, as the range of $^{87}Sr/^{86}Sr$ during that time is very large compared to the obtainable precision in measurement and intervals where $^{87}Sr/^{86}Sr$ is nearly constant lasted no more than ~2 myr. For the Quaternary, however, the situation is much less favorable.

For the past 2.4 myr, the general trend of marine $^{87}Sr/^{86}Sr$ values has been an increase of roughly 0.007‰ per 100,000 yr (Capo and DePaolo, 1990; this study). At present, the routine (although not ultimate) run-to-run precision of a single $^{87}Sr/^{86}Sr$ analysis with mass spectrometers of modern design is on the order of 0.02–0.03‰ (95% confidence), so that even if (1) fine-structure superimposed on a linear secular marine $^{87}Sr/^{86}Sr$ trend is ignored, and (2) a linear $^{87}Sr/^{86}Sr$ trend is assumed and precisely known, the best age resolution that can be expected from a routine single measurement for the past 2.4 myr is approximately 300,000 yr. But given the evidence for fine structure in the secular marine $^{87}Sr/^{86}Sr$ trend of up to 0.02‰ (e.g., the reversal between 900,000 and 700,000 yr suggested by Capo and DePaolo's (1990) DSDP-590B data and our SNI data), it seems likely that the best single-analysis age resolution that can be expected for carbonates for much of the Quaternary is on the order of 400,000–500,000 yr. Moreover, neither improvements in analytical precision (for samples of unknown age) nor moderate increases in the sampling density with which the secular marine $^{87}Sr/^{86}Sr$ trend is inferred is liable to yield more than modest improvement in geochronometric precision.

APPENDIX: ANALYTICAL TECHNIQUES

Samples (>95% aragonite) were mechanically cleaned to expose interior portions of the fossils, ultrasonically cleaned in acetone followed by water, and dissolved in 1 *N* HCl. Sr was purified with conventional ion-exchange methods, then loaded onto a rhenium triple-filament assembly and analyzed with an automated Isomass 54E single-collector mass spectrometer. Amplifier nonlinearity effects were minimized by acquiring data within a 70 ± 5 pA ion-beam window. Amplifier time-constant effects were very small (11 ppm "memory" after 1.5 sec), and largely corrected in any case by ANALYST (Ludwig, 1985). Mass-

TABLE 2. SR-ISOTOPE DATA FOR ELEVATED TERRACES

Location	Terrace[a]	Sample species[b]	δ^{87}Sr (‰)[c]	Number of analyses
San Nicolas Island	Modern	A *E.c.*	+0.013 ± 11	4
		B *E.c.*	+0.001 ± 12	3
		C *E.c.*	−0.006 ± 12	3
		D *E.c.*	+0.002 ± 17	2
		E *E.c.*	−0.002 ± 17	2
	Weighted mean	—	+0.0025 ± 57	14
	2 (32 m) *120,000 yr*	SNI2-A *E.c.*	−0.007 ± 11	5
		B *E.c.*	−0.005 ± 11	5
		C *E.c.*	+0.003 ± 15	2
		D *E.c.*	−0.013 ± 17	2
		E *E.c.*	−0.010 ± 17	2
	Weighted mean	—	−0.0059 ± 59	16
	3 (80 m)	SNI3-A *E.c.*	−0.019 ± 11	4
		B *E.c.*	−0.012 ± 12	4
		C *E.c.*	−0.028 ± 12	4
		D *E.c.*	−0.025 ± 12	4
		E *E.c.*	−0.025 ± 14	3
	Weighted mean	—	−0.0210 ± 53	19
	4 (97 m)	SNI4-A *E.c.*	−0.038 ± 15	2
		B *E.c.*	−0.026 ± 11	4
		C *E.c.*	−0.029 ± 16	2
		D *E.c.*	−0.036 ± 17	2
		E *E.c.*	−0.028 ± 17	2
	Weighted mean	—	−0.0305 ± 64	12
	5 (120 m)	SNI5-A *E.c.*	−0.068 ± 22	1
		B *E.c.*	−0.052 ± 14	2
		C *E.c.*	−0.053 ± 15	2
		D *E.c.*	−0.047 ± 17	2
		E *E.c.*	−0.033 ± 17	2
	Weighted mean	—	−0.0496 ± 72	9
	8 (183 m)	SNI8-A *E.c.*	−0.021 ± 18	2
		B *E.c.*	−0.023 ± 18	2
		C *E.c.*	−0.045 ± 38	1
		D *E.c.*	−0.031 ± 20	2
		E *E.c.*	−0.032 ± 19	2
		M *O.*sp.	−0.035 ± 22	1
		N *O.*sp.	−0.024 ± 22	1
		O *O.*sp.	−0.037 ± 20	2
		P *O.*sp.	−0.027 ± 24	1
		Q *O.*sp.	−0.051 ± 14	3
		V *T.g.*	−0.046 ± 20	2
		W *T.g.*	−0.058 ± 28	2
		X *T.g.*	−0.039 ± 18	2
		Y *T.g.*	−0.049 ± 16	2
		Z *T.g.*	−0.066 ± 24	1
	Weighted mean	—	−0.0386 ± 50	26
	10 (240 m)	SNI10-A *E.c.*	−0.065 ± 16	2
		B *E.c.*	−0.092 ± 15	2
		C *E.c.*	−0.083 ± 15	3
		D *E.c.*	−0.068 ± 17	2
		E *E.c.*	−0.063 ± 17	2
	Weighted mean	—	−0.0753 ± 70	11
	14 (274 m)	SNI14-A *E.c.*	−0.061 ± 17	2
		B *E.c.*	−0.049 ± 18	2
		C *E.c.*	−0.064 ± 21	2
		D *E.c.*	−0.037 ± 23	2
		E *E.c.*	−0.064 ± 24	2
	Weighted mean	—	−0.0553 ± 88	10
San Clemente Island	2 (32 m) *125,000 yr*	SCI2-A *E.c.*	−0.030 ± 17	2
		B *E.c.*	−0.008 ± 17	2
		C *E.c.*	−0.011 ± 16	2

TABLE 2—*Continued*

Location	Terrace[a]	Sample species[b]	δ^{87}Sr (‰)[c]	Number of analyses
		D *E.c.*	−0.011 ± 16	2
		E *E.c.*	−0.041 ± 29	1
	Weighted mean	—	−0.0157 ± 78	9
	5 (100 m)	SCI5-A *T.g.*	−0.022 ± 17	2
		B *T.g.*	−0.041 ± 15	2
		C *T.g.*	−0.050 ± 16	2
		D *T.g.*	−0.051 ± 20	1
		E *T.g.*	−0.042 ± 20	1
	Weighted mean	—	−0.0427 ± 71	8
Palos Verdes Hills	2 (46 m)	PVH2-A *E.c.*	−0.017 ± 16	2
	125,000 yr	B *E.c.*	−0.006 ± 22	1
		C *E.c.*	−0.011 ± 20	1
		D *E.c.*	−0.003 ± 25	1
		E *E.c.*	−0.006 ± 18	2
	Weighted mean	—	−0.0099 ± 86	7
	5 (137 m)	PVH5-A *E.c.*	−0.015 ± 16	2
		B *E.c.*	−0.019 ± 16	2
		C *E.c.*	−0.014 ± 16	2
		D *E.c.*	−0.017 ± 19	2
		E *E.c.*	−0.024 ± 20	1
	Weighted mean	—	−0.0173 ± 75	9
	7 (183 m)	PVH7-A *E.c.*	−0.026 ± 12	4
		B *E.c.*	−0.025 ± 13	4
	Weighted mean	—	−0.0255 ± 86	8
	9 (290 m)	PVH9-A *E.c.*	−0.025 ± 14	2
		B *E.c.*	−0.019 ± 15	2
		C *E.c.*	−0.039 ± 17	2
		D *E.c.*	−0.037 ± 21	1
		E *E.c.*	−0.035 ± 24	1
	Weighted mean	—	−0.0288 ± 75	8
	12 (370 m)	PVH12-A *E.c.*	−0.033 ± 10	6
		B *E.c.*	−0.050 ± 11	5
		C *E.c.*	−0.042 ± 14	3
		D *T.g.*	−0.050 ± 18	2
		E *T.g.*	−0.024 ± 29	1
	Weighted mean	—	−0.0409 ± 58	17

[a] Elevation of terrace inner edge (shoreline angle) given in parentheses after terrace number. Where known, age of terrace is given in italics.
[b] *E.c.*, *Epilucina californica; T.g.*, *Tegula gallina; O.*sp., *Olivella* sp. All samples were >95% aragonite, except for *Tegula*, which precipitates both calcite and aragonite.
[c] δ^{87}Sr is the difference between the ^{87}Sr/^{86}Sr of the sample and that of present-day seawater Sr, as represented by our modern marine-carbonate standard EN-1 (Ludwig *et al.*, 1988); uncertainties are 95% confidence limits, and represent the weighted mean (weighted by inverse square of analytical errors) of the values from the number of replicate analyses given in column to right.

dependent fractionation was corrected assuming an ^{86}Sr/^{88}Sr of 0.1194 and an exponential fractionation law. Data were acquired for about 2.5 hr to achieve a within-run precision (95% confidence limit) for the ^{87}Sr/^{86}Sr ratio of better than 10×10^{-6}. Every fourth run was of our modern marine-carbonate standard EN-1 (Ludwig *et al.*, 1988), so that we could monitor run-to-run precision and any instrumental drift. Over most of the study, the mean measured ^{87}Sr/^{86}Sr for the EN-1 standard was 0.70925, which (because of amplifier nonlinearity) is probably about 0.14‰ higher than the "true" value.

Errors were calculated at the 95% confidence limit from the sum of variances from (1) the within-run statistics, (2) the "external" variance (i.e., variance in run-to-run reproducibility not accounted for by within-run statistics) indicated by multiple replicate analyses of the EN-1 standard during

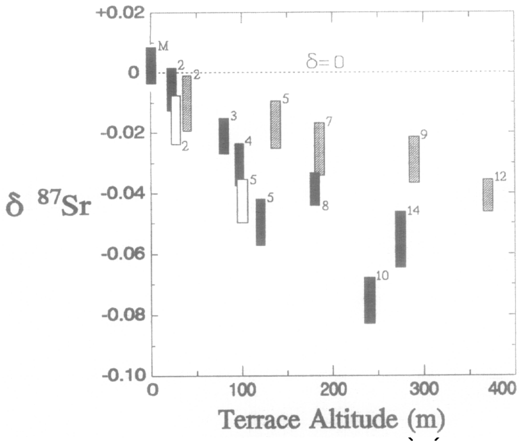

FIG. 9. Sr-isotopic composition of fossils from elevated marine terraces in southern California as a function of elevation. Boxes indicate weighted-mean values for all samples from a given terrace; vertical dimension shows analytical uncertainty. Solid boxes, SNI; open boxes, SCI; diagonal-lined boxes, PVH. Numbers at corners of boxes indicate terrace number; dotted line shows $\delta^{87}Sr$ for modern seawater.

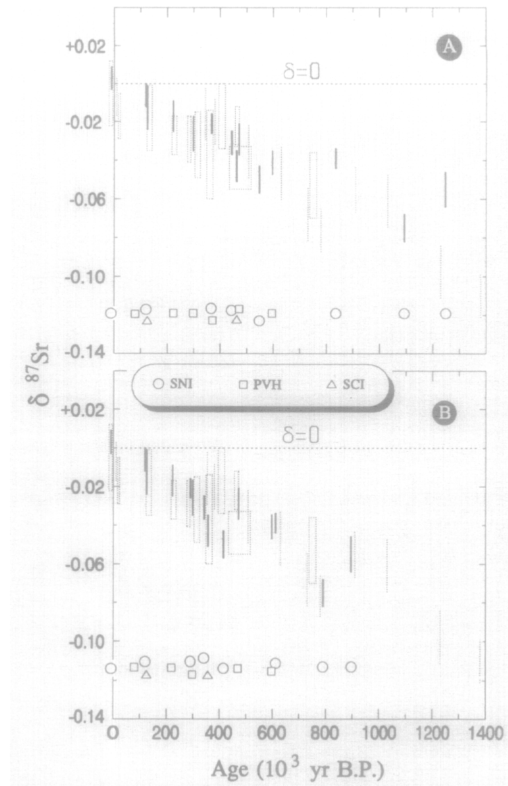

FIG. 10. Sr-isotopic compositions versus estimated age for fossils from elevated marine terraces in southern California, compared to high-precision marine-carbonate data. Solid lines, California terrace fossils (locality indicated by open symbols directly below); dotted boxes, corals from submerged Hawaiian terraces (data pooled for similar ages); dotted lines, DSDP carbonates (Capo and DePaolo, 1990, excluding two samples with anomalously high δ values). Vertical dimension of line and box symbols, analytical error in $\delta^{87}Sr$; width of dotted boxes, $^{234}U/^{238}U$ age error; zero-age samples offset to left of Y-axis for clarity. (A) Ages of >125,000-yr California terraces are estimated from uplift rates of 0.22 mm/yr (SNI, SCI) or 0.32 mm/yr (PVH), as calculated from the height of the corresponding second terrace. (B) Ages of >125,000-yr California terraces are estimated from uplift rates of 0.32 mm/yr for all terraces. Use of the higher uplift rate for SNI gives a better match to the marine Sr-isotopic trend (no significant difference for SCI).

the relevant time interval, and (3) the uncertainty in the mean of the suite of EN-1 runs for the appropriate time interval. Typical uncertainties in $^{87}Sr/^{86}Sr$ associated with (1), (2),and (3) were 10×10^{-6}, 13×10^{-6}, and 4×10^{-6}, respectively. The overall uncertainties are not necessarily comparable with those reported by other workers, in that the "external" error component was well characterized, and the appropriate Student's t multipliers were used to convert standard errors to 95% confidence limit errors.

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