STRONTIUM ISOTOPE EVIDENCE FOR TIMING OF TERTIARY CRUSTAL EROSION SANTA CRUZ ISLAND

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ABSTRACT

Tertiary rocks on Santa Cruz Island record the erosion products of mid-crustal igneous rocks (Vaqueros Formation), blueschist-bearing subduction rocks (San Onofre Breccia), and products of active volcanism (Beechers Bay and Blanca Formations). The time span of deposition for the Oligocene-Miocene Vaqueros Formation through Miocene Beechers Bay-Blanca Formations, based on biochronology, is between 8 million years (Ma) and at least 17 Ma. This study measured strontium isotopic ratios in pectens and oysters from the Vaqueros and Blanca Formations and San Onofre Breccia. The ratios were correlated with the strontium sea water curve for an age estimate. Diagenetically unaltered samples were selected based on visual inspection, carbon and oxygen isotopic analysis, and x-ray diffraction (XRD). The strontium isotopic method yielded an age of 19 ± 1 Ma (early Miocene) for the upper Vaqueros Formation. Strontium ratio results from the San Onofre Breccia-Rincon Formation boundary indicate an age of 18.5 ± 1 Ma. The results from the basal Blanca Formation indicate an age of 19 ± 1 Ma, which is the same age as an unpublished result obtained on the basal Blanca Formation. The results of this study narrowly constrain the time span of deposition of the strata and indicate that volcanism, sedimentation, and inferred unroofing occurred almost synchronously at approximately 19 Ma.

Keywords: Santa Cruz Island, strontium isotopes, Vaqueros Formation, San Onofre Breccia, Blanca Formation, Transverse Ranges.

INTRODUCTION

Purpose

In this study, strontium isotope work was undertaken to determine the age of Oligocene-Miocene rocks of the Vaqueros, Rincon, Beechers Bay[1], and Blanca Formations and San Onofre Breccia in outcrops on the southwest part of Santa Cruz Island from Canada Posa Canyon to Laguna Canyon (Figure 1; Figure 2). This is the first study to use strontium isotopes to estimate the age of the strata on the southwest part of Santa Cruz Island. Previously, the formation ages were constrained solely by biochronology from marine fossils (Bereskin and Edwards 1969). A comparison of their faunal ages with Correlation of Stratigraphic Units of North America (COSUNA) time charts (Lindberg 1984) indicates wide age ranges with overlapping boundaries during the late Saucesian and Relizian (Figure 3). Strontium isotope ratios of oysters and pectens were measured and compared to published strontium ratios of Tertiary sea water. The results constrain the formation's boundaries to narrower time intervals than those from the biostratigraphic studies. Based on our new understanding of the timing of deposition of the Miocene strata, we infer that there was rapid erosion (uplift?) of deep crustal rocks within the Transverse Range block during the Miocene.

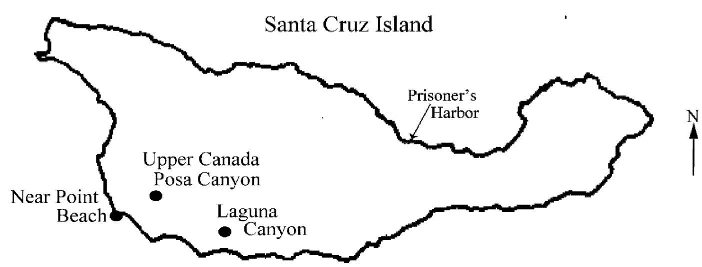

Figure 1. Location map showing sample areas, southwest Santa Cruz Island.

Previous Work

The age and biostratigraphy of the sedimentary rock units on Santa Cruz Island have been broadly defined by paleontological work of Bereskin (1966) and Doerner

[1] The Beechers Bay was originally defined as a member of the Monterey Formation; but, due to its volcaniclastic character, we use the term "Beechers Bay Formation" (Howell and McLean1976).

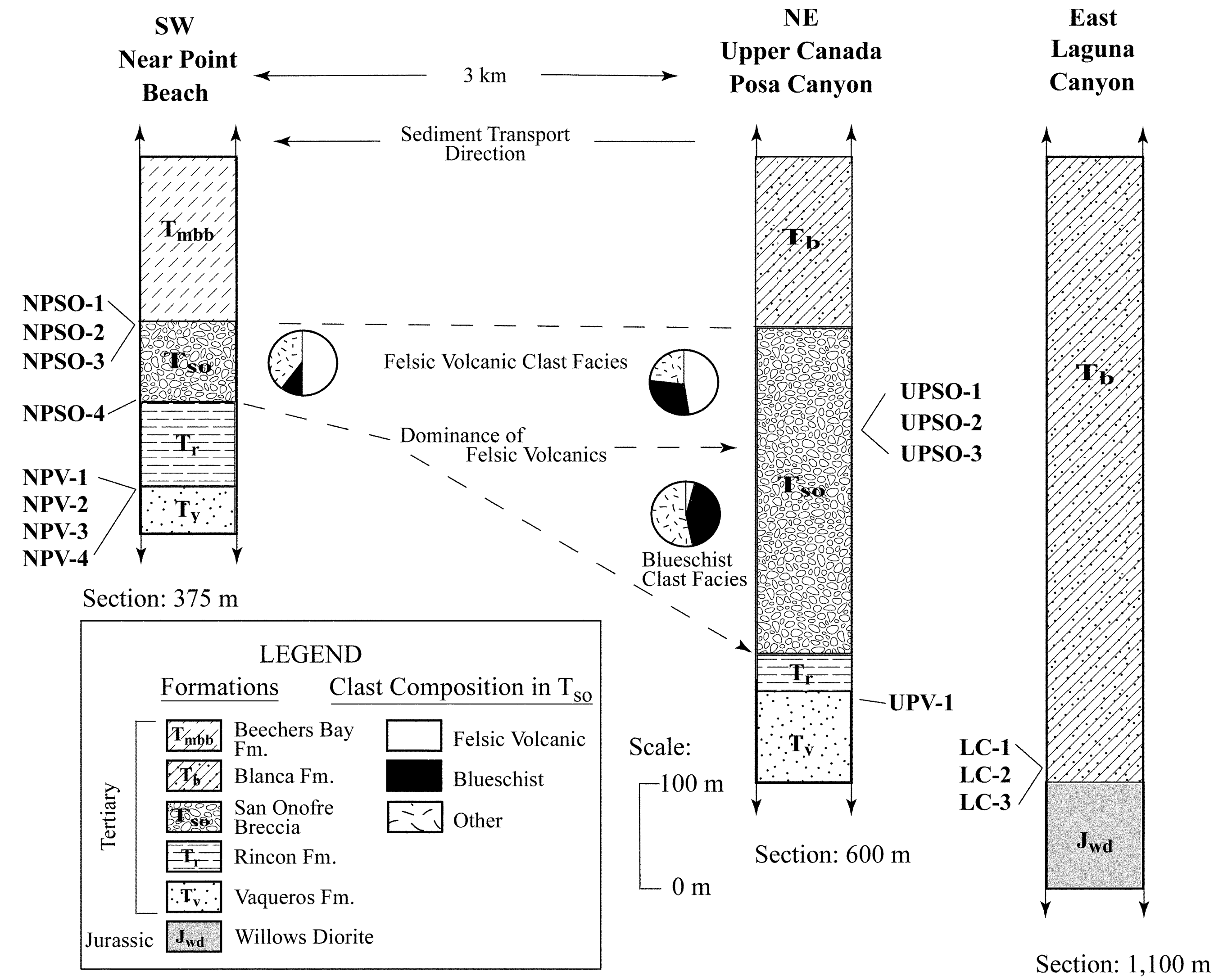

Figure 2. Stratigraphic columns of Miocene strata in Near Point Beach outcrops (distal facies), upper Canada Posa Canyon (proximal facies), and Laguna Canyon on Santa Cruz Island. The pie charts indicate the percentages of clast types in the San Onofre Breccia, (representative clast counts of greater than 100 pebble-size clasts in 1 m^2 grids) (Boles 1997). Sample locations are indicated in stratigraphic sections.

(1968), and are summarized in Weaver et al. (1969). Using the biostratigraphic time correlations from COSUNA (Lindberg 1984), we have estimated the biostratigraphic ages for the units (Figure 3) as follows: the Vaqueros as early Saucesian (~30 to 24 Ma), the Rincon as middle Saucesian to late Saucesian (~24 to 17.0 Ma), the San Onofre as late Saucesian to Relizian (~17.1 to 15.4 Ma), and the Beechers Bay-Blanca Formations as Relizian through Luisian, possibly Mohnian (~15.8 to 13 Ma). Based on these ages, deposition of the Vaqueros Formation through Beechers Bay-Blanca Formations represents a minimum time interval of 8 Ma to as much as at least 17 Ma. Our results suggest deposition occurred in a significantly shorter time interval.

Prior to this study, one fossil from the southwest corner of Santa Cruz Island was collected for strontium analysis. The fossil was collected at the Blanca-San Onofre boundary in upper Canada Posa Canyon. The $^{87}Sr/^{86}Sr$ value of 0.7086 correlates with an age of approximately 19 Ma, early Miocene (J. Schultz, UCSB, unpublished data). The biochronologic age suggested by the work of Bereskin and Edwards (1969) for the equivalent Beechers Bay-San Onofre boundary at Near Point Beach is 5 Ma older than the Blanca-San Onofre boundary determined by Schultz.

The age of the sparsely fossiliferous, volcaniclastic Blanca Formation is based on Potassium/Argon (K/Ar) dating. A volcanic clast from the middle member of the Blanca Formation yielded a K/Ar age of 13.3 ± 0.8 Ma, middle Miocene (McLean et al. 1976). An andesite flow from the upper member of the Blanca Formation yielded K/Ar ages of 14.9 ± 0.8 Ma (McLean et al. 1976). On the bases of these K/Ar dates, the age of the Blanca Formation is interpreted as late Saucesian to early Luisian.

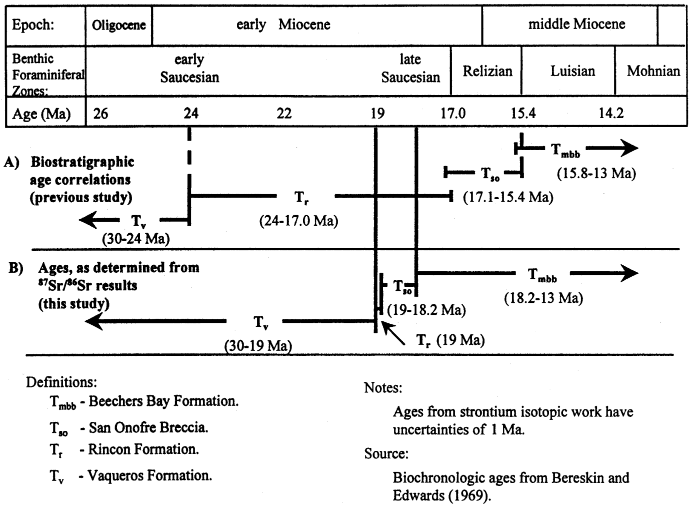

Figure 3. Time chart comparing ages of stratigraphic units determined from A) previous studies, based on biochronology and B) this study, based on $^{87}Sr/^{86}Sr$ results.

STRATIGRAPHY AND SAMPLE COLLECTION

Representative stratigraphic sections of the Vaqueros Formation, Rincon Formation, San Onofre Breccia, Beechers Bay Formation, and Blanca Formation are exposed along a three-kilometer transect from upper Canada Posa Canyon southwest to Near Point Beach (Figure 2). Correlation of the stratigraphic units at Near Point Beach with those at upper Canada Posa Canyon indicates the thickness of the units decreases from northeast to southwest (the general direction of sediment transport). The section at Laguna Canyon is 1,100 meters (m) thick, the upper Canada Posa Canyon section is 600 m thick, and the Near Point Beach section is 375 m thick. Two outstanding differences between the Near Point Beach section and the upper Canada Posa Canyon section are: 1) the Rincon Formation is comparatively thinner in the upper Canada Posa Canyon section, and 2) the San Onofre Breccia at Near Point Beach is finer grained, thinner bedded, and has a higher volcanic/blueschist clast ratio compared to upper Canada Posa Canyon outcrops (Figure 2) (Boles 1997). The following summary of these formations is taken from Boles (1997); interpretations of depositional environments are those of Weaver and others (1969).

The Oligocene-Miocene Vaqueros Formation (disconformably overlying the Eocene Cozy Dell Shale) is a brown, thick-bedded, conglomerate overlain by brown sandstone. It is interpreted as having been deposited in an inner shelf to nonmarine environment, based on paleoecology and stratigraphic evidence. Marine fossil samples from the Vaqueros Formation were collected at Near Point Beach from the coarse sands and conglomerates within the upper 20 m of the stratigraphic section (Figure 2). The sample from upper Canada Posa Canyon was collected approximately 32 m below the Vaqueros-Rincon boundary.

The Rincon Formation and the San Onofre Breccia are Miocene in age. The Rincon Formation is a gray to brown, calcareous shale and mudstone. The depositional environment of the Rincon Formation at Near Point Beach is interpreted as middle to outer shelf (Bereskin and Edwards 1969).

The San Onofre Breccia is a bluish-gray conglomerate, sandstone, and mudstone. The upper Canada Posa Canyon section was deposited in a very shallow marine environment; whereas, the Near Point Beach section was deposited approximately 5 km in the direction of sediment transport. The samples collected from Near Point Beach are from the uppermost conglomerate of the San Onofre Breccia. The sample collected from the lower San Onofre Breccia at Near Point Beach is from the lowermost conglomerate above the Rincon Formation. The samples collected from upper Canada Posa Canyon are from approximately two-thirds up in the formation.

The Beechers Bay and Blanca Formations are time-equivalent Miocene units. The Beechers Bay Formation is a gray, thin-bedded siltstone to fine-grained volcaniclastic sandstone. The Blanca Formation is a light gray to buff, thick-bedded, volcaniclastic conglomerate, tuffaceous sandstone, and tuff. These strata were deposited on a relatively shallow shelf. The samples collected from the Blanca Formation are from the basal 5 m of the formation.

METHODS

We have compared strontium isotope ratios from marine shell tests with the time variations of $^{87}Sr/^{86}Sr$ values in sea water (Oslick et al. 1994). Oslick et al. (1994) data are based on comparing $^{87}Sr/^{86}Sr$ values of planktonic foraminifera to magnetostratigraphy that is constrained to about 40,000-yr variations. The $^{87}Sr/^{86}Sr$ value in sea water, currently 0.70906, is homogeneous because strontium has a long residence time in the ocean (about 5 x 10^6 yr), compared with the mixing time of the oceans (10^3 yr) (Faure 1997). The ratio of strontium in sea water has systematically increased in the past 30 Ma. Because oyster and pecten shells incorporate the same ratio of strontium in sea water into their shells, comparison of the ratio of strontium in the fossils to the strontium sea water curve yields age estimates. Recent resolution of the sea water curve (Oslick et al. 1994) permitted assignments of ages with a narrow range of uncertainty (± 1 Ma). The method described depends on selecting unaltered fossils that retain their original strontium isotopic ratio. Our selection criteria are described below.

Selection

Shell material was first selected by visual inspection. Criteria used to help select unaltered material included translucency, foliation of material, and retention of opalescence. Shell material lacking these qualities was avoided as it had a higher possibility of having undergone alteration of the original strontium isotopic ratio. Relatively large aliquots of powdered sample (0.4 grams) were prepared to ensure homogeneity for carbon, oxygen, and strontium isotopic analyses and x-ray diffraction (XRD).

Carbon and oxygen isotope values were used to determine if, and to what extent, the original $\delta^{18}O$ and $\delta^{13}C$ values of the shells were reset. Unaltered carbonate fossils should have $\delta^{18}O$ and $\delta^{13}C$ values close to 0 parts per million (‰) relative to the Cretaceous Peedee Formation standard (PDB). The $\delta^{13}C$ values of modern marine mollusks around the world vary within a small range of +4.2‰ to -1‰, and values have not appreciably changed since Cambrian times (Faure 1997). The $\delta^{18}O$ values are more variable throughout the oceans, and can be affected by ocean temperature (Faure 1997). Miocene waters had lower $\delta^{18}O$ values than today by approximately -1.5‰ (J. P. Kennett, pers. comm.). Because shells attain the same $\delta^{18}O$ values as the waters in which they form, values of -2‰ are reasonable for Miocene unaltered oysters. It is also possible that some of the oysters grew in brackish water, which would have a slightly negative $\delta^{18}O$ value. However, differences in temperature and salinity of the oceans during shell formation can cause unaltered shells to have values greater than 1‰ and less than -1‰. Based on the above, we considered samples with $\delta^{18}O$ and $\delta^{13}C$ values within ± 2.5‰ of 0‰ (PDB scale) to be unaltered and suitable for further analysis.

XRD analysis was conducted on a few samples to determine if the shells were pure calcite or had some impurities or alterations (such as clay, gypsum, dolomite, siderite, etc.) that could affect their strontium isotopic ratio. Analysis of five, randomly selected, apparently unaltered samples (based on visual and stable isotopic composition) indicated they were all pure calcite. The other remaining samples were not analyzed for their mineral composition because we believe visual inspection for impurities and oxygen and carbon isotopic analysis are more sensitive indicators of diagenetic alteration. Further analysis of the strontium concentration in the samples would have additionally helped in determining if diagenesis had occurred. Because oysters and pectens typically have greater than 1,000‰ strontium, a lower concentration could possibly indicate that strontium has been removed and the ratio likely reset.

Analytical Techniques

Unaltered samples were dissolved in dilute HCl (<0.2 M). After evaporation, residues were re-dissolved in 3 M HNO_3. Standard ion-exchange chromatography (Sr Spec resin, ElChrom Ind.'s Inc.) was employed to concentrate the strontium (G. Tilton, UCSB, unpublished data). Sr Spec resin is especially selective in separating calcium and other elements from strontium. Strontium concentrates were then analyzed on a Finnigan MAT 261 multicollector mass spectrometer at the Mattinson Laboratory in the Geological Sciences Department at the University of California, Santa Barbara (UCSB). Carbon and oxygen isotope values were determined using a VG mass spectrometer at the Kennett Laboratory in the Geological Sciences Department, UCSB. Samples with high $\delta^{13}C$ values (>2.5‰ and <-2.5‰) were deemed unacceptable, as the values likely indicate alteration.

RESULTS

Samples

Fifteen total samples of oysters and pectens were analyzed from Near Point Beach, upper Canada Posa Canyon, and Laguna Canyon (Figure 1; Figure 2). The complete stratigraphic sequence at Near Point Beach is exposed, which allowed us to obtain samples from the upper Vaqueros, lower San Onofre, and upper San Onofre (Figure 2). Eight samples analyzed were from this site. Four samples from the upper Vaqueros and middle San Onofre were also collected in upper Canada Posa Canyon. Three samples from the Blanca Formation were analyzed from upper Laguna Canyon. The stratigraphic locations of the analyzed samples are shown in Figure 2.

Carbon-Oxygen Results

Oxygen and carbon isotopic compositions were measured for thirteen of the fifteen samples. Three samples (LC-2, LC-3, and UPSO-2) had $\delta^{18}O$ and $\delta^{13}C$ values that approach or exceed -2.5‰ (Table 1), and are considered to be altered. Sample UPSO-2 appeared to be highly altered, as there was visible calcite growth between shell layers of the oyster. For comparison, sample UPSO-1, which was collected from the same location and did not appear altered, has $\delta^{18}O$ and $\delta^{13}C$ isotopic values within -2.5‰ of 0‰. The corrected carbon isotope results of sample UPSO-2 were below average (-6‰) compared with most other samples (-2‰). In addition, the strontium isotope ratios of UPSO-1 and UPSO-2 yielded different age results: 19.1 and 20.5 Ma respectively. These results support our selection criteria of using visual inspection and carbon and oxygen isotopes to gauge diagenetic alteration in the samples.

Strontium Results

The measured $^{87}Sr/^{86}Sr$ values are reported in Table 1 along with the analytical errors. The age reported in Table 1 was derived by comparing the $^{87}Sr/^{86}Sr$ value with the Miocene sea water curve of Oslick et al. (1994). In the study by Oslick et al. (1994), the Oligocene-Miocene data were fitted with two linear regression models. For the time period between 15.6 and 22.8 Ma (0.708789 to 0.708305) the determined slope was 0.000068 per Ma. Therefore, data were correlated to a trend line, $t = -(1/0.000068)*x + 10,439$, where t is the resulting age correlation, x is the $^{87}Sr/^{86}Sr$ isotopic result, and 10,439 is the y-intercept.

Uncertainties of strontium isotopic measurements are listed in Table 1. The largest uncertainty results in an age of ± 400,000 years. The analytical uncertainty of the correlated data from Oslick et al. (1994) is ± 1 Ma. Therefore, the uncertainty of ± 1 Ma given for all the age values is the estimated range of the data from Oslick et al. (1994).

Near Point Beach

The data of the Near Point Beach samples are presented in Figure 4. The $^{87}Sr/^{86}Sr$ results of the Vaqueros

Table 1. $^{87}Sr/^{86}Sr$, carbon and oxygen isotopic analyses of oysters and pectens from Santa Cruz Island.

Location	Sample #	Age*1 (Ma)	$^{87}Sr/^{86}Sr$*2	Standard Error*3	Sr Concentration	$\delta^{18}O$ PDB	$\delta^{13}C$ PDB
Near Point Beach							
Upper San Onofre	NPSO-1	18.2	0.708613	–0.000018		-1.200	-0.254
Breccia	NPSO-2	16.6	0.708721	–0.000020	810 Sr	n/a	n/a
	NPSO-3	16.5	0.708727	–0.000020	405 Sr	-2.078	-2.004
Lower San Onofre	NPSO-4	18.5	0.708593	–0.000015		-2.004	0.319
Breccia		18.6	0.708586	–0.000014			
Upper Vaqueros Fm.	NPV-1	18.9	0.708574	–0.000014		-1.893	-1.720
		18.4	0.708598	–0.000011			
	NPV-2	19	0.708563	–0.000015		-1.923	-2.094
	NPV-3	19.4	0.708535	–0.000016		-2.042	-2.060
	NPV-4	19.5	0.708526	–0.000027		-2.012	-1.422
		19.8	0.708509	–0.000023			
Upper Canada Posa Canyon							
San Onofre	UPSO-1	19.1	0.708554	–0.000017		-2.314	-2.300
Breccia	UPSO-2	20.5	0.708457	–0.000026		-1.607	-5.996
	UPSO-3	19	0.708559	–0.000012		n/a	n/a
Vaqueros Fm.	UPV-1	18.7	0.708581	–0.000024		-0.520	0.255
Laguna Canyon							
Blanca Fm.	LC-1	19.8	0.708508	–0.000017		-2.488	-2.123
	LC-2	-	0.705948	–0.000015	810 ppm Sr	-9.547	-15.273
	LC-3	nd	nd	nd		-1.155	-11.266
		987 Standards					
	2/20/98		0.710244	–0.000013			
	2/22/98		0.710224	–0.000013			
	2/23/98		0.710251	–0.000012			
	5/2/98		0.710259	–0.000015			
	5/3/98		0.710253	–0.000014			

Definitions:

$\delta^{13}C$ - Delta carbon 13

$\delta^{18}O$ - Delta oxygen 18

n/a - Not analyzed

nd - Not determined, the strontium concentration of the sample was too low to analyze

PDB - The PDB is the most widely used standard to determine the fractionation of carbon or oxygen isotopes. It is prepared from belemnites (Belemnitella americana) collected from the Cretaceous Peedee Formation.

- Parts per million

Notes:

*1 - Correlated age from Oslick et al. (1994).

*2 - Standards were run intermittently throughout analysis and the 987 reference sample data are within the commonly accepted value of 0.701250. Since the standard 987 data falls within the accepted value of 0.701250, the $^{87}Sr/^{86}Sr$ ratios are not adjusted.

*3 - Standard error of the mean: (2sigma)x10^{-6}

Comments:

Carbon and Oxygen Isotope analyses were from the Kennett Laboratory, Geology Dept., UCSB.

Samples UPSO-2, LC-2, and LC-3 may be altered, and their $^{87}Sr/^{86}Sr$ are suspect.

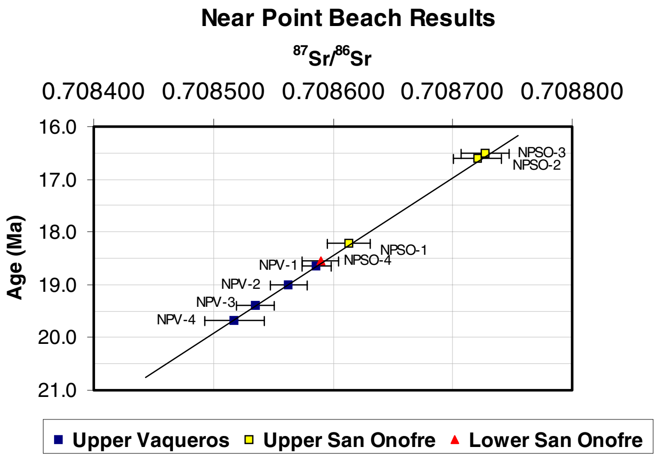

Figure 4. Graph showing results of Near Point Beach samples. Correlation of age with strontium isotopic ratios is based on Oslick et al. (1994).

Formation samples (NPV-1 through NPV-4) place their ages in the same relative order in which they were sampled from the stratigraphic column, indicating decreasing age (Figure 2) and confirming the validity of the strontium method. The data show that the boundary between the Rincon Formation and the upper Vaqueros Formation is 19 ± 1 Ma (early Miocene), at least 5 Ma younger than the 24 Ma age as suggested by biochronology of Bereskin and Edwards (1969). It is likely that this age of 19 ± 1 Ma approximates the age of the whole unit because the lower unit is comprised of thick-bedded conglomerate sequences that suggest rapid deposition.

One sample was analyzed from the lower San Onofre Breccia. The $^{87}Sr/^{86}Sr$ results of this sample indicated that the boundary between the lower San Onofre Breccia and the Rincon Formation is at 18.5 ± 1 Ma (early Miocene). Three samples were analyzed from the upper San Onofre. All three samples contained low amounts of strontium (<800‰). Results for sample NPSO-1 indicated an age of 18.2 ± 1 Ma. Two of these samples, NPSO-2 and NPSO-3, were spiked to check for strontium concentration in addition to the strontium isotopic values. The $^{87}Sr/^{86}Sr$ results for NPSO-2 and NPSO-3 correlated with ages of 16.6 Ma and 16.5 Ma, respectively. We believe that samples NPSO-2 and NPSO-3 have undergone some diagenetic alteration, due to the low concentration of strontium, (810‰ and 405‰, respectively). This would change the $^{87}Sr/^{86}Sr$ value; therefore, we believe the true depositional age of the upper San Onofre is closer to sample NPSO-1 at 18.2 ± 1 Ma (early Miocene).

Upper Canada Posa Canyon

The data for the San Onofre and Vaqueros samples from upper Canada Posa Canyon are shown on Figure 5. Strontium results of samples UPSO-1 and UPSO-3 from the middle San Onofre indicate an age of 19.1 ± 1 Ma and 19.0 ± 1 Ma, respectively (early Miocene). Results of sample UPV-1 from the top of the Vaqueros Formation correlate

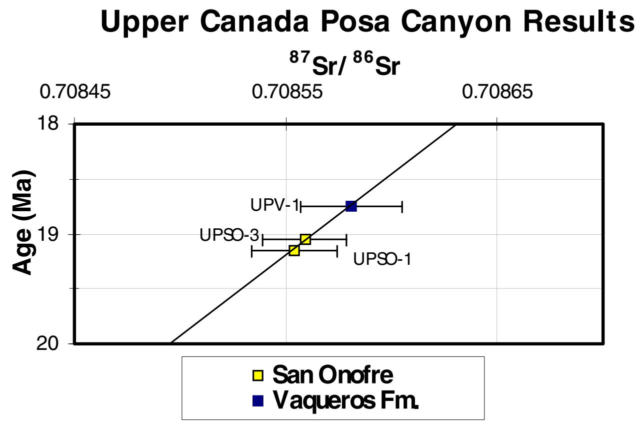

Figure 5. Graph showing results of upper Canada Posa Canyon samples. Correlation of age with strontium isotopic ratios is based on Oslick et al. (1994).

with an age of 18.7 ± 1 Ma. Although the results may appear to be problematic in light of the relative stratigraphic positions of the units (i.e., 18.7 Ma Vaqueros sample stratigraphically below the 19.0 Ma San Onofre Breccia samples), they are not problematic if their uncertainties are considered (e.g., Vaqueros sample may be as old as 19.0 Ma and San Onofre Breccia samples may be as young as 18.7 Ma).

Laguna Canyon

The results from sample LC-1, from the basal Blanca Formation, show a $^{87}Sr/^{86}Sr$ value of 0.708508. This ratio correlates with previous work by Schultz (unpublished data), which resulted in a $^{87}Sr/^{86}Sr$ value of 0.70856 for a basal Blanca Formation sample from upper Canada Posa Canyon. This close agreement of the data indicates that the age of the base of the Blanca Formation is 19 ± 1 Ma (early Miocene).

DISCUSSION

The results of this study of southwest Santa Cruz Island constrain the time interval of deposition for the Oligocene-Miocene strata (Figure 3). The strontium results for Near Point Beach and upper Canada Posa Canyon indicate the age of the formation boundaries as follows: the Vaqueros-Rincon boundary is at 19 ± 1 Ma; the Rincon-San Onofre Breccia boundary is at 18.5 ± 1 Ma; and the San-Onofre Breccia-Beechers Bay boundary is at 18.2 ± 1 Ma (early Miocene).

Our results indicate the Vaqueros Formation and San Onofre Breccia depositional ages on the island are much closer then previously believed. This work shows that the time interval represented by the Rincon Formation is very short (less than 1 Ma) and that the deposition of the Vaqueros Formation and San Onofre Breccia were nearly synchronous events. In contrast, the age of the Vaqueros Formation in the western Transverse Ranges is 26 ± 2 Ma, based on strontium isotopic ratios (Rigsby 1989). Also, the San Onofre Breccia is believed to be 17-13 Ma in the San Diego area.

These strata on the mainland represent a much larger time interval than on Santa Cruz Island.

These results are important to the chronology of tectonic reconstruction of the region. Before the onset of rotation of the Transverse Ranges, Santa Cruz Island and San Diego were in close proximity (Figure 6). Evidence for this is seen in paleomagnetic records (Kamerling and Luyendyk 1985), and in the similarity of Eocene conglomerates in San Diego and on Santa Cruz Island (Abbott and Smith 1978). During the Miocene, the western Transverse Range block rifted, rotated, and translated northwestward with the Pacific plate (Atwater 1997). As a result, the region in its wake underwent extreme extension and crustal unroofing that became the inner California Continental Borderland (Nicholson et al. 1994). The tectonic rearrangement during the early Miocene in the area of San Diego caused uplift (shedding of clastic sediment of the Vaqueros Formation) and unroofing of high-pressure, low-temperature metamorphic rocks (blueschists and greenschists). The metamorphic rocks are observed in the San Onofre Breccia in San Diego, on the Coronado Islands, and on Santa Cruz Island (Stuart 1979). The Catalina Schist is believed to be a source rock for the San Onofre Breccia (Stuart 1979; Boles 1997). The timing of the inception of rifting of the Transverse Range block and subsequent unroofing of mid-crustal rocks can be inferred from the depositional age of the San Onofre Breccia. Crouch and Suppe (1993) infer uplift of the Catalina Schist from 22-25 Ma (early Miocene) and that it would take 3 Ma for it to be exposed[2]. During this time interval, strike-slip faults developed on the Pacific plate (within the Transverse Range block) through strain partitioning due to coupling of the Monterey plate with the Pacific plate (Nicholson et al. 1994). Perhaps at this time, the Transverse Range block began to break up, allowing for the deposition of the San Onofre Breccia to the west of present-day San Diego.

The results indicate the San Onofre Breccia on Santa Cruz Island was deposited rapidly and confirms it is the oldest part of the Formation, older then the Relizian-Luisian age (17.0-14.2 Ma) San Onofre Breccia in the San Diego area (Stuart 1979). This age relationship may indicate the source for the San Onofre Breccia on Santa Cruz Island was derived from an outboard sequence, and was uplifted 2-6 Ma earlier then the San Diego section which was derived from an inboard sequence (Figure 6A). This would concur with previous suggestions that the rifting occurred in a progressive arcuate fashion, based on the premise that the Vaqueros Formation and San Onofre Breccia are older on southwest Santa Cruz Island than on the mainland (Kamerling 1994). It is worth noting that the sediment transport direction for the San Onofre Breccia on Santa Cruz Island is opposite to that expected for a source from the inner borderland rift basin (Figure 6A).

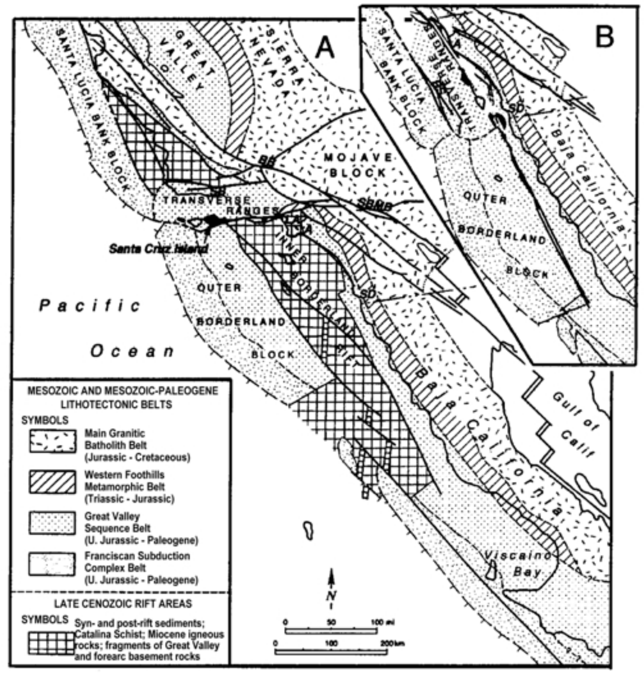

Figure 6. Map showing regional tectonic setting, indicating distribution of principal Mesozoic and Mesozoic-Paleogene lithotectonic belts (Atwater 1997; and Couch and Suppe 1993). A. Present configuration from central California to central Baja California, including inferred late Cenozoic rift areas (after Crouch and Suppe (1993)). Filled circles show the location of Santa Cruz Island. B. Likely mid-Cenozoic configuration of southwestern California and northern Baja California (after Crouch and Suppe (1993)). Split halves of filled circles show approximate reconstruction locations of northern and southern halves of Santa Cruz Island (Kamerling and Luyendyk (1985)). Cities located on map: SB, Santa Barbara; LA, Los Angeles; SD, San Diego. Tranpressional bends in the San Andreas fault: BB, "Big Bend"; SBMB, San Bernardino Mountain Bend.

Results indicate that volcanism, which was apparently related to extension, was active by 19 Ma (early Miocene). An age of 19 ± 1 Ma has been determined for volcanism on Santa Cruz Island (recorded by the Blanca Formation), and in San Diego (recorded by tholeiites on Coronado Islands (Lamb 1979)). Because blueschist detritus underlies and is interbedded with the volcanic rocks in both of these areas, we conclude that unroofing, erosion, and redeposition of the blueschist rocks were nearly synchronous with volcanism.

[2]It is assumed that the Catalina Schist was unroofed from mid-crustal depths of 10 to 15 km before being eroded. It is also assumed that the average rate of Neogene clockwise rotation was 5°-6°/Ma, and that the detachment surface had an eastern dip of approximately 35°.

SUMMARY AND CONCLUSIONS

In this study, fifteen megafossil samples from the Vaqueros and Blanca Formations and the San Onofre Breccia from Santa Cruz Island were analyzed to determine their strontium isotopic ratios. Strontium isotope analyses of the sampled rock units narrowly constrain the timing of deposition of blueschist and volcaniclastic detritus. The age of the top of the Vaqueros is 19 ± 1 Ma, 5 Ma younger than indicated by Bereskin and Edwards (1969) and 6 Ma younger than mainland rocks (Rigsby 1989). We are confident that these samples have undergone little or no alteration based on the carbon and oxygen isotopic results; also, the strontium ratio data from Near Point Beach place the samples in the same relationship as their position in the stratigraphic column.

The strontium isotope work suggests the basal San Onofre Breccia is 19 ± 1 Ma, more than 2 Ma older than in San Diego. The age of the boundary between the San Onofre Breccia and Beechers Bay Formation, determined from this study (18.2 ± 1 Ma), correlates with previous strontium data indicating an age of approximately 19 Ma (J. Schultz, unpublished data). Previous work (Bereskin and Edwards 1969) suggested the age of the San Onofre Breccia was late Saucesian to Relizian (17.0 to 15.4 Ma). The $^{87}Sr/^{86}Sr$ results suggest that the 300-m San Onofre Breccia conglomerate was deposited in approximately 1 Ma.

The onset of volcanism, which is indicative of rifting, and recorded by tholeiites in San Diego (Lamb 1979) and by the Blanca Formation on Santa Cruz Island (this study), was 19 ± 1 Ma. The results of the study indicate volcanism, sedimentation, and inferred unroofing occurred almost synchronously at approximately 19 Ma.

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LITERATURE CITED

Abbott, P. L. and T. E. Smith. 1978. Trace element comparisons of clasts in Eocene conglomerates, southwestern California and northwestern Mexico. Journal of Geology 86:753-762.

Atwater, T. M. 1997. Plate tectonic history of southern California with emphasis on the western Transverse Ranges and Santa Cruz Island. Pages 50-58 *in* Boles, J. R. and W. Landry (eds.), Santa Cruz Island, Geology Field Trip Guide. San Diego Association of Geologists, Annual Field Trip, October, 1997.

Bereskin, S. R. 1966. Miocene Biostratigraphy of Southwestern Santa Cruz Island, California (Master's thesis): University of California, Santa Barbara, CA.

Bereskin, S. R. and L.N. Edwards. 1969. Mid-Tertiary stratigraphy, southwestern Santa Cruz Island. Pages 68-79 *in* Weaver, D. W., D. P. Doerner, and B. Nolf (eds.), Geology of Northern Channel Islands (California). American Association of Petroleum Geologists, Pacific Section, Special Publication.

Boles, J. R. 1997. Geologic introduction and lithologic units. Pages 3-18 *in* Boles, J. R., and W. Landry (eds.), Santa Cruz Island, Geology Field Trip Guide. San Diego Association of Geologists, Annual Field Trip, October, 1997.

Crouch, J. K. and J. Suppe. 1993. Late Cenozoic tectonic evolution of the Los Angeles basin and inner California borderland: A model for core complex-like crustal extension. Geological Society of America Bulletin 105(11):1415-1434.

Doerner, D. P. 1968. Lower Tertiary Biostratigraphy of Santa Cruz Island (Master's thesis): University of California, Santa Barbara, CA.

Faure, G. 1997. Principles of Isotope Geology. John Wiley and Sons, New York, NY.

Howell, D. G. and H. McLean. 1976. Middle Miocene paleogeography, Santa Cruz and Santa Rosa Islands. Pages 266-293 *in* Howell, D. G. (ed.), Aspects of Geologic History of the California Continental Borderland. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 24.

Kamerling, M. J. 1994. Paleomagnetism and Tectonics of the Southern California Continental Borderland (Ph.D. dissertation): University of California, Santa Barbara, Santa Barbara, CA. 217 p.

Kamerling, M. J. and B. P. Luyendyk. 1985. Paleomagnetism and Neogene tectonics of the northern Channel Islands, California: Journal of Geophysical Research. 90:12485-12502.

Lamb, T. N. 1979. Geology of Coronado Islands, Baja California. Pages 119-138 *in* Stuart, C. J. (ed.), Miocene Lithofacies and Depositional Environments, Coastal Southern California and northwestern Baja California. Society of Economic Paleontologists and Mineralogists, Pacific Section, 138 p.

Lindberg, F. A. 1984. Correlation of Stratigraphic Units of North America (COSUNA), Southern California Region. American Association of Petroleum Geologists, Miscellaneous Publication.

McLean, H., D. G. Howell, and J. G. Vedder. 1976. Miocene strata on Santa Cruz and Santa Rosa Islands - A reflection of tectonic events. Pages 241-255 *in* Howell, D. G. (ed.), Aspects of Geologic History of the California Continental Borderland. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 24.

Nicholson, C., C. C. Sorlien, T. Atwater, J. C. Crowell, and B. P. Luyendyk. 1994. Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low angle fault system. Geology 22:491-495.

Oslick, J. S., K. G. Miller, and M. D. Feigenson. 1994. Oligocene-Miocene strontium isotopes: stratigraphic revisions and correlations to an inferred glacioeustatic record. Paleoceanography 9(3):427-443.

Rigsby, C. A. 1989. Depostional Environments, Paleogeography, and Tectonic Implications of the Oligocene-Early Miocene Vaqueros Formation in the Western Transverse Ranges of California (Ph..D. dissertation): University of California, Santa Cruz, Santa Cruz, CA. 144 pp.

Stuart, C. J. 1979. Lithofacies and origin of the San Onofre Breccia, coastal California. Pages 25-42 *in* Stuart, C. J. (ed.), Miocene Lithofacies and Depositional Environments, Coastal Southern California and Northwestern Baja California. Society of Economic Paleontologists and Mineralogists, Pacific Section, 138 p.

Weaver, D. W. 1969. Mid-Tertiary stratigraphy, southwestern Santa Cruz Island. Pages 68-79 *in* Weaver, D. W., D. P. Doerner, and B. Nolf (eds.), Geology of Northern Channel Islands (California). American Association of Petroleum Geologists, Pacific Section, Special Publication, 200 p.

Weaver, D. W., D. P. Doerner, and B. Nolf (eds.). 1969. Geology of Northern Channel Islands (California). American Association of Petroleum Geologists, Pacific Section, Special Publication, 200 p.

SOURCES OF UNPUBLISHED MATERIALS

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