

U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

CORRELATION AND CHRONOLOGY OF PACIFIC COAST MARINE TERRACE DEPOSITS OF
CONTINENTAL UNITED STATES BY FOSSIL AMINO ACID STEREOCHEMISTRY -
TECHNIQUE, EVALUATION, RELATIVE AGES, KINETIC MODEL AGES, AND
GEOLOGIC IMPLICATIONS

by

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OPEN-FILE REPORT

77-680

This report is preliminary and has not been edited or reviewed
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nomenclature.

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ABSTRACT

Enantiomeric (D/L) ratios of six or more amino acids have been determined in Pleistocene mollusks from fifty-one terrace localities on the Pacific coast of the United States from Puget Sound, Washington, to San Diego, California. Samples have been selected for the purpose of evaluation of various aspects of the amino acid dating technique as well as for the application of the technique to unresolved chronologic problems. Samples with known stratigraphic relationships (upper and lower Pleistocene, Pliocene) have been examined to document the relationships between geologic age and extent of racemization. Most genera investigated exhibit the expected trend of increasing extent of racemization with increasing age, but some genera do not document this trend, probably because of contamination during diagenesis. Of all genera examined in this manner, the bivalve mollusk Saxidomus appears to be the most reliable.

Generic effects on apparent racemization kinetics are evident: consistent differences (of 40% to 80%, depending on the amino acid) in enantiomeric ratios are seen between two groups of molluscan genera of late Pleistocene age. Those genera that constitute a "fast-racemizing" group are Tegula, Macoma, and Epilucina, while those that form a "slow-racemizing" group include Protothaca, Saxidomus, Chione, and Tivela. Within the latter group several slight (5%-10%) differences in enantiomeric ratios are usually observed among the different genera, but occasional "inversions" of these relationships are also apparent. Within the former group, inversions of generic relationships of the enantiomeric ratios are observed more frequently. Differences in the apparent

kinetics of racemization between the two groups are explained in terms of a model of diagenetic racemization that includes natural hydrolysis of peptide bonds as the most important rate-determining reaction. Relative resistance of calcified peptide material to natural hydrolysis is estimated from data on the relative abundance of aspartic acid (of major importance in calcification) in samples from each of the two groups. Samples with high relative abundances of aspartic acid (approximately 25% of the total amino acid residues) are those that are slowest to racemize; those with lower relative abundances of aspartic acid (approximately 10% of the total residues) are faster to racemize.

Interpretation of amino acid results in terms of relative and absolute age of terrace localities is performed by qualitative examination of the similarities in enantiomeric ratios among samples of one or more genera from localities with similar present-day mean annual temperatures. The presence of three reliably dated (uranium-series dates on coral material) localities (all between 120,000 and 140,000 years in age) is of prime importance in this qualitative approach. A more quantitative kinetic model is proposed for one amino acid, leucine, and this approach also relies heavily on the uranium-series results from the three calibration localities.

The kinetic model is derived from the apparent kinetics of racemization of both leucine and isoleucine in foraminifera samples from deep-sea sediments. Methods are proposed for the conversion of foraminifera model kinetics into model kinetics appropriate for the interpretation of results in different molluscan genera. The kinetic model yields age assignments for terrace localities, and these age

assignments can be evaluated by comparison with radiochemical age assignments and late Pleistocene temperature histories inferred from one or more paleoclimatic records. The kinetic model ages can also be evaluated within the constraints of both eustatic sea-level and isotopic ice-volume records.

Age assignments for many of the late Pleistocene localities investigated in this work are in the range of 100,000 to 140,000 years and these localities are correlated with the early part of Stage 5 of the marine isotopic record (Shackleton and Opdyke, 1973). These age assignments are, in all cases, consistent with the radiometric age assignments for the calibration localities. Samples from high terraces on San Nicolas Island, Palos Verdes Hills, and San Joaquin Hills, and from the San Pedro Sand have kinetic model ages of between 350,000 and 550,000 years and appear correlative with all or part of Stages 9 and 11 of the marine isotopic record. Three low terrace localities in southern California have yielded samples with ages in the range 200,000 to 250,000 years (correlative with Stage 7 of the marine isotopic record), though previous interpretations of these localities had implied correlation with localities that are shown to be younger. Some of these older samples may have been reworked into younger deposits. Localities with late Stage 5 (80,000 to 100,000 yrs.) ages are found at Santa Cruz, California and on Point Loma, San Diego, California (the Bird Rock Terrace). Both radiometric and geologic information are consistent with these age assignments. Samples from Cape Blanco, Oregon, appear to be either late- or post-Stage 5 in age; samples from Goleta, California are definitely post-Stage 5 in age, and appear to be approximately 40,000 years in age.

Several of these age assignments permit revisions in the interpretation of pre-existing paleoecologic data. In addition, long-term average uplift rates for each dated locality can be estimated: most of the Stage 5 localities reported herein have apparent uplift rates between .1 and .3 meters/1000 yrs. Uplift rates of .15 to .75 meters/1000 yrs. are inferred from the results for San Nicolas Island and the Palos Verdes Hills. Quite rapid uplift rates of 1.5 to 2.75 meters/1000 yrs. for Goleta and Cape Blanco are also inferred from our results.

I. INTRODUCTION

Emergent marine terraces provide the most visible and complete means of determining climatic fluctuations along tectonically active coastlines. To date, the most detailed reconstructions of glacio-eustatic sea level changes and rates of local tectonic movements have been derived from emergent marine terrace sequences in Barbados and New Guinea, which have been dated by uranium-series disequilibrium determinations on fossil corals (Mesolella et al., 1969; Bloom et al., 1974). Emergent terraces older than about 35,000 years (the approximate limit of C-14 dating using shell carbonate) along temperate and higher latitude coastlines have remained virtually undated because of the paucity of fossil corals, the most reliable fossil type used in uranium-series dating.

Miller and Hare (1975) and Mitterer (1974; 1975) have recently demonstrated the applicability of using fossil amino acid enantiomeric (D/L) ratios for correlating uplifted marine Pleistocene deposits in Arctic Canada and in Florida, respectively. Other applications of the technique have been reviewed by Bada and Schroeder (1975), Kvenvolden (1975), Dungworth (1976), and Schroeder and Bada (1976). Mitterer and Hare (1967) and Hare and Mitterer (1967) demonstrated that racemization in fossil shells (conversion of biogenic, L-amino acids into equilibrium mixtures of L- and D-amino acids) occurs in a monotonic fashion in samples of known stratigraphic age. These observations were reported for samples of Miocene through Holocene age from the Atlantic coastal plain and for samples from successively older (higher) terraces in the Palos Verdes Hills, near Los Angeles, California. In this report we elaborate

on our previous studies (Wehmiller et al., 1974; Lajoie et al., 1975) and report on our use of amino acid techniques in the problems of correlation and chronology of fifty-one Pleistocene localities along the Pacific Coast of North America from San Diego, California, to Puget Sound, Washington.

We report here on the use of two parallel and complimentary approaches to the evaluation and application of amino acid techniques in the study of marine terrace deposits. First, we use the geologic control that is provided by many of these terrace deposits to evaluate the technique as a relative age dating tool. Secondly, we use a few reliably-dated localities to evaluate the ability of the technique to distinguish slight temperature (latitude) differences between samples of similar ages. These dated localities also permit us to develop kinetic models for amino acid racemization and to use these models for the estimation of absolute ages to un-dated localities.

Wherever possible, these evaluative exercises should be performed on multiple individuals of several genera so that information on the geological and analytical reliability of the technique is established. Sample availability often limits the extent of these evaluations, however. Results are presented here for nine different molluscan genera that have been evaluated either for their concordance with known stratigraphic ages or for their apparent analytical reproducibility. Generic differences in observed enantiomeric ratios are presented here and the importance of these differences as stratigraphic tools is discussed. Generic differences in observed enantiomeric ratios also aid in the understanding of the geochemistry of diagenetic amino acid racemi-

zation and in the development of the kinetic models for absolute age assignment.

In the following two sections we summarize background information on the available geochronology of the marine Pleistocene localities used in this study and on the amino acid dating technique itself. In Section II we provide a chronologic division of the Pleistocene as it has been presented by other workers so that the time implications of our terminology are unambiguously defined. In Section III we review previous studies of amino acid racemization phenomena so that the need for the evaluative work presented here is clearly established.

II. PREVIOUS STUDIES OF COASTAL MARINE TERRACE CHRONOLOGY, WESTERN UNITED STATES

The resolution of correlative and chronological problems of coastal marine terraces has implications for a broad range of subjects, including paleoecologic correlations, eustatic sea-level records, and local tectonic deformation rates. Consequently, a large body of literature has developed as a result of numerous studies of one or more of these aspects of the marine Pleistocene of the west coast. Here we cite literature that has provided direct insight into either absolute or relative geochronology of the marine deposits that have been considered in this work.

Approximately one dozen localities between San Francisco and San Diego have been dated by analyses involving the uranium series decay scheme ($\text{Th}230/\text{U}234$ and $\text{Pa}231/\text{U}235$) in calcareous fossils, primarily mollusks. These localities primarily represent the lowest emergent terrace, since it is these terrace remnants which contain abundant well-preserved fossil material that is within the range of available dating techniques. Few, if any, terrace deposits lie within the nominal range of carbon-14 dating. The locality at Cape Blanco, Oregon, has been dated at approximately 35,000 years B.P. by both C-14 and $\text{Th}230/\text{U}234$ analyses of mollusks (Richards and Thurber, 1966), though additional data suggest a greater age (Janda, 1969; 1971).

Fossil corals have proven to be the most reliable for dating by uranium-series decay (Kaufman, et al., 1971; Ku and Kern, 1974) but only three localities along the Pacific Coast have yielded enough corals for age determinations. These localities are:

- a. Cayucos, San Luis Obispo County, California
 (Veeh and Valentine, 1967)
 130,000 \pm 30,000 and 140,000 \pm 30,000 yrs. B.P.
 (The latter date considered a minimum age for a chiton sample.)
 (Terrace \sim 10-20 meters above sea level.)
- b. Nestor Terrace, Point Loma, San Diego County, California
 (Ku and Kern, 1974)
 120,000 \pm 10,000 yrs. B.P.
 (Terrace \sim 15-20 meters above sea level.)
- c. 30-meter terrace, San Nicolas Island, California
 (Valentine and Veeh, 1969)
 87,000 \pm 12,000 and 120,000 \pm 20,000 yrs. B.P.

These dates are correlative with terrace dates from many parts of the world and represent eustatic high sea levels between 75,000 and 140,000 years B.P. (Bloom et al., 1974; Broecker and van Donk, 1970).

Uranium-series dates on molluscan material from these and several other localities on the central and southern California coast are consistent with these age assignments, but usually the isotopic results must be interpreted in terms of open-system diagenetic models (Szabo and Rosholt, 1969; Szabo and Vedder, 1971). A few of the isotopic analyses of mollusks have been interpreted in terms of closed system diagenesis and indicate ages of 70,000 to 100,000 years for the lowest terrace at Newport Beach, Santa Cruz, and Point Año Nuevo (Szabo and Vedder, 1971; Bradley and Addicott, 1968).

Correlation of marine terrace deposits has often been attempted on the basis of geomorphologic, sedimentologic, or faunal characteristics. In most cases, precise correlation is complicated by lack of horizontal continuity, though most previous investigations have assumed that the lowest emergent terraces along the coast are synchronous in age. The hazards of such an assumption are evident in the work of Bradley and

Griggs (1976) who have shown that terrace platforms can be reoccupied by one or more sea-level "events" and that sediments and fossils found on a given bedrock platform may have multiple ages.

The terms "late Pleistocene" or "upper Pleistocene" have been commonly used in the description of many of the low terrace localities studied in this work. The terms "early Pleistocene" or "lower Pleistocene" have been in common use for description of most of the stratigraphically older localities studied here. Little, if any, formal absolute chronological meaning can be attached to these terms. We use these terms as they were presented in the original descriptions of the localities, but for purposes of generalization of our age assignments, we propose the following chronological divisions of the Pleistocene:

late Pleistocene, ca. 130,000 to ca. 10,000 yrs. B.P.

middle Pleistocene, ca. 700,000 to 130,000 yrs. B.P.

early Pleistocene, ca. 1,800,000 to 700,000 yrs. B.P.

Butzer (1974) has formally suggested the use of the Olduvai magnetic event, the Brunhes/Matuyama magnetic reversal, and the last period of interglaciation as the stratigraphic divisions of the Pleistocene (Lower, Middle, and Upper, respectively) and our chronological terminology follows Butzer's proposal, since the chronology of these important stratigraphic markers is well established. As each locality is discussed herein, its absolute age assignment and age category will be designated.

III. REVIEW OF AMINO ACID DATING TECHNIQUES

Amino acids, as the constituents of high-molecular weight polypeptide material, are incorporated into shells of living calcareous organisms during the biological mineralization process. During fossilization, a variety of diagenetic reactions can occur to alter this high-molecular weight material. These reactions include deamination, decarboxylation, oxidation of either high- or low-molecular weight components, hydrolysis and cleavage of peptide bonds liberating free amino acids and small peptides, and recombination of free amino acids with other organic compounds in the fossils (Hare, 1969). Integrated into this complex array of reactions is the phenomenon of racemization, or conversion of the L-configuration amino acids present in living biological material into an equilibrium mixture of D- and L-amino acids. The time- and temperature-dependence of the racemization reaction has led to a number of studies of its applicability to geologic problems.

Deep-sea marine sediments have provided the best stratigraphic and temperature control for the documentation of racemization kinetics. Studies of the epimerization (racemization about the α -carbon) of isoleucine in calcareous foraminifera from deep-sea sediments have shown that complex, non-first-order reversible kinetics are followed in samples ranging in age from 0 to 5 million years in age (Wehmiller and Hare, 1971; Bada and Schroeder, 1972; 1975; King and Hare, 1972a). Isoleucine epimerization kinetics have also been documented in high-temperature pyrolysis experiments with several different fossil shell types (Hare and Mitterer, 1969; Bada and Schroeder, 1972; 1975; Mitterer, 1975), and these experimental data provide useful information on the temperature

sensitivity of the isoleucine epimerization reaction. Isoleucine is the amino acid that has been most thoroughly studied because ion-exchange chromatographic techniques can successfully resolve the product of L-isoleucine epimerization, D-alloisoleucine (see Bada et al., 1970; Wehmiller and Hare, 1971, and others). Additional data on the D/L ratios of several other amino acids (usually between five and seven besides isoleucine) in foraminifera (Kvenvolden et al., 1973), vertebrate bone material (Bada et al., 1973), mollusks (Hare and Hoering, 1973), and corals (Wehmiller et al., 1976) have become available since the development of capillary column gas-chromatographic techniques for the analysis of diastereoisomeric derivatives of the fossil amino acid mixtures (Kvenvolden et al., 1972). These studies have qualitatively established the relative rates of racemization of different amino acids in various sample types. Quantitative modelling using gas-chromatographic analytical techniques has been performed primarily for bone samples (Bada et al., 1973; Dungworth, 1976).

The chronologic value of racemization reactions has been a repeated focus of study. However, several factors exist that prevent these reactions from providing an "absolute" chronologic tool with the precision characteristic of many radiometric techniques. Perhaps the most important restraint is the thermal history of the samples being studied, since this history will rarely (if ever) be accurately known. Kinetic models and age estimates must be derived from estimates of maximum and minimum temperatures to which the sample might have been exposed, and the approximate time spent at these and intermediate temperatures.

Differences in apparent racemization rates among several genera of foraminifera and mollusks have been noted (King and Hare, 1972; King and Neville, 1977; Miller and Hare, 1975) and certainly must be considered as an important variable in any geologic applications of amino acid techniques. These generic effects on apparent racemization kinetics are probably the result of variable relationships between mineral and organic phases within the fossil genera and also the type and amount of organic material present in the shell matrix. In this paper we present additional data for generic differences in enantiomeric ratios and we demonstrate the usefulness of such data in correlation of terrace deposits. We also use these data to identify possible mixtures of faunas of different ages.

Contamination of samples during diagenesis is an additional cause of uncertainty. It is usually assumed that contaminant amino acids (with "modern" D/L ratios) would have the effect of lowering the D/L ratios of the uncontaminated sample. Evidence of contamination has been presented by several workers (Wehmiller and Hare, 1971; Bada et al., 1973; Schroeder, 1975, Wehmiller et al., 1976). Approaches that can be used to evaluate the significance of contamination for a given fossil type are:

1. Quantification of unstable amino acids and/or extraneous compounds that might be present in the sample (Schroeder, 1975; Wehmiller et al., 1976).
2. Demonstration of the "ability" of a given genus to reach equilibrium (D/L = 1.0) and maintain this racemic state for significant lengths of time.
3. Demonstration of "anomalous" relative rates of racemization among a suite of amino acids in a sample (Bada et al., 1973).

Each of these approaches requires rigorous stratigraphic control of the samples, and for this reason samples of calcareous foraminifera from

stratigraphically and radiometrically dated deep sea marine sediment sequences have proven most useful for the documentation of both the racemization phenomenon itself and the magnitude of potential contamination problems. In this paper we use the stratigraphic framework provided by vertical sequences of marine terrace deposits for the evaluation of the durability and resistance to contamination of most of the genera that have been used for correlative purposes. Several of the genera that we have studied do demonstrate diagenetic contamination, and we use this evidence not only for the selection of reliable genera but also for the estimation of trace quantities of contamination in samples of all genera.

Various kinetic model options exist for the interpretation of amino acid enantiomeric ratios in fossil calcareous organisms. Mitterer (1975) has shown that linear (first-order reversible) kinetics are observed in high temperature pyrolysis of fragments of the bivalve Mercenaria. Bada and Schroeder (1972) have shown that non-linear kinetics are observed in high temperature pyrolysis of foraminifera. Non-linear kinetics are clearly observed in foraminifera samples from geological environments (Wehmiller and Hare, 1971; Bada and Schroeder, 1972; 1975; King and Hare, 1972a). Since it is only for these samples that have well-controlled ages that the actual kinetics of racemization have been documented for typical ambient temperatures, we will use kinetic models derived from the deep-sea sediment foraminifera data for the interpretation of the molluscan results reported here. The various model options are briefly evaluated in this work and are more fully discussed elsewhere (Wehmiller and Belknap, in press).

IV. LOCALITY INFORMATION AND SAMPLE SELECTION

This study is based upon the determinations of enantiomeric ratios of six or more amino acids in 160 fossil mollusk samples from 51 localities along the Pacific Coast of North America from San Diego, California to Puget Sound, Washington. Most of the samples have been obtained from existing collections at the U.S. Geological Survey, Menlo Park, and the Los Angeles County Museum of Natural History. Additional sources of samples are noted where appropriate. Published references to specific sample localities and to available radiometric dates are given in Table 1. Complete descriptions of all localities are found in Appendix

Table 1 near here

I. Figures 1 and 2 (a through n) show locations of all sample localities

Figures 1-2a-n near here

used in this study

Ideally a study such as this should utilize fossil genera that occur over a wide latitude range. Two genera of bivalves (i.e., pelecypods), Protothaca (P. staminea) and Saxidomus (S. giganteus and S. nuttalli) generally meet this criterion and have been readily available in the collections used in this work. Five other genera of bivalves (Chione, Cumingia, Epilucina, Macoma, and Tivela) and three genera of gastropods (Diodora, Polinices, and Tegula) have also been examined and data for these can, in most cases, be compared directly with results for either Protothaca or Saxidomus from the same locality.

Only rarely have fossils been found with articulated valves in growth position. Therefore we have been forced to work with samples that have probably been transported by marine action, and the possibility of mixing of samples of different ages always exists in such a situation. We have avoided the use of shell fragments or extensively abraded samples, but nevertheless several examples of reworking are evident in our results. To our knowledge, only at three of the localities studied here (M1690, M1477, and at several places on the Nestor Terrace) have articulated samples in growth position been documented.

V. TEMPERATURE ZONATION ALONG THE COAST AND THERMAL ENVIRONMENT OF SAMPLES

Both past and present temperatures must be evaluated in the derivation of either kinetic model ages or apparent relative ages from enantiomeric ratio determinations. Our discussion of the kinetic effects of late Pleistocene temperature fluctuations is deferred to a later section; here we consider only the problem of the estimation of present-day thermal environments.

Data on mean annual air temperatures as compiled from various sources are given in Table 2. Temperature records do not exist for all localities

Table 2 near here

of interest, so in these cases we have estimated temperatures by interpolation between mean annual air temperatures for the nearest coastal recording stations. In a few cases we have estimated mean annual temperatures from short-term (less than 10 years) records. For the purposes of discussion of qualitative differences and similarities in observed enantiomeric ratios, we define the following present-day temperature regions in relation to the localities being considered herein.

Puget Sound Region:	Orcas Island, Bainbridge Island: Mean Ann. Temp. 9.9° - 11.0° C.
Northern Region:	Cape Blanco and Trinidad Head: Mean Ann. Temp. 10.0 - 11.5° C.
Central Region:	Point Año Nuevo, Santa Cruz, and Cayucos: Mean Ann. Temp. 13.3 -

14.0° C.

Southern Region:

Goleta to Point Loma: Mean Ann.

Temp. 15.5 - 16.5° C.

Within each of these temperature regions, local variations in mean annual temperature are apparent. These variations are not directly correlative with latitude and must be related to local effects of oceanographic and meteorological conditions. It is difficult to delineate how these intraregional gradients might have varied during the late Pleistocene.

In subsequent discussions we make the assumption that temperature gradients along the coast have remained constant during time, and then we refine this assumption by considering evidence for its validity in particular cases.

Mean annual air temperatures are the only readily available type of temperature record with which to interpret our results. However, two additional pieces of information are important in the evaluation of present-day thermal environments; the actual temperature of the terrace sediments at the depth of burial (usually between .25 and 2.0 meters) of the fossil samples, and the effective annual air temperature. The latter is the seasonally-adjusted "effective kinetic" air temperature, and it is a measure of the proportionally greater kinetic effect that warm summer months have on racemization, compared to cold winter months. The effective annual temperatures in Table 2 have been calculated from mean monthly temperature data using the temperature dependence equation of Bada and Schroeder (1972):

$$\log k (\text{yr}^{-1}) = 15.77 - 5939/T \quad (1)$$

where k = the rate constant for reversible first order racemization, and

T = absolute temperature. This equation is specifically valid for isoleucine epimerization in pyrolyzed calcareous foraminifera. It is used here as a working model for racemization of all amino acids. Various geological tests of the model are presented below and it is shown to be reasonably reliable, though not without need of refinement.

The concept of effective annual temperatures has been recently discussed by Friedman and Long (1976). The difference between effective annual temperature and mean annual temperature becomes most pronounced in continental climates with significant seasonal temperature variation. The climates of Pacific Coast marine terraces demonstrate seasonal temperature fluctuation of between 13°C and 20°C in southern California. In general, the calculated effective annual air temperatures are only 0.5°C to 1.5°C greater than mean annual temperatures.

The magnitude of the seasonal temperature fluctuations in the terrace sediments themselves is not known. A program of ground temperature determinations over one- and two-year periods is presently being conducted. Current information on ground temperatures within the terrace deposits consists of thermometer measurements made at depths of 0.2 to 2.0 meters during the summers of 1975 and 1976 at Cape Blanco, Point Año Nuevo, Cayucos, Newport Beach, and Point Loma. These temperature measurements (all made after equilibration times of only five to ten minutes) suggest that summer ground temperatures are between 2°C and 4°C warmer than mean annual temperatures at the respective localities. These few results are consistent with observations on ground temperatures at two comparable localities for which more thorough data are available: Mt. Vernon, Washington, and Riverside Experimental Station, California

(U.S. Dept. Commerce Soil Temperature Records). Though the Riverside Experimental Station is not a coastal locality, we use soil temperature data from this locality for comparison with coastal terrace localities in southern California. The lack of abundant soil temperature data requires that this comparison be made, but it seems valid because the mean annual air temperature at Riverside is only 1° - 2°C greater than the mean annual air temperatures at most of the terrace localities discussed in this work. Summary data for these soil temperature measurement stations is included in Table 2.

It is apparent in the soil temperature records for the Riverside Experimental Station (Table 2) that ground temperatures below depths of about 2 meters probably undergo little seasonal variation and that these temperatures are equal, or slightly greater than, mean annual air temperatures. For convenience, we use the differences in mean annual air temperatures in the comparison of enantiomeric ratio results from different localities. Since there is little difference between effective annual air temperatures and mean annual air temperatures for most of these coastal localities (see Table 2), the use of mean annual air temperatures in these comparisons appears valid as long as the differences between ground and air temperatures are constant for the localities considered. The validity of these assumptions must await additional ground temperature data. Our kinetic models, developed in Section IX, are calibrated to mean annual air temperatures and therefore automatically compensate for probable differences between ground and air temperatures.

In the evaluation of the kinetic effects of late Pleistocene

temperature fluctuations, a number of factors must be considered. The mean annual air temperatures at the terrace localities discussed herein are presently dominated by the nearby marine environment. During periods of ice volume expansion and marine regression, these coastal localities would have been less effected by the marine environment, and might have been as much as 25-30 km inland from the low-sea level coastline. Data presented in Table 2 for temperature recording stations in southern California up to 65 km inland from the coast show that present day mean annual air temperatures increase inland with a gradient of approximately $0.5^{\circ}\text{C}/10\text{ km}$.

The actual thermal effect that any shift in position relative to a coastline would have would depend on the magnitude of the temperature reduction in both the marine and continental environments and the exact position of the terrace locality in the altered thermal gradient. Full glacial temperature reductions for coastal waters off California are estimated at between 2°C and 4°C (CLIMAP, 1976). Full glacial temperature reductions of between 9° and 11°C in the western continental United States are estimated by Gates (1976) as averages for $4^{\circ} \times 5^{\circ}$ grid areas. Temperature reductions intermediate between these estimates would seem reasonable for coastal localities, and full glacial temperature reductions of between 4° and 7°C are judged to be most consistent with the kinetic models developed in Section IX. Nevertheless, it is conceivable that if full glacial temperature reductions, at localities presently between 10 and 40 km inland, were no more than $4^{\circ} - 5^{\circ}\text{C}$, the net thermal effect of a shift in position of a fossil locality relative to the coastline might have been a very slight temperature reduction of $1^{\circ} - 2^{\circ}\text{C}$ during full glacial regression.

VI. ANALYTICAL TECHNIQUES AND RESULTS

Fossil shells are rarely well preserved throughout. Leaching is commonly associated with the surface layers and is variable depending on the diagenetic history of the individual shell and the internal shell structure of the shell itself. Extensive care has been taken to select only the thickest portions of the shell samples used in this study, in order to minimize the problems of "open-system" diagenesis (see Wehmiller et al., 1976, for discussion). Samples have been cleaned mechanically with a small carborundum wheel mounted on a dental drill, then subjected to triplicate washing in dilute (approximately 0.50 N) hydrochloric acid while under sonication. This latter procedure removed approximately 10-15% of the original sample fragment, insuring that the actual fragment analyzed (usually about 0.5 gm CaCO_3) was representative of the interior portions of the shell. This approach reduces the chance of leached or contaminated shell being included in the analysis.

Gastropod shells in temperate and boreal waters do not often obtain the bulk or thickness of bivalves, and suitable gastropods have been difficult to obtain. In addition, the internal structure of various shell layers found in many gastropods precludes finding thick portions of a single shell type. Gastropods have in general proven to be unreliable samples. In bivalves, the thickest portion of the shell is often the hinge plate, and all samples have been taken from this region. Only in Tivela stultorum were samples routinely cut from another region, the central disc area. We have not specifically investigated the possibility of variability of results between different shell layers (Hare and Mitterer, 1969).

Calcite/aragonite determinations (see Turekian and Armstrong, 1960) have been performed on most samples, the data being presented with the enantiomeric ratios (Tables 3 and 4). Mineralogic determinations may be useful indicators of diagenetic alterations, although we have not encountered any obvious examples of anomalous D/L ratios being associated with significant sample recrystallization. Only sample 74-1, Table 4, was rejected because of its high calcite content (2.5%) and even in this case the enantiomeric ratios are not much different from those in unaltered samples from the same locality.

The gastropods studied were all subjected to dilute HCl washing while under sonication, but only the Tegula samples were mechanically cleaned prior to sonication. Mechanical cleaning of the Tegula samples was necessary to remove the outer, pigmented shell layer of this genus. The presence of significant amounts of calcite in some gastropods cannot be interpreted as being a diagenetic product since many gastropod genera form shells of both polymorphs of calcium carbonate (Turekian and Armstrong, 1960).

Sample preparation and amino acid enantiomeric determinations have been made according to procedures described in Kvenvolden et al., (1972; 1973). Samples have been dissolved in enough concentrated HCl to make them 6N in HCl, hydrolyzed for 22 hours at 110°C in a sealed tube under nitrogen, desalted by ion-exchange chromatography on Dowex 50-X8, and derivitized by esterification with (+)-2-butanol and acylation with either trifluoroacetic anhydride or pentafluoropropionic anhydride. Capillary column gas chromatographic analyses have been performed using at least two different liquid phases (Carbowax 20M and OV 225). All

reagents have been prepared from triply-distilled water. Procedural blanks on the entire preparative scheme show only traces of glycine and a few unidentified chromatographic peaks are apparent in these blanks as well. Procedural blanks on mixtures of free and peptide-bound L-amino acids carried through the entire procedure show that racemization caused by the preparation steps is slight but measurable; D/L ratios on amino acids carried through this procedure are generally between 0.004 and 0.015. Data presented in this work are not corrected for any racemization possibly induced by the analytical procedure.

Two amino acids, leucine and glutamic acid, are judged to provide the most reliable results. These two amino acids satisfactorily meet the following criteria: abundance in the sample, excellent chromatographic resolution, and apparent resolution from stray peaks (impurities, diagenetic by-products) that elute at various times during the gas-chromatographic analysis of some samples. The latter observation is based upon the comparability of results obtained by chromatographic analysis with three different liquid phase capillary columns (Kvenvolden et al., 1972, 1973). Valine, alanine, proline and phenylalanine generally meet the above criteria but occasionally produce results which appear inconsistent with the leucine and glutamic acid data. Aspartic acid, which is always abundant, is not well resolved in most cases, and though the results for aspartic acid are generally consistent with the other amino acids, they are not given any weight in our interpretations.

As mentioned previously, various unstable amino acids can be used as indicators of potential contamination of a sample. The relative abundance of serine has been used extensively in this manner (Wehmiller

et al., 1976). We give data in this work on both relative abundance and enantiomeric ratios of serine in all of our samples. Large relative amounts of serine and/or low ($\sim .40$) enantiomeric ratios are taken to be indicative of geologic contamination. Specific examples of contaminated samples will be cited where appropriate.

The enantiomeric ratio results are grouped into two tables. Analyses from localities that are in locally-controlled stratigraphic order or are of pre-Pleistocene or post-Pleistocene age are given in Table 3. These samples are mostly from vertical flight sequences in

Table 3 near here

southern California: Palos Verdes Hills, San Nicolas Island, Newport Beach-Corona del Mar, and San Diego. Studies of sequences such as these are important for the evaluation of a given genus "ability" to document the phenomenon of racemization in samples of increasing geologic age. The deficiency of samples from most of the older terraces has precluded many repetitive analyses, but we have been able to test seven genera within a vertical terrace framework. A few additional lower Pleistocene (San Pedro Sand, Timms Point Silt) and Pliocene (Fernando Formation, San Diego Formation) samples have also been examined. Samples from isostatically rebounded marine deposits in the Puget Sound area with C-14 ages of about 3,200 and 12,500 yrs. are also presented in Table 3 and provide control for the younger part of the time span investigated.

Enantiomeric ratios for all samples from the first (i.e., lowest) terrace localities are presented in Table 4. The lower and upper terraces

Table 4 near here

(Bird Rock and Nestor) on Point Loma are presented in Table 4 for ease of comparison with other low terrace localities along the coast. It is from several of the lowest terraces that enough samples have been available for the evaluation of analytical precision and generic effects on the rates of racemization. Wherever possible, mean values for all genera from a single locality are also given in Table 4.

VII. DISCUSSION OF RESULTS: TECHNIQUE EVALUATION

1. Analytical and Geological Precision

We have investigated the overall precision of the racemization technique by replicate analyses of individual samples and by multiple analyses of several individuals of the same genus at a given locality. This latter approach then deals with the combined uncertainties of the technique itself and the possible range of sample ages that might be encountered in the same terrace deposit. Replicate analyses of nine samples (samples 50-31, 74-16, 74-21, 75-2, 75-3, 75-11, 75-20, 75-25, and 75-47) indicate that in almost all cases, enantiomeric ratios are reproducible to within about three percent.

Table 5 gives results for mean values of enantiomeric ratios and

Table 5 near here

standard deviations from the means for all genera from which three or more individuals have been analyzed from a given terrace. Protothaca, Saxidomus, and Tegula have been most rigorously examined. Five Saxidomus samples from Point Año Nuevo (loc. M 1690), three Protothaca from Cayucos (loc. M 5922), and three Saxidomus and three Tegula from Newport Beach (loc. M 2074) have been analyzed. These represent specific localities from which multiple samples have been taken.

Additional data on the above genera and others are available for samples from locally correlative localities. Three Saxidomus from two localities in San Pedro (both from the Palos Verdes Sand) are considered together for the evaluation of the analytical precision for this genus.

Three Epilucina individuals from two localities in the Corona del Mar area are considered correlative and are used in a similar manner. Three Tivela samples from two correlated localities (M 2074, M 1477) at Newport Beach are used for the evaluation of this genus. Multiple analyses of Epilucina, Protothaca, and Tegula from several localities on the Nestor Terrace on Point Loma, have also been performed. In several cases two individuals of a given genus have been analyzed from a specific locality, and in Table 5 information on the apparent range of results (as a percentage of the mean value) for Protothaca, Chione, and Macoma is presented.

The results presented in Table 5 indicate that in many cases, standard deviations are on the order of five percent of the mean value. In a few cases, standard deviations are as large as ten percent of the mean value, but among the data presented in Table 5, there is no clear indication of any one amino acid being more reliable than another, though large uncertainties are observed more frequently for phenylalanine than for the other amino acids. It appears that the uncertainties encountered in the Protothaca and Saxidomus results are usually less than four percent of the mean values for the enantiomeric ratios of particular amino acids. It also appears that the uncertainties encountered in the Protothaca and Saxidomus results are generally slightly less than those for other genera. The data presented in Table 5 do not support or deny our subjective preference for the leucine and glutamic acid results. It will be clear in following sections that these two amino acids present the most consistent stratigraphic picture.

2. Generic Differences in Enantiomeric Ratios

The results presented in Tables 3, 4, and 5 document the generic relationships that are observed among samples from the same or correlative terraces. Many of these relationships are presented in graphical form in Figures 3 through 13. Protothaca, Tivela, Chione, and Saxidomus have quite similar enantiomeric ratios at all localities where they have been studied together (see Figures 4-7). Saxidomus usually has ratios about 5% greater than any of the other three, and in spite of the fact that this difference is only slightly greater than typical analytical uncertainties, it occurs so frequently (especially between Saxidomus and Protothaca) that it appears to be a real generic difference. Differences in rates of racemization in Protothaca and Saxidomus have been duplicated in laboratory pyrolysis experiments as well (Wehmiller, unpubl.). Occasionally "inversions" of these generic enantiomeric relationships are observed in fossil samples; these inversions can be interpreted as indications of complex racemization kinetics, of analytical uncertainties, or of mixing of samples of slightly different ages.

Most enantiomeric ratios in Macoma are about 15-20% greater than those of Protothaca, and those in Epilucina and Tegula are about 40-50% greater than in Protothaca samples of equal age. This generic relationship is magnified by proline enantiomeric ratios (see Figure 7), in particular: Tegula usually exhibits proline D/L ratios about a factor or two greater than those in Protothaca. For most amino acids except valine, Tegula and Epilucina do not demonstrate a consistent generic relationship. Epilucina valine ratios are generally greater than Tegula

valine ratios. In comparison of leucine and glutamic acid, Tegula appears more racemized than Epilucina at Cayucos but less so at Point Loma (Nestor Terrace). In the Newport Beach-Corona del Mar area, the two genera show quite similar ratios. As is shown in following sections, unambiguous conclusions cannot be derived from the results for these two genera alone.

3. Stratigraphically Controlled Sequences

Figures 3a, 3b, 3c near here

Analytical results from low terrace localities suggest that two amino acids yield the most consistent enantiomeric information, and that three genera of bivalves (Protothaca, Saxidomus, and Tivela) are the most reliable (of those studied) in terms of analytical precision and consistent inter-generic relationships. In addition, the reliability of a given genus can be evaluated by the analysis of stratigraphically controlled samples and by the documentation of the "ability" of a genus to achieve a racemic state (i.e., equilibrium D/L ratios) and maintain it.

Saxidomus, primarily because of its durability during diagenesis, seems to yield the least ambiguous results when tested by analysis of stratigraphically controlled samples. Thus, with only a few exceptions, enantiomeric ratios that steadily increase with age are seen in Saxidomus from a vertical sequence of terraces on San Nicolas Island (Figure 3a and Table 3), as well as in a comparison of upper Pleistocene Saxidomus from the Palos Verdes Sand (samples 75-52, 75-53, 76-16) with lower Pleistocene Saxidomus from the San Pedro Sand (samples 76-6, 76-7) and

Timms Point Silt (76-8, 76-9). One Pliocene Saxidomus from the San Diego Formation (Table 3) contains nearly racemic amino acids; two other Pliocene Saxidomus samples from the Fernando Formation in Los Angeles (Table 3) appear less racemized than the San Diego Formation Saxidomus, especially in comparison of valine and glutamic acid ratios. The Fernando Formation samples thus appear slightly younger than the San Diego Formation sample, though the observed differences in enantiomeric ratios could also be due to slight differences in diagenetic temperatures. A late Pliocene or early Pleistocene (Wheelerian, or approximately 1.5 to 2.0 million years B.P.) is probable for the Fernando Formation samples (Yerkes, pers. comm., 1977; see Yeats, 1977).

Tivela has been tested only in the case of the (probable) early Pleistocene Lindavista Formation (Kennedy, 1973). Samples of Tivela from the Lindavista Formation are racemic or very nearly so; because of generic differences, it cannot be said whether the Lindavista Formation Tivela samples are actually younger than the San Diego Formation Saxidomus sample, though the geologic control indicates that the Lindavista Formation is, in fact, younger than the San Diego Formation (Kennedy, 1973). The possibility of reworking of San Diego fossils into the Lindavista cannot be eliminated, either. The Tivela results are at least an indication of the durability and potential utility of this genus.

Four pre-late Pleistocene samples of Protothaca have been analyzed, two from the tenth (240 meter) terrace on San Nicolas Island (samples 75-24 and JW-9), and two from the lower Pleistocene San Pedro Sand. Three of these yield D/L ratios that are consistent with the Protothaca - Saxidomus relationship observed in the low terrace samples previously

described. Sample 75-24, from the same terrace as JW-9, shows D/L ratios about 30% lower than those of JW-9; 75-24 shows significant amounts of serine, and while serine itself may be indigenous to the sample, its D/L ratio is quite low, suggesting contamination with amino acids having low D/L ratios. In the case of sample 75-24, the D/L serine ratio is .15, and there is a quantity of serine approximately equal to 13% of the leucine in the sample. Sample JW-9 shows such small relative amounts of serine (ser/leu = .02) that measurement of the D/L ratio of serine (approx. .15) is quite difficult. Since serine racemizes rapidly relative to other amino acids and is commonly rather unstable, we can use either its enantiomeric ratio, the relative amount of serine, or a combination of these two parameters to estimate the magnitude of possible geologic contamination. Ideally, we would be able to use the serine data to estimate the amount of other L amino acids that might be contaminant, and then to "correct" the measured D/L values to true ratios. However, such an exercise would require knowledge of the composition of the contamination and the time since the sample was contaminated, and this is not possible to determine. In the following discussions of particular localities and individual samples, cases of low serine D/L ratios are specifically cited and data for that particular sample are rejected or interpreted with caution.

Uncertainties in the results for Epilucina are apparent in samples that have been tested in the stratigraphic control of the San Nicolas Island terrace sequence. Two Epilucina from the tenth (240 meter) terrace (samples 75-25 and 75-66) yield ambiguous results in that 75-25 agrees reasonably well with 75-66, but sample 75-25 itself shows poor

precision in duplicate analysis (75-25A). The greatest discrepancies are in the leucine data. The high terrace Epilucina generally appear to have lower ratios than would be expected from the racemization trends established by Epilucina from lower terraces on San Nicolas Island (samples 75-26 and 75-27) (see Figure 3a for these trends). The ratios for the high terrace Epilucina also appear to be lower than would be expected for the Epilucina - Saxidomus relationship observed in the samples of these genera from lower terraces. Serine is absent from these questionable samples, so the problem appears to be more complex than simple geological contamination.

The only other Epilucina tested for its long-term durability is from the 90 meter terrace at Corona del Mar (sample 75-19, loc. M 3759) and this sample yields nearly racemic ratios that appear internally consistent and generically consistent with the Tegula sample from this same locality. Thus, both stratigraphic and generic evaluation indicate that Epilucina can yield ambiguous results more frequently than any of the other bivalves studied, and that caution must be exercised in the interpretation of Epilucina data.

Tegula presents a combination of the characteristics cited above. This genus appears to reach a racemic state quite rapidly in comparison to bivalves (see results for high terraces on San Nicolas Island, Figure 3a) and in none of the stratigraphic tests (Figures 3a, 3b, 3c) does Tegula show a reversal of trends in enantiomeric ratios. However, we have noted that significant inversions of generic relations involving Tegula are seen in the results from the low terraces. Because of the physical durability of Tegula shells, we conclude that these inversions

may not be totally due to diagenetic contamination.

Two other genera of gastropods, Diodora and Polinices, have been tested within the vertical flight framework (Figures 3a, 3b). Diodora (D. aspera) is judged to be an unacceptable genus for amino acid studies based upon the evidence from San Nicolas Island (decreasing amino acid ratios with increasing age) and from Goleta (where sample 50-30 shows essentially "modern" enantiomeric ratios in comparison with all other samples for this low terrace locality). Sample 50-30 (Goleta Diodora) also demonstrates the serine effect (contamination) described above. Polinices demonstrates both increasing and decreasing enantiomeric ratios with increasing stratigraphic age in the vertical flight sequence at Corona del Mar, implying that Polinices may be of moderate reliability but that it cannot be expected to routinely achieve a racemic state.

The stratigraphically controlled samples discussed above are useful for the evaluation of the long-term chemical durability of the various genera, and we conclude that Saxidomus is probably the most reliable of the genera that we have studied. The stratigraphically controlled samples are also of considerable value in establishing the range of enantiomeric ratios that we might expect to encounter in low terrace samples. Samples that are most useful in this application are those from the Palos Verdes Sand, San Pedro Sand, and Timms Point Silt. Saxidomus samples from these three units show leucine D/L ratios of approximately .52, .62, and .72; thus defining the range of enantiomeric ratios encountered in upper Pleistocene (Palos Verdes Sand) and lower Pleistocene (San Pedro Sand and Timms Point Silt) samples exposed to temperatures typical of southern California. Saxidomus samples from the

higher terraces on San Nicolas Island define a similar range of enantiomeric ratios.

VIII. DISCUSSION OF RESULTS: APPARENT RELATIVE AGES, SOUTHERN AND CENTRAL TEMPERATURE REGIONS

In this section we compare the enantiomeric ratios in samples both from within and between the Southern and Central Temperature Regions. Relative age and/or temperature distinctions can be made by simple qualitative examination of enantiomeric ratios. These qualitative discussions are valuable for the formulation of kinetic models, which are a more quantitative way of considering both age and temperature effects on the samples. In Section IX kinetic models and age assignments based upon the results for only one amino acid, leucine, will be discussed. The results for four amino acids (leucine, glutamic acid, valine, and proline) and the qualitative implications that these results have for relative age assignments are considered below.

Figures 4 through 13 give the enantiomeric ratios of leucine, glutamic acid, valine, and proline as they relate to discussions of particular localities or temperature regions. Results for alanine and phenylalanine generally support the conclusions derived from these four, but they are not presented graphically because of occasional analytical ambiguities.

The systematic generic differences in enantiomeric ratios previously discussed are readily apparent in Figures 4 through 13. Examples of inversions in the generic relationships are observed at a few localities and are interpreted as being the result of either complex geological or geochemical phenomena. Each of these inversions is cited specifically in following discussions.

1. Southern Temperature Region

Figures 4, 5, 6, 7 near here

Figures 4 through 7 give the results for all genera except Tegula and Cumingia from localities in the Southern Temperature region. For interpretive purposes, the results for Tivela, Protothaca, and Chione are considered together since we cannot recognize unequivocal differences in the results (except for proline) among these three genera. Nevertheless, the results for each genus are plotted separately in Figures 4 through 7 so that correlative conclusions can be derived from the individual genera when possible. Results for Saxidomus, Macoma, and Epilucina are always considered individually; the Saxidomus data are given initial consideration in all discussions.

Within the Southern Temperature Region, the following similarities in enantiomeric ratios are observed:

- a.) Saxidomus from LACM 332 (San Pedro), LACM 66-2 (Newport Beach), M 1479 (Newport Mesa), and M 5902 (Huntington Beach) have D/L leucine ratios between .60 and .64 (see Figure 4). This similarity is observed in the results for the other amino acids in Saxidomus as well (Figures 5-7). Locality LACM 332 is from the San Pedro Sand, traditionally considered lower Pleistocene (Woodring, et al., 1946; Kennedy, 1975). Localities LACM 66-2 and M 1479 have been assigned to the upper Pleistocene Palos

- Verdes Sand (Kanakoff and Emerson, 1959; Szabo and Vedder, 1971; Vedder, unpubl.). Locality M 5902 has been referred to as both upper and lower Pleistocene (Hoskins, 1957; Valentine, 1959; Poland et al., 1956).
- b.) Saxidomus from M 2074 (Newport Mesa), M 5908 and LACM 1210 (San Pedro), and M 1018 (Laguna Beach) are all quite similar (D/L leucine $.52 \pm .02$) though slightly higher ratios are observed in samples of all genera from M 5908 when compared to samples of the same genera from M 2074. These relationships are seen for each amino acid studied. Localities M 5908, LACM 1210, and M 2074 have been assigned to the Palos Verdes Sand (Woodring et al., 1946; Hoskins, 1957; Kennedy, 1975; Vedder, unpubl.). Ratios in these samples are distinctly lower than in those samples of Palos Verdes Sand described in item a, above. Locality M 1018 is referred to as the first terrace at Laguna Beach and is thought to be correlative to Palos Verdes Sand in the Newport Beach area (Vedder et al., 1957; Szabo and Vedder, 1971).
- c.) Saxidomus and Protothaca from the Nestor Terrace on Point Loma have enantiomeric ratios equal to, or slightly ($\sim 5\%$) less than those of the same genera from Newport Mesa (M 2074) and the first terrace at Newport Beach (M 1722). The Epilucina samples from the first terrace at Corona del Mar (M 1481 and M 1482) show enantiomeric ratios slightly greater than those seen in Epilucina from the

Nestor Terrace. The first terrace at Corona Del Mar is thought to be correlative with the Newport Beach and Newport Mesa localities mentioned above (Vedder et al., 1957; Szabo and Vedder, 1971). The difference in Epilucina results between Corona del Mar and the Nestor Terrace is probably not significant in light of the apparent reliability of Epilucina, but it might be due to slight differences in diagenetic temperatures between the Corona del Mar and Nestor Terrace localities. Slight differences in effective temperature might be invoked as an explanation of the slight differences in enantiomeric ratios in Saxidomus from Newport Mesa and the Nestor Terrace, but similar differences in enantiomeric ratios are not apparent in the results for Protothaca from the Nestor and Newport localities.

d.) Saxidomus from LACM 2662 (Torrey Pines) and from USGS 21664 (San Nicolas Island, 30-meter terrace) have similar ratios (D/L leucine = $.45 \pm .02$) that are equal to or less than those observed in Saxidomus from M 2074 (Newport Mesa). The Torrey Pines Saxidomus have ratios slightly less than those seen in the one Nestor Terrace (Point Loma) sample of Saxidomus. These lower ratios can either be interpreted as the result of slightly cooler temperatures or of a slightly younger age. The one Protothaca sample from LACM 2662

shows ratios that are greater than those in Saxidomus from the same locality, but these ratios are not beyond the range of ratios observed in Protothaca from the Nestor Terrace on Point Loma.

- e.) Saxidomus and Protothaca from the first terrace at Laguna Beach (M 1018) show quite similar results to samples of the same genera from Newport Mesa (M 2074 and M 1477). However, Tivela from the first terrace at Laguna Beach have significantly greater ratios in all cases than do Tivela from Newport Mesa (M 2074 and M 1477). One Polinices from M 1018 appears quite similar to a Polinices from M 1476, the second terrace above Upper Newport Bay, and is clearly more racemized than one Polinices from Newport Mesa (M 1477).
- f.) One Protothaca from M 1722 (Newport Beach first terrace) appears quite similar to Protothaca from Newport Mesa, Laguna Beach, and the Nestor Terrace on Point Loma but has significantly lower ratios than at least two samples in the Protothaca - Chione group from nearby localities LACM 66-2 and M 5898. A third sample (sample 76-24) of Protothaca from LACM 66-2 has enantiomeric ratios lower than the other samples of this group at LACM 66-2, but greater than those of the Protothaca from M 1722.
- g.) The Protothaca - Chione group from LACM 66-2 and M 5898 appears quite similar to two samples (one

Protothaca, one Chione) from SDSU 1854, a terrace deposit that has usually been considered as correlative with the Nestor Terrace on Point Loma (Ku and Kern, 1975; Kern, in press). Enantiomeric ratios for these two samples from SDSU 1854 (75-39 and 76-47) are distinctly greater than the ratios observed in samples of the genera from the Nestor Terrace on nearby Point Loma, from which a uranium series date of $120,000 \pm 10,000$ years was obtained (Ku and Kern, 1974). Two additional samples from SDSU 1854, samples 76-89 and 76-102

(shown in Table 4) have enantiomeric ratios within the ranges observed among samples of Protothaca from the Point Loma Nestor Terrace. These results suggest mixing of samples of two different ages at locality SDSU 1854.

- h.) The relationship of the Protothaca - Chione results from LACM 66-2 and M 5898 to the Saxidomus results from LACM 66-2 is generally consistent with the relationships among these genera observed at other localities (M 2074, M 5908, M 5790) but not consistent with the Protothaca - Saxidomus relationship observed at locality LACM 332 (San Pedro Sand) in San Pedro.
- i.) Results for Tivela and Macoma from M 5902 and M 1479 (Figures 4-7, Table 4) are entirely consistent with those for Saxidomus from the same localities, and all

three genera indicate that the shells from these two localities are older than the shells from Newport Mesa localities M 1477 and M 2074. Two Tivela from M 5902 (samples JW-10 and 76-13) have enantiomeric ratios that are much lower than those in a third Tivela sample from M 5902 (sample 75-28) or a Tivela (sample 76-46) from M 1479. Only the latter two samples are judged to be reliable, the others (JW-10 and 76-13) being quite "chalky" (i.e., leached) and poorly preserved. Though there is no evidence of recrystallization or significant contamination (c.f. serine data) in these samples, leaching during diagenesis has probably affected the samples, as shown by their poor physical condition. Reduction of enantiomeric ratios by leaching is consistent with available diagenetic models (Wehmiller, et al., 1976). The results for these two samples are rejected though the ratios themselves are still greater than those seen in Tivela from Newport Mesa or San Pedro.

- j.) As outlined above, the results for samples from localities usually identified as Palos Verdes Sand or as upper Pleistocene (M 2074, M 1477, M 1722, M 1479, LACM 66-2, M 5898, LACM 1210, M 5908, and M 5902) appear to cluster into two distinct age groups. Among those localities that appear to form the younger group (M 1477, M 2074, M 1722, LACM 1210,

and M 5908) there is a slight but consistent difference in enantiomeric ratios (those from the San Pedro area being greater than those from the Newport Beach area) in all genera studied. This difference is not significant compared to analytical uncertainties, but it is seen so consistently that it should be considered to be real, indicating either age or temperature differences between these two areas. These differences are estimated to be approximately 0.75°C or about 20,000 years, whichever effect is invoked (see section IX). The possible significance of the temperature difference between the San Pedro and Newport Beach areas is demonstrated by the leucine results plotted in Figure

Figure 8 near here

8. Other amino acids usually, but not always, support the conclusions derived from this Figure. It is noted that upper Pleistocene (Palos Verdes Sand) Macoma, Saxidomus, Protothaca, and Tivela from San Pedro (M 5908) and Newport Mesa (M 2074, M 1477) all document this apparent temperature effect. Macoma from LACM 332 and M 1479 appear to document the difference in temperatures between these two localities and to support the conclusion that M 1479 is correlative to the San Pedro Sand (LACM 332) in San Pedro. However,

Saxidomus from LACM 332 appear numerically similar to Saxidomus from both M 1479 and LACM 66-2; if all these samples are actually of the same age, then no temperature effect is seen for this genus. If a temperature effect should be considered for these Saxidomus samples, then actual age equivalents of the M 1479 and LACM 66-2 Saxidomus might be those from LACM 130-7 (Timms Point Silt). Similar consideration of the Protothaca results from LACM 332 suggest that the samples of equivalent age might be the Protothaca and Chione from LACM 66-2 and M 5898. The above observations indicate either that samples of mixed ages exist at localities M 1479 and LACM 66-2 or that inverted generic relationships are encountered among samples of different ages in different temperature environments. These uncertainties are considered further in section IX.

- k.) Protothaca from the Bird Rock Terrace (SDSU 2523) on Point Loma have ratios between 10 and 20% less than those from the Nestor Terrace on Point Loma. Cumingia results (not shown in Figures 4 through 7, see Table 4) are consistent with this relationship.
- l.) Protothaca, Saxidomus, and Macoma from Goleta (M 5790) have consistently lower ratios than any of the samples of these genera discussed above, though one Protothaca (sample 74-9, not plotted in Figures 4

through 7, see Table 4) appears significantly older (more racemized) than the other two Protothaca from here. Sample 74-9 is interpreted as being reworked from an older deposit since its ratios are quite similar to many of the older Protothaca (e.g. Nestor Terrace and Palos Verdes Sand) previously discussed.

m.) The results for Epilucina and Tegula are somewhat ambiguous. Tegula samples from Newport Mesa (M 2074), the fourth terrace on the Palos Verdes Hills, and the 30-meter terrace on San Nicolas Island all have similar ratios. Tegula from the Nestor Terrace show ratios somewhat lower (10-15%) than seen in Tegula from the other three localities. The Nestor Terrace Tegula show an inversion of the Epilucina - Tegula relationship that is usually observed for most amino acids at the other three localities within the southern region and also at Cayucos. Epilucina from the first terrace at Corona del Mar, the fourth terrace on the Palos Verdes Hills, the Nestor Terrace on Point Loma, and the 30-meter terrace on San Nicolas Island show similar ratios. These ratios for Southern Region Epilucina are also consistent with expected latitude/temperature trends along the coast when compared with the Epilucina results from Cayucos (see section VIII, 2). Neither Tegula nor Epilucina enantiomeric ratios allow for unambiguous interpreta-

tions of relative ages, but the Epilucina results appear more internally consistent. Enantiomeric ratios in samples of both of these genera from higher terraces (Palos Verdes Hills, San Nicolas Island, Corona del Mar) are usually consistent with predicted age relationships (see section VIII, 3).

Our interpretation of the above results in terms of relative age assignments is based upon the following definitions or assumptions:

- a.) The absolute age of $120,000 \pm 10,000$ years for the Nestor Terrace on Point Loma (Ku and Kern, 1974).
- b.) An assumption that the pair of terraces on Point Loma (Nestor and Bird Rock) is related to eustatic high sea levels between approximately 140,000 and 70,000 years B.P. Ample documentation of terrace formation during this period exists on several tropical islands (see Bloom et al., 1974).
- c.) A definition of the time periods between 140,000 years B.P. and 70,000 years B.P. as being roughly equivalent to Stage 5 of the marine isotopic record (Shackleton and Opdyke, 1973). The results for the samples from the two terraces on Point Loma then become the "early Stage 5" (equivalent to Stage 5e) and "late Stage 5" (equivalent to Stages 5a, 5c) references. Kinetic models of the Protothaca results from these two terraces (calibrated by the date for the Nestor Terrace) suggest

an age of 70,000 to 90,000 years for the Bird Rock Terrace (see discussion in section IX). In Section X we discuss in detail the correlation of both relative and absolute terrace age assignments with the marine isotopic record. We specifically avoid the use of terms such as "Sangamon" or "Wisconsin" in our discussion of the apparent ages of these terraces since such usage could lead to misleading or incorrect correlations among various records of climatic change.

d.) The use of the term "pre-Stage 5" for all those samples with enantiomeric ratios similar to, or greater than, those from the lower Pleistocene (original terminology of Woodring et al., 1946) San Pedro Sand (LACM 332). Without the kinetic models that are developed in section IX we do not attempt to make any qualitative age distinctions among these older samples.

Within the framework of the above definitions, relative age assignments for all samples from the Southern Temperature Region are presented in Table 6.

Table 6 near here

2. Central Temperature Region
Point Año Nuevo, Santa Cruz, and Cayucos are the three localities

that are considered within the Central Temperature Region. Enantiomeric

Figure 9 near here

ratios for samples from these localities are given in Figure 9. Cayucos provides the chronologic reference for samples from this temperature region (U-series date of 130,000 to 140,000 years: Veeh and Valentine, 1967).

Enantiomeric ratios for samples from all three localities appear quite similar and a Stage 5 age for all three localities is indicated. However, several subtle trends in the results, combined with available information on present-day temperatures at these localities, suggest that the Santa Cruz (mean annual temperature, 13.7°C) samples are younger than those from Cayucos (mean annual temperature, 13.3°C) (late Stage 5 vs. early Stage 5). Point Año Nuevo (mean annual temperature, 13.0°C) appears to be intermediate in age between these two localities, though we cannot be very precise in our age assignment for Point Año Nuevo because of uncertainties in temperature for this locality.

The Saxidomus results from Point Año Nuevo and Santa Cruz appear almost identical; these could be due to equivalent ages and temperatures for both localities, or due to Santa Cruz being slightly younger and having been exposed to slightly warmer temperatures. The data in Table 2 support the latter possibility. Protothaca results from Point Año Nuevo and Santa Cruz are entirely consistent with this interpretation.

Ratios observed in Protothaca from Santa Cruz are clearly lower than those seen in Protothaca from Cayucos; the percentage differences

are similar to those observed in the Protothaca samples from the Nestor and Bird Rock Terraces on Point Loma. The available temperature data (Table 2) suggest that these results should be considered as a reflection of real age differences between Santa Cruz and Cayucos; Santa Cruz, although being warmer, appears less racemized, and therefore younger. Macoma from Point Año Nuevo and Cayucos appear quite similar in their ratios, contradicting the trends that are suggested by the Protothaca results from these two localities. The relative age assignments in the Central Temperature Region are summarized in Table 7; additional support

Table 7 near here

for these age assignments comes from the discussion of apparent latitude/temperature effects in section VIII, 3.

3. Southern and Central Temperature Region Comparisons:

Latitude/Temperature Effects

In Figures 10 through 13 we present enantiomeric ratio results

Figures 10-13 near here

which are most easily interpreted as being the effect of thermal zonation along the coast (assumed to have been nearly constant through time) on samples of approximately equal age. We use the terms "early", "late", and "post" in Figures 10-13 to identify results that are apparently correlative and of early Stage 5, late Stage 5, and post Stage 5 age, respectively. Early Stage 5 localities plotted in Figures 10 through 13,

are Cayucos, Point Loma (Nestor Terrace) and Newport Mesa (M 2074). Late Stage 5 localities are on Point Loma (Bird Rock Terrace) and at Santa Cruz. The results for Point Año Nuevo are presented in Figures 10 through 13 for comparison with these other localities that have less ambiguous relative age relations.

The best test of the latitudinal-temperature effect is the comparison of samples from Cayucos (mean annual temperature, 13.3°C) and from the Nestor Terrace on Point Loma (mean annual temperature, 16°C). Protothaca and Epilucina from the Nestor Terrace have consistently higher enantiomeric ratios than do their Cayucos counterparts. Protothaca and Epilucina from the Newport Beach-Corona del Mar area have been previously correlated (section VIII,1) to these two reference localities. Tegula and Macoma from Cayucos and Newport Beach also appear quite consistent with this temperature trend, but Tegula from the Nestor Terrace on Point Loma have ratios that are too low in comparison to the Epilucina from the Nestor Terrace and also too low in comparison with the temperature effects observed in other genera. The Nestor Terrace Tegula results represent a significant inversion in the generic relationship observed for Tegula and Epilucina at several other localities. The Nestor Terrace Tegula enantiomeric ratios actually appear too low and more like what might be observed in Tegula samples from the Bird Rock Terrace. Such an explanation would require complex geological processes in order to mix younger samples onto an older (higher) terrace, so we are hesitant to propose such a phenomenon. It is important to point out that this ambiguity would be unrecognizable without plentiful data from several genera.

Figures 10 through 13 define an apparent difference of about 10% in enantiomeric ratios observed in the two temperature regions for samples of apparently equal age. The Bird Rock-Nestor Terrace comparison is important in defining the expected range of early and late Stage 5 enantiomeric ratios in both temperature regions, and within the framework of this definition, the Santa Cruz locality definitely appears late Stage 5 in comparison to Cayucos. Goleta appears distinctly younger than the Bird Rock Terrace in this graphical format and is defined as post Stage 5 in age.

One amino acid, proline (Figure 13), contradicts some of the trends seen in Figures 10 through 12. Proline does not demonstrate the latitudinal-temperature effect seen in Protothaca (Cayucos vs. Nestor Terrace), nor does proline in Macoma document the apparent "youth" of Goleta. Ambiguities such as these might be unrecognized without the large body of data presented here. We suspect that the explanation lies in analytical problems or in a complex racemization mechanism for proline. Results for this one amino acid should probably not be used independently of those for other amino acids in the assignment of relative ages.

IX KINETIC MODEL AGE ASSIGNMENTS

1. Leucine Kinetic Model

Evidence presented in sections VII and VIII documents the various phenomena that must be incorporated into any quantitative kinetic racemization model: i.e., sample reliability, age, thermal environment, and generic effects on apparent enantiomeric ratios. The qualitative approach has been useful because it considers several amino acids in the assignment of relative ages. In principle, development of quantitative models of the racemization kinetics for each of the fossilized amino acids should be possible, but in fact, few such models exist. In this section we propose a kinetic model for one amino acid, leucine, and use this model for the age estimation of our samples. The geological significance of these model ages (as well as those derived previously) will be discussed later. Since the stratigraphic framework of many of our samples has been used as an evaluative control in this work, we must also consider the validity of our model within this framework, and the implications of these results for the development of kinetic models that would be applicable to a variety of sample types. The validity of the leucine kinetic model ages is tested further by evaluation of the consistency of these ages with the enantiomeric rates for other amino acids.

Figure 14 is a diagrammatic model of leucine racemization kinetics

Figure 14 near here

for temperatures relevant to geologic restraints of our samples. Shown

is a plot of the variable $(X_E - X)/X_E$ vs. time, where X is the value of D/(D + L) leucine at any time and X_E is the value of D/(D + L) leucine at infinite time. X_E for leucine and most other amino acids has a value of 0.50. The curves in Figure 14 have been derived from observations of isoleucine and leucine racemization kinetics in foraminifera in deep-sea sediments (Wehmiller and Hare, 1971; Bada and Schroeder, 1972; Kvenvolden, et al., 1973). As recent studies of individual genera of foraminifera show (King and Neville, 1977), the racemization kinetics of each genus should be considered independently. The curves of Figure 14 are presented as a general model that needs to be "adjusted" to fit the kinetics for each genus considered herein. The proposed methods for applying these general kinetics to various genera are discussed in Section IX, 2, below.

The following assumptions have been used in developing the model curves shown in Figure 14:

- a.) The temperature sensitivity for isoleucine epimerization (racemization) observed by Bada and Schroeder (1972) as expressed by the equation

$$\log k (\text{yrs}^{-1}) = 15.77 - 5939/T \quad (1)$$

is a valid expression for the estimation of isoleucine epimerization kinetics at temperatures of 10 - 25°C. by extrapolation from 2 - 4°C (marine sediment temperatures). An identical assumption has been used by Wehmiller et al. (1976), in the study of isoleucine epimerization in fossil corals.

- b.) That isoleucine and leucine have identical temperature

sensitivities (apparent in the results of Bada et al., 1973) and that D/L leucine ratios are approximately 5% to 10% less than the corresponding allo/iso (D - allo-isoleucine/L-isoleucine) ratios in the same samples. This assumption is required by the fact that the gas chromatographic technique employed in this work does not usually yield accurate values for the allo/iso ratios in a sample, though in a few cases this ratio can be read accurately (Kvenvolden et al., 1973; Wehmiller et al., 1976). The bases for the assumed relative rate of racemization of these two amino acids are primarily results for molluscan analyses (Hare and Hoering, 1973; Wehmiller, unpubl. data) but also include results for foraminifera (Kvenvolden et al., 1973) and corals (Wehmiller et al., 1976).

- c.) That the enantiomeric ratio results obtained on Holocene-age samples (with known age and temperature histories) can be used to predict model kinetics through a large portion of the time required to achieve racemic equilibrium (i.e., up to D/L ratios of at least 0.80 and perhaps even greater). This assumption implies that a given kinetic curve is "conservative"; i.e., that once one point on the curve is defined for both time and temperature, then all points on that curve are defined. Particular temperatures for which the calculated curve will be appropriate will depend on the particular genus

being considered and the relation of this genus' observed kinetics to those extrapolated from foraminifera calibration samples.

The position of the curves in Figure 14 are determined from the results from Bainbridge and Orcas Islands (LACM 5012 and LACM 5009) in Puget Sound. Leucine enantiomeric ratio results from both Protothaca and Saxidomus from these two localities are used to establish the positions of the kinetic curves for each of these genera and to estimate the magnitude of the differences in diagenetic temperatures to which these two localities have been exposed.

The curves of Figure 14 are constructed with the basic assumption that the overall racemization mechanism is not a simple first-order reversible one, and therefore that non-linearity is a general characteristic of amino acid racemization reactions in all calcareous fossils such as foraminifera, mollusks, and corals, at least (see Wehmiller and Hare, 1971, and Wehmiller and Belknap, in press, for discussion of "non-linearity"). Nevertheless, to a first approximation it is possible to model the early parts of the racemization kinetics in terms of the mathematical expressions that are appropriate for first-order reversible (i.e., linear) kinetics. To do so, we use the expression of Bada and Schroeder (1972):

$$\ln \frac{1 + D/L}{1 - D/L} - C = 2 k t \quad (2)$$

to calculate apparent first order rate constants (k) for samples with known ages (t) and D/L ratios. The constant C in equation 2 is a

function of the D/L ratio measured in modern samples. Truly modern (living) samples of Protothaca and Saxidomus have not been analyzed in this work, but samples of these two genera collected on beaches in southern California during the summer of 1976 show enantiomeric ratios for various amino acids between 0.02 and 0.05. Live samples of several Atlantic ocast genera show ratios of 0.01 or less (Belknap, unpubl.; Mitterer, 1975). L-amino acids and polypeptides of L-amino acids carried through the entire analytical procedure also show enantiomeric ratios of 0.01 or less (Wehmiller, unpubl.). Therefore, we suggest that the proper enantiomeric ratio for modern samples should be ≤ 0.01 for most amino acids, and we use a value of 0.02 for the integration constant in equation 2 in all subsequent discussions of the kinetics of leucine racemization (see Bada and Schroeder, 1972, for derivation of equations for rate constants and integration constants). The larger ratios observed in the samples collected from beaches appear to be a consequence of exposure to higher temperatures on the beach surface for short periods of time. Geologically short but extreme thermal effects such as these can have profound consequences on the measured enantiomeric ratios in very young samples (Wehmiller, in prep.) but they are considered to be of minor significance for most, if not all, of the older (Pleistocene) samples discussed in this work.

The apparent first-order rate constants for leucine in Protothaca and Saxidomus from the Puget Sound localities are shown in Table 8. Also

Table 8 near here

given in Table 8 are the apparent kinetic temperatures that are calculated from equation 1 using isoleucine rate constants estimated from the observed leucine data according to assumptions given above.

Two important statements can be made from these apparent kinetic temperatures. First, they show that Holocene Protothaca and Saxidomus (from Bainbridge Island, LACM 5012) follow kinetics for temperatures 2°C to 4°C warmer than actual mean annual air temperatures (\approx 11.1°C) at this locality. Part of this difference could be due to real differences in the racemization kinetics between the mollusks and the foraminifera on which the kinetic model is based, and part could be due to the greater effective temperatures in the ground compared with mean annual air temperatures (see Table 2). Secondly, the differences in kinetic temperatures between the samples from Bainbridge Island (LACM 5012, 3260 C-14 years B.P.) and Orcas Island (LACM 5009, 12,350 C-14 years B.P.) are an indication of the kinetic effect that cold latest Pleistocene temperatures have had on the older samples. The apparent differences in effective temperatures (see Section IX,3 for further discussion of effective temperatures) between the two Puget Sound localities is $2.6^{\circ}\text{C} \pm 0.9^{\circ}\text{C}$ (uncertainty due to differences in results for the two genera being considered). Since the Holocene locality (LACM 5012) is presently exposed to a mean annual air temperature of approximately 11°C, these results indicate that the Orcas Island locality has been exposed to an effective diagenetic air temperature of approximately 8.5°C. Apparent first-order rate constants for other amino acids in the Puget Sound samples differ by relative amounts that are comparable to those presented here for

leucine, though there are discrepancies of as much as $\pm 2^{\circ}\text{C}$ depending on the amino acid considered. These uncertainties could be due to a number of variables, including a lack of information on the activation energies for racemization of the various amino acids, analytical uncertainties in the measurement of very low ratios, variable initial ratios for different amino acids, and non-linearity of the kinetics during early diagenetic racemization.

Schroeder and Bada (1973) have used enantiomeric ratio determinations of Holocene and late Pleistocene bone samples to evaluate the magnitude of glacial/post-glacial temperature changes. The results for the Puget Sound samples can be used in a similar manner. Enantiomeric ratios in samples such as these cannot be used to specify the details of the chronology of these temperature changes since they are merely the integrated result of all temperature changes that the samples might have experienced. Figure 15 shows one possible history for mean annual air

Figure 15 near here

temperatures at Orcas Island that would be consistent with the enantiomeric ratio results and models for latest Pleistocene and Holocene climatic change in the Puget Sound region (Easterbrook, 1969; Heusser, 1973). It should be emphasized that the model temperature history shown in Figure 15 is only one of many possible histories, and the model only suggests a history that would be consistent with probable maximum and minimum temperatures for the Orcas Island locality (ca. 10°C and 0°C , respectively). Details of this temperature history, such as post-Everson

glacial readvance and the actual timing of isostatic emergence, are difficult to quantify and are not considered in this generalized model.

The enantiomeric ratio results from the Puget Sound samples indicate kinetic temperatures that are several degrees warmer than the present day mean annual air temperatures in the area. The Protothaca kinetic temperatures are quite similar to effective annual ground temperatures in the region but the Saxidomus kinetic temperatures are greater than either effective annual air or ground temperatures for the locality (see Table 2). Since data for mean annual air temperatures are generally most available, we chose to calibrate all the curves of Figure 14 for mean annual air temperatures, and we made the assumption that differences between mean annual air temperatures and effective annual air and ground temperatures have remained constant through time. Thus, the temperature values assigned to the curves of Figure 14 are arbitrarily chosen to be mean annual air temperatures, though these temperatures might differ by several degrees from the true temperatures of the calibration samples. As long as the curves are well-calibrated with Holocene samples, they can be used for chronological purposes if the relation between air and ground temperatures has not changed significantly during the sample history.

The data presented in Table 8 show that Protothaca samples from the Puget Sound localities follow kinetics predicted by equation 1 for temperatures between 2° and 3°C greater than the mean annual (or effective diagenetic) air temperatures at the two localities. This means that Protothaca follows a kinetic pathway that mixed foraminifera would follow if they were exposed to temperatures 2° to 3° greater than those of the Bainbridge and Orcas Island samples. Similarly, mixed

foraminifera kinetics for temperatures 4° to 5°C greater than those of the Puget Sound localities seem appropriate for Saxidomus kinetics. Therefore, for the purposes of the kinetic model of Figure 14, we assume that a racemization curve derived by extrapolation of mixed foraminifera kinetics to a selected temperature would have to be adjusted by factors of 2° and 4° for Protothaca and Saxidomus, respectively, to make the model kinetics consistent with mean annual air temperatures at the calibration localities. These adjustments are shown in Table 9, in which

Table 9 near here

all numerical information necessary for the generation of the curves in Figure 14 is presented. The temperatures assigned to the curves in Figure 14 are appropriate only for Protothaca.

Procedures listed below are used for the derivation of the model curves of Figure 14. All numerical information used in these procedures is summarized in Table 9.

- a.) Selected alloisoleucine/isoleucine data in foraminifera at 3°C (Wehmiller and Hare, 1971) are used for the calibration curve. Uncertainties of 1°C in this calibration curve are assumed and must be propagated through all subsequent derivations.
- b.) Hypothetical curves of $(X_E - X)/X_E$ for isoleucine in foraminifera at temperatures greater than 3°C are calculated by solving for the time required to reach the same value of $(X_E - X)/X_E$ at different temperatures. The expression

required for this calculation is:

$$(k_{iso})_1 (t)_1 = (k_{iso}) (t)_2 \quad (3)$$

The rate constants (k_{iso}) required for this calculation are derived from equation 1. The ratio of times (t_1, t_2) required to reach a given value of $(X_E - X)/X_E$ is a simple inverse function of the relative rate constants for the chosen temperatures.

- c.) Values of leucine enantiomeric ratios can then be estimated from these predicted isoleucine kinetics, and kinetic curves for leucine racemization can be plotted for any given temperature. These curves still would represent those appropriate for foraminifera. The exact value of the leucine ratio estimated by this approach will be dependent on the choice of correction factors (0.90 or 0.95) but this introduces an uncertainty that is less than that observed for multiple analyses of a single genus from the same locality.
- d.) The "foraminifera leucine" curves calculated by steps a-c above are then labelled for a particular temperature, depending on the genus that is selected. The curves in Figure 14 are assigned temperatures based on Protothaca results only. Paralellism in the curves for all genera (especially in those for Protothaca, Chione, Saxidomus, and Tivela) is implied though not always confirmed by some of our results.

The curves derived from the information presented in Table 9 appear to have a sharp "kink" in the region around an $(X_E - X)/X_E$ value of

0.50. This kink is largely an artifact of the choice of calibration points in the foraminifera curve (Wehmiller and Hare, 1971), where a significant amount of uncertainty exists in this particular region of the kinetic curve. Age assignments for samples that fall in this portion of the curve are given relatively large uncertainties, but these uncertainties do not appear to effect the geological conclusions that are presented in Section X.

2. Generic Differences in Enantiomeric Ratios: Kinetic Implications

Previous work has shown that systematic generic relationships exist among several genera of foraminifera (King and Hare, 1972a; King and Neville, 1977). Each genus has its own characteristic non-linear curve, and components of each curve are approximately parallel with corresponding components of other curves. No inversions of apparent generic racemization rate relationships are observed in foraminifera samples of varying ages. Since several significant generic inversions are observed among samples in this work (especially Protothaca-Saxidomus at both LACM 332 and LACM 2641 and Tegula-Epilucina on the Point Loma Nestor Terrace) we must appeal to either geological or geochemical complexities for an explanation. Conceivably each molluscan genus has its own kinetic pathway that is similar, though non-parallel, to those of another genera. If the temperature sensitivities of the diagenetic racemization mechanisms in two different genera are in fact different, then their kinetic pathways might cross at different relative points in time depending on their thermal environments during diagenesis. If, as the foraminiferal evidence suggests (King and Hare, 1972a), the apparent

kinetics of racemization in different genera do not intersect, then reworking and mixing of samples of different ages must be invoked to explain our observations of inverted kinetics at several localities. Because of these possibilities, we choose to make only one distinction among two groups of genera, those that are "fast-racemizing" (Tegula, Macoma, Epilucina, and Cumingia) and those that are "slow-racemizing" (Protothaca, Tivela, Chione, and Saxidomus). The kinetic models of Figure 14 are best applied to the slow racemizing group as a whole, although in a few cases we have considered genera within this group individually.

It is also possible to distinguish between these two groups (fast and slow-racemizing) by examination of at least one other aspect of their amino acid composition, the ratio of aspartic acid to leucine (asp/leu). This ratio is a useful measure of the relative abundance of aspartic acid in the sample. Among the foraminifera that have been studied (King and Hare, 1972a, 1972b; King and Neville, 1977) the slowest-racemizing genus has a molar ratio of aspartic acid to leucine (asp/leu) of 8.2 (modern sample) while the fastest racemizing genus has an asp/leu ratio of 3.9. Published ratios of aspartic acid to leucine in modern samples of molluscan genera here considered are as follows: Protothaca, 6.0 (Hare and Abelson, 1965); Saxidomus, 5.6 (Degens and Spencer, 1966); Tivela, 7.3 (Hare and Abelson, 1965); Macoma, 2.2 (Degens and Spencer, 1966); Polinices, 1.4 (Degens and Spencer, 1966). Semi-quantitative measurements of this ratio by the gas-chromatographic technique employed here are summarized in Table 10. We conclude that the asp/leu ratios of genera in the fast-racemizing group are less than 3.0. Among the slow-

Table 10 near here

racemizing genera, there is slightly more scatter but the ratio is almost always greater than 4.0 and usually between 5.0 and 9.0. The asp/leu ratio is probably time dependent (Vallentyne, 1964); however, a time dependence is seen only among the Saxidomus samples herein. The mixed foraminifera samples from which the kinetic model curves of Figure 14 were derived have asp/leu ratios between 4.95 and 6.40 (Wehmiller, 1971).

Aspartic acid is usually one of the most abundant amino acids in organic matter within calcareous shells (Hare, 1969); its abundance appears to be related to the important role that it plays in calcification processes (see Weiner and Hood, 1975, and references therein). Peptide bonds involving aspartic acid are among those most resistant to natural hydrolysis in calcareous matrices (Hare et al., 1975). The rate of hydrolytic breakdown of calcified peptides during diagenesis is particularly important (and may be the rate determining step) in the apparent kinetics of racemization in fossil calcareous organisms (Wehmiller and Hare, 1971; Bada and Schroeder, 1972, 1975). Because of this relationship between hydrolysis and racemization, we suggest that those genera with high relative abundances of aspartic acid would have a large proportion of "resistant" peptide bonds that should be expected to liberate free amino acids relatively slowly during diagenetic hydrolysis. Genera with low relative amounts of aspartic acid should have fewer resistant peptide bonds and should be expected to liberate free amino acids more quickly. This latter group should have apparent

racemization kinetics significantly more rapid than those of the former group, though during the latest stages of racemization (D/L ratios greater than approximately 0.80) the kinetics of the two groups would begin to converge. Since the slow-racemizing group of genera studied in this work have asp/leu ratios most like those of foraminifera, we feel that our proposed kinetic model curves (whose shapes are derived from the foraminifera kinetics) are only appropriate for the interpretation of the results for the slow-racemizing group of genera. Protothaca and Chione have asp/leu ratios most like those of the mixed foraminifera samples used for the calibration curve, so it is possible that these two genera would be the best ones to interpret in terms of the foraminifera kinetic model. The apparent agreement of observed foraminifera and Protothaca kinetic temperatures in the Holocene samples from Puget Sound is further evidence for the similarity of Protothaca and foraminifera racemization kinetics. However, since we have not analyzed Protothaca or Chione from every locality, we must, in some cases, apply the kinetic model of Figure 14 in a more general way to all samples of the slow-racemizing group, though we recognize that the model may not be specifically valid for all samples within this group.

3. Paleotemperature Considerations

As was stated previously, the curves shown in Figure 14 have been calibrated with the results for Protothaca from the Puget Sound localities. Superimposed upon these curves are the leucine enantiomeric ratio results for the slow-racemizing genera from most of the localities considered in this work. A few localities are omitted from Figure 14 only for the sake of clarity; discussion of their probable ages is found

in following sections. For most localities, the results for both Protothaca and Saxidomus are plotted in Figure 14, as mean values of multiple analyses. The ratios observed in these two genera are plotted in Figure 14 to demonstrate the age/temperature significance of the generic differences in enantiomeric ratios. Results for Tivela and Chione, the other two members of the slow-racemizing group, almost always fall between those for Protothaca and Saxidomus. Age and paleotemperature interpretations can be derived from considerations of the entire group of slow-racemizing genera or by comparison of results for one genera. The latter approach reduces some of the uncertainties associated with comparisons of two localities. Both approaches are used in subsequent discussions.

Three of the most reliably-dated late Pleistocene localities from Table 1 (uranium-series dates on corals) are identified in Figure 14. These localities are:

- 1.) Point Loma, Nestor Terrace: $120,000 \pm 10,000$ yrs.
- 2.) Cayucos: $135,000 \pm 20,000$ yrs. (average of two determinations).
- 3.) San Nicolas Island, 30-meter terrace: $120,000 \pm 20,000$ yrs.
(one of two ages published, assumed to be correct based on results of this work).

These localities are particularly important because they allow estimation of effective diagenetic temperatures for the late Pleistocene and because they can serve as calibration localities for other Pleistocene samples for which age information is sought. Effective diagenetic temperatures are the temperatures associated with an effective rate constant, which is the time-averaged rate constant estimated by inte-

gration through a probable temperature history for a sample:

$$k_{\text{eff}} = \frac{\int_0^T k(t) dt}{\int_0^T dt} \quad (4)$$

where T is the age of the sample. A discussion of effective rate constants and effective diagenetic temperatures can be found in Wehmiller et al (1976).

Following Wehmiller et al (1976), the model of Shackleton and Opdyke (1973) is used for an estimate of the chronology of late Pleistocene sea-surface temperature changes in conjunction with the estimates of CLIMAP (1976) for full-glacial (stage 2, 18,000 yrs. B.P.) temperature reductions of California and Oregon coastal waters. These estimates suggest full-glacial sea-surface temperature reductions of between 2°C and 4°C, with reductions perhaps being slightly greater in southern California than in central California and Oregon. A diagram representing the chronology of these probable temperature fluctuations is shown in Figure 16. Several models are considered in Figure 16. Models 1, 2, and

Figure 16 near here

3 are constructed with the chronology of temperature fluctuation as proposed by Shackleton and Opdyke (1973) but with full-glacial temperature reductions of either 3°C, 5°C, or 7°C. This range of possible temperature reductions is considered because it seems compatible with the CLIMAP (1976) estimates for the full-glacial sea-surface temperatures in the region and the models of Gates (1976) for continental surfaces in the western United States. Temperature reductions as great as those proposed by Gates (1976) (between 9°C and 11°C) are not

considered because they are modelled for large continental areas and probably do not account for the thermal buffering effect that the marine environment (2° to 4°C cooler than at present) would have had on coastal marine terrace localities during full-glacial times. As discussed in Section V, the position of each terrace locality would have shifted inland relative to the coastline during periods of ice-volume expansion. We suspect that these shifts in position relative to the coastline might have had kinetic effects equivalent to an uncertainty of $+ 0.50^{\circ}\text{C}$ in the relative effective diagenetic temperatures discussed here. Only in the comparison of results from the Palos Verdes Sand in San Pedro and the Nestor Terrace on Point Loma is this subtle thermal effect apparent (see Section IX,4c, below).

Model 4, also shown in Figure 16, represents a synthesis of temperature reductions suggested by the other models, and it postulates a temperature history that is perhaps more consistent with various paleoclimatic records that suggest that the thermal histories of marine isotopic Stages 2, 3, and 4 might have been somewhat different (see, for example, Shackleton and Opdyke, 1973, Emiliani and Shackleton, 1974, or Bloom, et al., 1974). Model 4 is considered to be the most realistic of those presented in Figure 16, though none of these models can be unambiguously proven by any of the enantiomeric ratio results. Table 11

Table 11 near here

presents values of effective diagenetic temperatures (calculated with equation 4) for samples of selected ages for each of the temperature

models shown in Figure 16. These calculations show that samples less than 125,000 years in age should be interpreted in terms of effective temperatures slightly cooler (0.5°C to 1.5°C) than those of the effective diagenetic temperatures for the 125,000-year samples. The relative magnitude of the differences in effective temperatures is constant for models 1, 2, and 3, but significant differences in relative temperatures for model 4 are seen when compared with models 1 through 3. For samples with ages greater than 125,000 years, we assume an effective diagenetic temperature equal to that observed for radiometrically-dated localities, unless otherwise stated.

The late Pleistocene calibration locality that is best interpreted within the kinetic model format of Figure 14 is the Nestor Terrace on Point Loma. This locality has the smallest uncertainty in its age assignment and samples of several of the slow-racemizing genera have been analyzed. The results for Protothaca from the Nestor Terrace indicate that an effective diagenetic temperature of approximately $13.5^{\circ} \pm .5^{\circ}\text{C}$ is appropriate for this locality. An effective diagenetic temperature of approximately $11.0^{\circ} \pm .5^{\circ}\text{C}$ is estimated for the Cayucos locality, though with less certainty because of possible "adjustments" in the Cayucos age assignment that are discussed more fully in Section IX,4d. An effective diagenetic temperature of about 11°C is estimated for the 30-meter terrace on San Nicolas Island by comparison of the Saxidomus results from this locality with the Protothaca kinetics of Figure 14.

Since the model curves of Figure 14 have been calibrated with the assumption that present-day mean annual air temperatures are the equiva-

lents of present-day effective diagenetic temperatures, the effective diagenetic temperatures estimated for the late Pleistocene calibration localities can be easily compared with modern mean annual air temperatures in order to estimate the magnitude of full-glacial temperature reductions. The differences between effective diagenetic temperatures and modern mean annual air temperatures for these localities are $2.5 \pm .5^{\circ}\text{C}$ (Nestor Terrace); $3.8^{\circ} \pm .75^{\circ}\text{C}$ (San Nicolas Island); and $2.5^{\circ} \pm .5^{\circ}\text{C}$ (Cayucos). These temperature differences are consistent with models 2 or 4 (see Figure 16 and Table 11) and suggest full-glacial temperature reductions of between 4°C and 7°C . The temperature differences also seem consistent with the possibility of slightly greater full-glacial temperature reductions in coastal waters off southern California (CLIMAP, 1976) though the range of uncertainties in our results does not allow us to unambiguously state that temperature gradients along the coast actually were less during full-glacial times than at present.

4. Kinetic Model Age Assignments, Southern, Central, and Northern Temperature Regions

Age assignments based upon the leucine kinetic model for every locality discussed herein are summarized in Table 12. These model age

Table 12 near here

assignments are derived from comparisons of leucine results with those from one or more of the calibration sites. Possible differences in thermal histories between unknown and calibration sites are taken into

consideration, though it appears that these differences are within the temperature uncertainties ($\pm .75^{\circ}\text{C}$) described in Section IX,3, above. Because generic differences within the slow-racemizing group are roughly equivalent to two degrees centigrade of temperature difference (or approximately 25,000 years in samples 100,000 to 150,000 years in age) we express all kinetic model age assignments as a range of ages equivalent to two degrees of temperature uncertainty. Only in cases where individual genera from calibration and unknown localities are compared can the uncertainties be decreased.

a.) San Nicolas Island

Samples from the vertical sequence of terraces on San Nicolas Island provide the best demonstration of the kinetic model age assignment approach. If the Saxidomus sample from the 30-meter terrace on San Nicolas Island is used as a 120,000 year calibration sample, then the Saxidomus sample from the 120-meter terrace would have an age estimate of 280,000 to 380,000 years. A sub-parallel hypothetical curve calibrated to the Epilucina sample (fast-racemizer) from the low terrace on San Nicolas Island would predict a similar age for the Epilucina from the 120-meter terrace. The higher terrace (240 meter) on San Nicolas Island would be estimated to be about 350,000 to 550,000 years in age, based upon only the Saxidomus results. These age estimates for the higher terraces could be increased by about 20% if lower temperatures at higher elevations were invoked (see Table 2). However, if the low terrace (30-meter) calibration sample is younger than 120,000 years (see Table 1) then the age assignments for the upper terraces would have to be reduced by about 15-20%. Since the maximum age estimate that would be possible

within the leucine model for the high (240-meter) terrace is less than 600,000 years, these age estimates can be tested by paleomagnetic polarity determinations on the terrace deposits.

b.) San Diego Area

Samples from the San Diego area (Pacific Beach and Point Loma) are important in the tests of the kinetic model because one genus (Protothaca) is available at three localities of apparently different age, and temperature histories for these three localities can be considered to have been quite similar. Protothaca samples from the Nestor Terrace on Point Loma serve as a calibration (120,000 \pm 10,000 years) point. An age of 60,000 to 80,000 years for the Bird Rock Terrace is derived from Figure 14 if the same effective diagenetic temperature is used in comparing the Nestor and Bird Rock samples. Since late Stage 5 terraces can be expected to have experienced proportionately greater periods of cooler temperatures than early Stage 5 ones (see Figure 16 and Table 11), they should be interpreted in terms of slightly cooler temperatures. When this factor is taken into account, the Bird Rock age assignment becomes 70,000 to 90,000 years. The results from SDSU 1854, Pacific Beach, are indicative of samples of two different ages being present. The older samples, 75-39 and 76-47, are estimated to have an age of 190,000 to 250,000 years when interpreted in terms of effective diagenetic temperatures equivalent to those of the Point Loma Nestor Terrace samples. The younger samples from SDSU 1854, samples 76-89 and 76-102, are interpreted as being correlative with samples of the same genus (Protothaca) from the Point Loma Nestor Terrace, and hence would be assigned an age of 120,000 \pm 10,000 years. This latter age is the actual

age of the terrace deposit, though it appears that older material has been reworked into this deposit. The source of the older material was probably several marine deposits slightly inland of this locality that also appear to be pre-Nestor Terrace in age (Wehmiller, unpublished).

The samples from Torrey Pines (LACM 2662) are difficult to interpret because of the inversion in the Protothaca-Saxidomus generic relationship that is typically seen at other late Pleistocene localities. The Saxidomus results alone, when compared to either Point Loma or Newport Beach samples, would suggest a late Stage 5 (80,000 to 100,000 yrs.) age. The Protothaca result would suggest an early Stage 5 (approximately 130,000 years) age. Neither of these age estimates is inconsistent with previous correlations of the Torrey Pines locality to other late Pleistocene localities, including the Nestor Terrace (Valentine, 1959). However, the data suggest that a mixture of Nestor and Bird Rock equivalent samples might be present in the Torrey Pines collection. Only further analyses can clarify this ambiguity.

c.) Newport Beach and San Pedro Early Stage 5 Localities

Samples from Newport Mesa and the First Terrace at San Pedro (localities M 2074, M 1477, and M 5908) have been shown to be correlative by qualitative comparison of results for several amino acids. Slight temperature differences between San Pedro and Newport Mesa are apparent in the enantiomeric ratios (see Section VIII, j). These samples, interpreted in terms of effective diagenetic temperatures equivalent to those for Point Loma, would have kinetic model ages of 140,000 to 180,000 years, depending on the genera being compared. However, we prefer to interpret these samples as being roughly equivalent in age to the Point

Loma Nestor Terrace (120,000 to 140,000 years) and as having been exposed to effective diagenetic temperatures between 0.5°C and 1.5°C greater than those on Point Loma. Part of this difference in effective temperatures can be accounted for by present-day differences in temperature, and part can be postulated as being the result of different thermal environments during both submergent and emergent phases in the histories of the Palos Verdes Sand and the Nestor Terrace. This "adjustment" of the apparent kinetic model ages of the samples from localities M 2074, M 1477, and M 5908 is required by both radiometric and geological evidence and is discussed more fully in section IX,5, below. It is important to emphasize that this "adjustment" of the kinetic model ages for the samples from these three localities is not required by the Protothaca results alone. Only the Saxidomus results appear to require such an adjustment of model ages. The Epilucina results from the Nestor Terrace and from the first terrace at Corona del Mar also suggest a slight difference in effective diagenetic temperatures, if the assumption of synchronicity of the Nestor and Corona del Mar terraces is correct.

Protothaca and Saxidomus samples from Laguna Beach (loc. M 1018) are assigned a similar age (120,000 to 140,000 years) because of their apparent similarity to respective samples from Newport Mesa. The age assignments for the Tivela samples (and probably also the one Polinices sample) from Laguna Beach are approximately 190,000 to 290,000 years, based upon a comparison with Tivela samples from Newport Mesa. The implications of this apparent mixing of sample ages are discussed below (Section X).

d.) Central Temperature Region Samples

Age assignments for Santa Cruz and Point Año Nuevo are best derived from the Protothaca results, since this genus also occurs at Cayucos, from the Central Region calibration site. If the Santa Cruz samples are interpreted in terms of temperatures identical to those at Cayucos, then an age of 80,000 to 100,000 years would be estimated. Since Santa Cruz is probably somewhat warmer than Cayucos (Table 2) a still younger age would be suggested. However, compensation for lower effective diagenetic temperatures of late Stage 5 samples (Table 11) would probably offset this probable temperature difference, so an age of 80,000 to 100,000 years is estimated for Santa Cruz. A late Stage 5 age for the Santa Cruz shells appears consistent with radiometric information from this terrace (Bradley and Addicott, 1968).

Because of uncertainties regarding temperature differences between Point Año Nuevo and Cayucos, we suggest that Point Año Nuevo is older than Santa Cruz and less than, or equal to, Cayucos in age. A numerical age assignment for Point Año Nuevo would then be approximately 90,000 to 140,000 years. Such an age assignment is only slightly greater than available uranium-series age estimates on mollusks for this locality (Bradley and Addicott, 1968).

The kinetic model ages for the Central Temperature Region are based upon the assumed age for Cayucos, the calibration site for this region, of between 130,000 and 140,000 years. The two age determinations for Cayucos (Veeh and Valentine, 1967) both have significant enough uncertainties ($\pm 30,000$ years) so that Cayucos could, in fact, be slightly younger in age and correlative with terraces at numerous lo-

calities around the world (including the Nestor Terrace on Point Loma) with ages between 120,000 and 130,000 years (i.e., Barbados, New Guinea, and others, as reviewed by Bloom et al., 1974). The marine isotopic record (Shackleton and Opdyke, 1973) does not indicate a minimum in ice-volume during the period between 150,000 and 130,000 yrs. B.P., though uranium-series ages suggest that terrace formation during this period may have occurred (Bloom et al., 1974; Stearns, 1976). The enantiomeric ratio results for Cayucos and the Nestor Terrace are consistent with a real age difference between these two localities (of about 15,000 years) if temperature gradients along the coast have been preserved during the past 130,000 years. We have used this assumption in the presentation of kinetic model ages and paleotemperature estimates that involve the Cayucos calibration locality.

e.) Post Stage 5 Samples

Fossils from Goleta have previously been identified (section VIII) to be post-Stage 5 (less than 70,000 years) in age. If the Goleta results are interpreted in terms of effective diagenetic temperatures equal to those at Point Loma, then we would estimate an age of about 30,000 years. Correction for probable lower effective diagenetic temperatures (as suggested in Figure 16 and Table 11) would indicate an age of about 40,000 years. These age assignments are complicated by the fact that the results fall into the complex region of the kinetic curve. For geological reasons (see Section X) we suggest that an age of 40,000 yrs. for Goleta is correct. The "youth" of this locality is suggested by one uranium-series mollusk analysis (approximately 18,000 yrs. B.P. if a closed system is assumed: Kaufman et al., 1971). No radiocarbon dates

are as yet available for this locality.

The Cape Blanco samples are difficult to interpret because the Protothaca-Saxidomus relationship in these samples is inverted from that observed at almost all other late Pleistocene localities. This inversion could be due to mixing of samples of two different ages or due to complexities in the kinetic pathways of these two genera. The Cape Blanco Saxidomus results (not plotted in Figure 14), interpreted in terms of effective diagenetic temperatures about three degrees C cooler than those of Santa Cruz, would imply an age of about 45,000 years. The Cape Blanco, Protothaca results, interpreted in the same way, would imply an age of about 75,000 years. If these samples were interpreted in terms of temperatures one or two degrees greater than the effective diagenetic temperatures of the Orcas Island (Puget Sound) samples, the age assignments would also be between 45,000 and 75,000 years. A younger age (40-50,000 yrs.) is preferred because of the relationship of Cape Blanco Saxidomus results with those from several other nearby localities (Wehmiller and Kennedy, unpublished). Radiometric information on the Cape Blanco locality is somewhat ambiguous but is certainly suggestive of a late- to post-Stage 5 age. Richards and Thurber (1966) have reported both C14 and Th230 dates (on mollusks) of approximately 35,000 years for Cape Blanco, while Janda (1969; 1971) has obtained C14 dates of greater than 40,000 years on wood samples from nearby terrace localities thought to be stratigraphically equivalent to the Cape Blanco locality. Stuiver (pers. comm., May, 1977) has recently obtained a C14 date of $34,200 \pm 300$ years on the interior portions of shells from locality M 1450 at Cape Blanco.

f.) Pre-Stage 5 Samples

Trinidad Head

The Saxidomus samples from Trinidad Head are best compared to Saxidomus from Point Año Nuevo, in spite of the uncertainties in the age assignment for the latter locality. If an effective diagenetic temperature of about two degrees centigrade cooler than that of Point Año Nuevo is assumed for Trinidad Head, then an age of approximately 400,000 to 600,000 years for the Trinidad Head locality is indicated. Such an age is consistent with the probable correlation of this locality to other middle Pleistocene localities in the area (Kennedy, unpubl.).

San Pedro Sand (LACM 332), and Timms Point Silt (LACM 130-7), and M 1479 and M 5902

Saxidomus results from localities LACM 332, LACM 66-2, M 1479 and M 5902 all appear nearly identical. The simplest interpretation of these results would be by comparison to the Saxidomus samples from the Palos Verdes Sand in the Newport Beach-San Pedro region. All four localities would fall in the age range of 200,000 to 300,000 years by this approach. A similar interpretation of the Timms Point Silt (LACM 130-7) Saxidomus results would suggest an age of about between 350,000 and 500,000 years. However, several additional factors must be considered in the estimation of ages for these samples:

- 1.) Generic inversions are observed at localities M 1479 and M 5902 (Saxidomus-Tivela in both cases) and at LACM 332 (Saxidomus-Protothaca). Uncertainties regarding these observations were previously discussed (Section VIII,j).
- 2.) Generic relationships between Saxidomus, Protothaca, and

Chione are not inverted at localities LACM 66-2 and M 5898.

- 3.) The San Pedro Sand and Timms Point Silt are recognized as being basin deposits rather than terrace deposits. Consequently the thermal histories of the San Pedro Sand and Timms Point Silt can be expected to have been significantly different from the thermal histories of emergent terrace deposits.

We suggest that the samples from localities M 5902, M 1479, and LACM 332 should be considered roughly equal in age and as having equal or greater ages than the samples from the terrace deposits at LACM 66-2 and M 5898. The correlation of the first three localities is based upon the similarities in the Saxidomus results at all three localities and upon the similarities in the Protothaca and Tivela results and the probable equivalent kinetics of these two genera. The assignment of these relative ages is based upon our consideration of factors 1 through 3, above. The samples from localities LACM 332, M 1479, and M 5902 are interpreted to be older than the samples from LACM 66-2 and M 5898 largely because of the inversions of the generic relationships among the slow-racemizing genera. If these inversions are the result of "crossing kinetic pathways" within the format of Figure 14, then we must conclude that significant lengths of time are required to produce these apparent kinetic effects. If crossing kinetic pathways are not invoked as an explanation for the results, then mixing of samples of different ages is apparent. This possibility is highly probable in the case of locality M 1479 (see Section X,2d, below).

Estimated depths of deposition of the San Pedro Sand and Timms Point

Silt are variable but are on the order of 25 and 100 meters, respectively, for the localities being considered in this work. Oxygen isotope measurements on samples from equivalent faunal zones suggests temperatures of about 10.5°C and 6.3°C, respectively, at the time of deposition (Valentine and Meade, 1960). These temperatures are about 6° and 10° cooler than the effective diagenetic temperatures that are applicable to the Palos Verdes Sand; if used for estimation of kinetic model ages, these temperatures would suggest maximum ages of approximately 550,000 (+ 150,000) years for the San Pedro Sand at LACM 332 and approximately 1.5 million years for the Timms Point Silt at LACM 130-7. For each of these units, these maximum age estimates can be adjusted by consideration of the possible thermal histories of the deposits. For example, emergence of the San Pedro Sand during eustatic sea level minima would have exposed the unit to warmer temperatures (approximately 3° cooler than present - see Figure 16). Continued uplift and shoaling of the San Pedro Sand (Woodring et al., 1946; Poland, et al., 1956) would also have exposed the San Pedro Sand to warmer temperatures. Though these thoughts are rather speculative, they are quite useful within the kinetic model framework of Figure 14. We suggest that effective diagenetic temperatures for the San Pedro Sand at locality LACM 332 have been between 2°C and 3°C cooler than those for the Palos Verdes Sand; an age of 350,000 to 450,000 years for the San Pedro Sand (at LACM 332) is implied. A similar adjustment of the interpretation of the Timms Point Silt age would suggest an age of approximately 1 million years. Preliminary results on Saxidomus and Macoma samples from the Ventura Basin (Wehmiller, unpublished) with stratigraphic association to a 600,000-year volcanic ash layer suggest

that the enantiomeric ratios observed in the Timms Point Silt Saxidomus samples could be indicative of an age as young as 450,000 to 500,000 years. Therefore we place a large uncertainty on the Timms Point Silt age assignment (Table 12) but we consider an age of less than 700,000 years to be highly probable. Paleomagnetic determinations (in progress) certainly could clarify the age assignment for the Timms Point Silt. Our age assignments for the San Pedro Sand and Timms Point Silt localities are consistent with the stratigraphic relationships of these two localities (see Woodring et al., 1946, Fig. 10) and the enantiomeric ratios observed in the Pliocene Saxidomus from the Fernando Formation (see Table 3). They are quite young in comparison with the 3.0 million-year age estimate for the Lomita Marl (Obradovich, 1968) which is stratigraphically equivalent with the Timms Point Silt and which is usually identified as the earliest Pleistocene marine deposit in the San Pedro area (Woodring et al., 1946, Fig. 10, and others).

Saxidomus samples from localities M 1479 (Newport Mesa) and M 5902 (Huntington Beach), with results quite similar to those of LACM 332, would be interpreted to be of equal age (350,000 to 450,000 years). The absence of local temperature effects for these Saxidomus samples (see Figure 8 and related discussion) suggests that local temperature differences have affected the results only in late Pleistocene samples, or that these particular samples from M 5902 and M 1479 have experienced depositional and thermal histories different from those of the LACM 332 samples. This latter possibility is supported by the stratigraphic relationships at M 1479, discussed more fully in Section X,2d, below. The MAC samples from M 1479 and M 5902 have D/L ratios 10-15% less than

the ratios in MAC from LACM 332, indicating either a temperature effect (see Fig. 8) or a real age difference. If the latter is the case, then the MAC from M 1479 and M 5902 would appear younger than the MAC from San Pedro Sand (LACM 332) but slightly older than MAC from the Palos Verdes Sand (M 5908).

LACM 66-2, M 5898, and M 1722

Samples from locality LACM 66-2, and from nearby locality M 5898, show no inverted generic relationships and therefore can be easily interpreted in terms of the kinetic models presented earlier. Using the Newport Mesa samples as a calibration, we estimate an age of between 190,000 and 290,000 years for these samples. A probable correlation of Protothaca-Chione results from these localities with those from Pacific Beach (the "older" samples at SDSU 1854) and with the Tivela results from M 1018 and M 1019 (Laguna Beach) is implied.

The Protothaca sample (74-11, Table 4) from M 1722, a locality quite near locality LACM 66-2 (and in the same "Palos Verdes Sand" deposit), appears much younger (120,000 to 140,000 years) than the samples from LACM 66-2. These results suggest that samples of at least two different ages are found in the beds exposed at both LACM 66-2 and M 1722. In addition, Pliocene fossils have been found at LACM 66-2, apparently reworked from the underlying bedrock (Vedder, unpubl.). Reasons for the apparent mixing of samples of different ages are discussed in Section X,2a, below.

High Terraces, Palos Verdes, and San Joaquin Hills

Age assignments for these upper terraces are based on the fast-racemizing genera Tegula, Epilucina, and Polinices. Tegula from the

third (90-meter) terrace (M 3759) at Corona del Mar have ratios quite similar to those of Tegula samples from high terraces on San Nicolas Island (ninth terrace) and the Palos Verdes Hills (twelfth terrace). Epilucina ratios from M 3759 (third terrace, Corona del Mar) are distinctly greater than those in Epilucina from the fifth (120-meter) terrace on San Nicolas Island. Since kinetic model age assignments are available for the higher terraces on San Nicolas Island (section IX,4a, above) we suggest that the relative ages implied by the Tegula and Epilucina results can be used to estimate ages of 350,000 to 550,000 years for the twelfth terrace on the Palos Verdes Hills and the third terrace on the San Joaquin Hills. Age estimates in this range have been suggested by other workers (Fanale and Schaeffer, 1965; Szabo and Vedder, 1971). As mentioned above, the results from localities M 1476, M 1018, M 1019, and LACM 66-2 indicate that samples with an age of approximately 190,000 to 290,000 years are found on the first terrace. These samples apparently are representative of the age of the second terrace on the San Joaquin Hills, and have been reworked into the deposits on the first terrace. Preliminary results from the first and second terraces at San Clemente, approximately 15 km south of Laguna Beach, support this inferred age relationship for the samples on the first terrace in the Newport Beach-Laguna Beach region (Wehmiller, unpubl.).

5. Kinetic Models - Implications of Geological Controls

The kinetic model ages presented above undoubtedly will undergo minor revisions as new data and new models are developed. Results for only one amino acid in a limited number of genera have been utilized. None of the model ages presented here are unreasonable within the available geological

context (see further discussion in Section X), and it is this geological context that places some important restraints on the type of kinetic model that is appropriate. Specific points relating to the kinetic model are outlined below:

- a.) Mitterer (1975) used linear kinetic models in the interpretation of isoleucine epimerization results in Mercenaria from Pleistocene deposits in Florida. Linear kinetics were inferred from laboratory pyrolysis experiments and were calibrated to several Holocene Mercenaria samples. Results for Pleistocene samples suggested ages of 134,000, 180,000, 236,000, and 324,000 years and the correlation of these ages with radiometric dates for high sea stands recognized elsewhere was noted (Mitterer, 1975). One calibration site (probable age, 120,000 years) was used (Mitterer, 1975) to infer "average diagenetic temperatures" (equivalent to our "effective diagenetic temperature" of 8° to 11°C for the Florida localities; such temperatures represent reductions of about 12°C from present-day mean annual temperatures. By the arguments outlined in section IX,3, above, a 12° reduction in effective diagenetic temperatures requires full-glacial temperature reductions of 20°C or more. Temperature reductions of this magnitude are inconsistent with the paleoclimatic evidence cited by Mitterer (1975) and other evidence as well (CLIMAP, 1976). Non-linear kinetic models applied to Mitterer's results would not require such large temperature reductions and would be

more consistent with radiometric information (Webmiller and Belknap, in press). Linear kinetic models applied to the Pacific Coast samples presented in this work would also lead to very large estimates of full-glacial temperature reductions ($15^{\circ} - 20^{\circ}\text{C}$) for the California coastal environment. Linear kinetic models calibrated to the 120,000-year and 135,000-year calibration sites (Figure 14) would suggest ages for some younger localities that would be in very good agreement with world-wide eustatic sea-level records (Bloom et al., 1974) but which would yield unreasonably young age estimates for the high terraces on San Nicolas Island and the lower Pleistocene San Pedro Sand and Timms Point Silt (less than 300,000 years for all). Linear models might appear to have more "resolving power" for samples of closely spaced ages within the late Pleistocene, but they appear to be incorrect when interpreted within a rigid geological framework.

b.) The results for samples from the San Nicolas Island terraces could be used as an argument for forcing the Pleistocene components of the model curves to have an even more gradual slope than shown in Figure 14. If constant uplift rates for San Nicolas Island were invoked, then the age of the 240-meter terrace on San Nicolas Island should be about ten times that of the 30-meter terrace (i.e., 1,200,000

years rather than 350,000 to 550,000 years), forcing a significant adjustment in the kinetic model. Geological implications of the younger age for the high terrace on San Nicolas Island are discussed in section X, below. Any such adjustment in the slopes of the Pleistocene components of the curves of Figure 14 must still be "rotated" around the results for the late Pleistocene calibration sites. Such a manipulation would increase the age estimates for various pre-Stage 5 samples identified above but would decrease the estimated ages for localities such as Point Loma (Bird Rock Terrace), Santa Cruz, Goleta, and Cape Blanco. These decreased age estimates would be unreasonable in light of available geological evidence.

Each of the points outlined above identifies a specific focus for additional geological and/or geochemical investigation. The model curves of Figure 14 are the ones that appear most consistent with available geological, geochronological, paleoclimatic, and kinetic information.

6. Possible Kinetic Models for Other Amino Acids: Consistency

With Leucine Model Age Assignments

Since the kinetic model ages presented in preceding discussions have been derived from the results for only one amino acid, it is important to ask whether these ages are consistent with the enantiomeric ratio results for other amino acids. Ideally, kinetic models for all amino acids would be available and ages could be estimated independently for each amino acid analyzed in a sample. However, such kinetic models do not exist

because of a lack of activation energy data for racemization in calcareous skeletal material.

Figure 17 shows how the leucine model ages can be used to propose

Figure 17 near here

model kinetics for other amino acids, and the validity of these models can be qualitatively evaluated by comparison with the kinetics of racemization observed for these various amino acids in foraminifera (Kvenvolden et al., 1973). Enantiomeric ratio results for valine, glutamic acid, leucine, proline, phenylalanine, and alanine in Protothaca and Chione from four Southern Temperature Region localities (Nestor and Bird Rock Terraces, Pacific Beach - SDSU 1854, and Goleta) are shown in Figure 17. These particular samples are chosen because they represent the racemization kinetics in a single species over a wide range of ages (leucine model ages) within a narrow range of effective diagenetic temperatures ($\leq 1^{\circ}\text{C}$). The results shown in Figure 17 do not prove the validity of the leucine kinetic model, but since apparent kinetics for these six amino acids as presented in Figure 17 are quite similar to those observed in foraminifera (similar non-linearity, relative rates), it can at least be suggested that the leucine kinetic model is not grossly inconsistent with the probable racemization kinetics for the other amino acids. The data for alanine are the only results that appear in conflict with the leucine model ages, though the divergence of alanine and leucine kinetics seen in Figure 17 is also apparent in the foraminifera data (Kvenvolden et al., 1973).

X. AGE ASSIGNMENTS: CORRELATIONS WITH OTHER RECORDS AND STRATIGRAPHIC, TECTONIC, AND PALEOCLIMATIC IMPLICATIONS

In this section we propose specific correlations of terrace ages with ice-volume minima identified in the marine isotopic record (Shackleton and Opdyke, 1973) and in the eustatic sea-level record (Bloom et al., 1974). These apparent correlations are, in some cases, quite obvious from the relative and kinetic model age assignments presented in preceding sections. In a few cases we "adjust" our age assignments to fit the chronology of the eustatic sea-level and marine isotopic records, since we recognize that the chronology of these records is generally more precise than that of the kinetic age models used in this work. Figure 18

Figure 18 near here

shows the marine isotopic record (from Shackleton and Opdyke, 1973) upon which we have superimposed the chronologic terminology adopted herein. Age assignments for the localities studied herein are presented in Figure 18 for comparison with the isotopic record. In following sections we discuss the validity and implications of these age assignments in terms of their correlation with the isotopic record. In addition, we discuss the implications of several of the terrace age assignments for paleoecologic reconstructions and for the estimation of tectonic uplift rates. For the latter discussion, we use the position of the sea surface (relative to that of today) as estimated by Bloom et al (1974) in calculating the magnitude of uplift since the time of terrace platform formation. These uplift rates are summarized in Table 13 and are cited

in following discussions.

Table 13 near here

1.) Late Pleistocene Localities

- a.) Palos Verdes Sand (San Pedro) and First Terrace, Newport Beach to Laguna Beach (locs. M 5908, LACM 1210, M 1477, M 1722, M 2074, M 1481, M 1482, M 1018, and M 1019).

Because of the apparent extensive nature of the Palos Verdes Sand and correlative deposits in the San Pedro-Newport Beach region, and because of the well-documented warm water fauna of the Palos Verdes Sand (Woodring et al., 1946, and others), we conclude from both geological and amino acid evidence that the Palos Verdes Sand represents a time period equivalent to the early portion of Stage 5 of the marine isotopic record (120,000 to 140,000 years). Both eustatic and isotopic records indicate that this was a time of ice volumes at least as small as those of today. Kinetic model ages for the San Pedro and Newport Beach localities (specifically, M 5908, LACM 1210, M 2074, M 1477, and M 1722) were adjusted slightly (Section IX,4c) because of the importance of relating the Palos Verdes Sand to this widely recognized and well dated time of high sea level. The adjustment in kinetic model ages is consistent with probable effective diagenetic temperature differences between the San Pedro-Newport Beach region and the Southern Region calibration site, the Nestor Terrace on Point Loma. Without such a manipulation, the kinetic model age estimate for the Palos Verdes Sand would place it in a time of full-glacial eustatic sea-level reduction (stage 6 of Shackleton and

Opdyke, 1973). Given the chronological framework adopted herein, a late Pleistocene age assignment is appropriate for all localities discussed in this section.

Average uplift rates calculated for the shoreline angles nearest to localities M 5908 and M 2074 (San Pedro and Newport Mesa) (Table 13) suggest that deposits associated with either the 105,000 or 80,000-year high sea stands (Bloom et al., 1974) would be within a few meters of present sea level and perhaps not preserved. However, open system uranium series dates on mollusks of $86,000 \pm 9,000$ years were reported by Szabo and Rosholt (1969) for a locality in central San Pedro (first terrace) about 1.6 km southwest of our locality M 5908. Since Valentine (1961) suggests that the Palos Verdes Sand in northeastern San Pedro (in the region of locality M 5908) might be faunally equivalent to deposits on the second terrace elsewhere in San Pedro, it appears possible that deposits of at least two ages (early and late Stage 5) might be present on the low terraces in San Pedro. A closed-system date on mollusks of $69,000 \pm 7,000$ years for locality M 1477 on Newport Mesa was reported by Szabo and Vedder (1971), but does not appear to be supported by our results.

The correlation of the lowest emergent terrace from Newport Beach south to Laguna Beach with the early Stage 5 high sea stand is geologically reasonable and, in fact, has been a working assumption of many previous workers who have considered these lowest emergent terraces as being time-equivalents of the last interglacial (Sangamon). Complexities associated with areas around localities M 1722 (near Upper Newport Bay) and M 1018/M 1019 (Laguna Beach) are discussed in Section

X,3, below.

b.) Point Loma Bird Rock Terrace (SDSU 2523)

The Bird Rock Terrace appears correlative with the 80,000-year high sea stand of Bloom et al. (1974). An age younger than that of the Nestor Terrace on Point Loma is certainly consistent with interpretations of the geomorphology of these two terraces (Ku and Kern, 1974; Kern, in press). Calculations based upon constant uplift-rate assumptions and the elevation of the Nestor Terrace on Point Loma would suggest that a terrace correlative to the 105,000-year high sea stand ought to be present at an elevation equal to that of the Bird Rock Terrace. If the Bird Rock Terrace is in fact 105,000 years in age, then revisions in the kinetic model are required. Alternatively, the younger age for the Bird Rock Terrace indicates that non-constant uplift has been occurring on Point Loma and that the 105,000-year terrace deposit has been eroded by the 80,000-year transgression. In light of extensive deformation of parts of Point Loma (Kern, 1973; in press) variable uplift rates are not unreasonable for this area.

A cooler-water fauna present on the Bird Rock Terrace (Kern, in press) would be consistent with either a late- or post-Stage 5 age. The late-Stage 5 age indicated by the amino acid results suggests that faunal investigations can resolve some of the subtle temperature changes apparent in the isotopic record (Shackleton and Opdyke, 1973).

c.) Santa Cruz and Point Año Nuevo

The Santa Cruz locality also appears to be correlative with the 80,000-year high sea stand, though the maximum age estimate of 100,000 years could indicate a correlation with the 105,000-year event. The

latter age seems consistent with uplift rates and conceptual models of the history of the area (Bradley and Griggs, 1976) though the former age is more in agreement with uranium-series ages on mollusks from this locality (Bradley and Addicott, 1968). Both ages imply uplift rates somewhat greater than in the Point Loma area (Table 13).

Northern extra-limital species (i.e., northern species which are now locally "extinct") occur in the terrace deposits at Santa Cruz and at nearby Point Año Nuevo (Addicott, 1966). As in the case of the Bird Rock Terrace, the faunal associations are consistent with late Stage 5 ages (i.e., cooler than early Stage 5) for these localities. Because of the uncertainties regarding the age assignment for Año Nuevo Point (80,000 to 140,000 years) the faunal data may be the best tool for assigning a late Stage 5 age to Point Año Nuevo.

d.) Goleta

Goleta appears to be correlative with either a 30,000 to 40,000-year sea level maximum (below present sea level) of Bloom et al. (1974), or Stage 3 of the isotopic record. We do not argue that Goleta represents a positive "mid-Wisconsin" high sea stand; rather we propose that relatively rapid uplift rates for this area are indicated. Since both of the interstadial sea-levels identified by Bloom et al. (1974) for this time period were at levels about 40 meters below present, the Goleta platform has been uplifted between 50 and 60 meters since the time of its formation. Inferred uplift rates of $1.6 \pm .2$ m/1000 yrs. for Goleta are almost an order of magnitude greater than those observed for Point Loma or the San Pedro first terrace.

Birkeland (1972) has pointed out that some stream deposits along

the Malibu coast east of Goleta are pre-Holocene in age and are graded to a sea-level below that associated with the shoreline angle of the youngest marine terrace in the area. These stream terraces are additional evidence for a "mid-Wisconsin" (Stage 3 correlative) sea-level maximum being recorded along the southern California coast, since the youngest terrace (Dume Terrace) is most likely equivalent to Stage 5 in age (U-Series dates on mollusks give an age for the Dume Terrace of $104,000 \pm 5,000$ years: Szabo and Rosholt, 1969). Birkeland (1972) also correlated this mid-Wisconsin sea-level maximum with the interstadials recognized in the New Guinea coral reef record (Bloom *et al.*, 1974).

The age assignment for the Goleta terrace clearly demands a revision of the working hypothesis that the lowest emergent terrace is everywhere correlative along the Pacific Coast. It is important to note that several paleontological investigations of this locality and others nearby have recognized a cool-water aspect to the fauna (Addicott, 1964b; Wright, 1972). In light of the ages presented here, such faunal characteristics do not need to be explained in terms of unusual oceanographic conditions during the period of formation of these terraces (Addicott, 1964b; Wright, 1972). These observations allow us to speculate that the entire suite of low terrace cool-water faunal associations noted by Addicott (1964b) on terrace platforms both east and west of Goleta is representative of terrace formation during interstadial rather than interglacial (Stage 3 vs. Stage 5) conditions.

e.) Cape Blanco

In spite of our uncertainties regarding the Cape Blanco age assignment, it seems reasonable to correlate this terrace with either the

40,000-year or 60,000-year sea level maxima of Bloom et al (1974). Some radiometric evidence (Richards and Thurber, 1966) supports the younger age. Either age leads to estimates of uplift rates roughly equal to, or almost twice as great as, those for Goleta (1.5 to 2.75 meters/1000 years). The maximum age that we could assign to the Cape Blanco terrace would be approximately 70,000 yrs. (Protothaca kinetic model). This age is perhaps in better agreement with geomorphic evidence from the area (Janda, 1969).

Association of the Cape Blanco terrace deposit with interstadial ice volumes is consistent with the presence of several northern extra-limital molluscan species in the fauna from this locality (Addicott, 1964a; Kennedy, unpubl.).

2.) Middle Pleistocene Localities and Samples

a.) San Pedro Sand, LACM 332

The age assignment for the San Pedro Sand is specifically derived from the results for locality LACM 332; equivalent ages for shells from localities M 5902 and M 1479 are indicated by the similarity of most of the results from these two localities with those for locality LACM 332. The estimated age range of 350,000 to 450,000 years for the San Pedro Sand suggests that deposition of the San Pedro Sand was, at least in part, synchronous with one or more of the eustatic high sea levels that cut the higher terraces on the Palos Verdes Hills. Given the tectonic and geomorphologic setting of the San Pedro Sand, it is quite likely that a wide range of ages might be associated with this unit. Correlation with Stages 9 through 11 of the isotopic record (Shackleton and Opdyke, 1973) is implied by our age estimate for locality LACM 332.

These stages represent two rather long periods of ice-volume minima separated by a short and intense ice-volume expansion. Continued uplift and shoaling combined with the relatively low sea levels associated with ice-volume minima during Stage 7 could have prevented any additional deposition in the basin until Stage 5.

This model for the history of the San Pedro Sand (at LACM 332), and the age estimate itself, require that the San Pedro Sand be designated as middle Pleistocene in age given the chronological divisions of the Pleistocene that are adopted in this work.

In the western Ventura Basin, a volcanic ash layer with a probable age of 600,000 years has been found in deformed marine strata generally referred to as the Santa Barbara Formation (Sarna-Wojcicki et al., 1976). Overlying the Santa Barbara Formation in the western Ventura Basin is the San Pedro Formation. The approximate time equivalence of the San Pedro and Santa Barbara formations in the Ventura Basin with the lower Pleistocene formations in the Los Angeles Basin is not proven but has long been assumed (Woodring et al., 1946; Weber et al., 1973). Preliminary results on Macoma samples from the San Pedro Formation in the Ventura Basin strongly support the age assignments proposed herein for the San Pedro Sand at locality LACM 332 (Wehmiller, unpubl.).

The apparent equivalence in age of locality M 5902 at Huntington Beach with the San Pedro Sand at LACM 332 appears to clarify the uncertainties that have been associated with this area (Poland et al., 1956; Valentine, 1959). It is important to note that the fauna at this locality (M 5902) does not appear to be "typical" of the San Pedro Sand (Valentine, 1959).

b.) Locality M 1479

Locality M 1479 (Figure 2,j) has been assigned to the Palos Verdes Sand (Vedder, 1975) because of the continuity of the beds into other sites on Newport Mesa that have been considered as part of the Palos Verdes Sand. The fossil site at M 1479 lies unconformably above deformed strata (with rare fossils) that have been assigned to the San Pedro Sand (Poland et al., 1956; 1957; Kanakoff and Emerson, 1959). Since the samples from M 1479 appear to be equivalent in age to samples from the San Pedro Sand (at LACM 332), either the shells have been reworked from the older strata or the exposures (and their inferred history) on the northwest face of Newport Mesa are more complex than previously thought. Since localities M 1479 and LACM 66-2 (both previously referred to as Palos Verdes Sand) have yielded samples that are distinctly greater than the Stage 5 age of the Palos Verdes Sand on the first terrace in San Pedro, a wide range of ages (equivalent to both Stage 5 and Stage 7) is represented by samples all previously considered contemporaneous with the Palos Verdes Sand in San Pedro. Designation of all localities in the Newport Beach area that are truly correlative with the Palos Verdes Sand in San Pedro must await the analysis of additional samples.

c.) Palos Verdes Hills: Late and Middle Pleistocene Terraces

Correlations with most of the Stage 5 and post-Stage 5 eustatic high sea levels of Bloom et al. (1974) are apparent in the preceding discussions. Our data suggest that the vertical flight of terraces in the Palos Verdes Hills may contain more of the details of the same sea-level curve. The age assignments for the Palos Verdes Hills are,

however, based upon the somewhat ambiguous genera Tegula and Epilucina. A Tegula sample from the fourth terrace on the Palos Verdes Hills (locality LDGO 830E) has enantiomeric ratios similar to those in Tegula from Newport Mesa but significantly (10-15%) greater than Tegula from the Nestor Terrace, Point Loma. Epilucina results from the fourth terrace on the Palos Verdes Hills (locality M 6720) generally fall within the range of enantiomeric ratios observed in Epilucina from Corona del Mar and the Nestor Terrace. Preliminary results on Olivella samples from M 6720 and Cayucos (Wehmiller, unpubl.) indicate a similarity (within 10%) in enantiomeric ratios in this genus from these two localities. Our results generally suggest an early Stage 5 age for the fourth terrace in the southwestern portion of the Palos Verdes Hills, but given our present understanding of the reliability of the various genera involved in the analysis of the Palos Verdes Hills localities, we consider the age assignments for the Palos Verdes Hills samples to be preliminary. If an early Stage 5 age for the fourth terrace is correct, then presumably the lower terraces (third, second, and first) in this area of the Palos Verdes Hills would be correlative to younger (late Stage 5) sea level events. The elevations of the fourth, third, and second terraces (~ 95, 65, and 50 meters, respectively - see Plate 22, Woodring et al, 1946) in the western portion of the Palos Verdes Hills conform quite well to the eustatic sea level curve of Bloom et al (1974) if constant uplift rates and an early Stage 5 (Stage 5e) age for the fourth terrace are assumed. Since the first terrace in San Pedro (M 5908) appears to be early Stage 5 in age, the absence of the younger terraces in regions of lower uplift is implied. Both radiometric and amino acid age assignments suggest rather

rapid uplift rates for the Palos Verdes Hills (see Table 13). The amino acid data for the fourth and twelfth terraces further imply relatively constant uplift rates. Middle Pleistocene ages would definitely be assigned to all Palos Verdes Hills terraces higher than the fourth.

d.) San Joaquin Hills: Examples of Middle Pleistocene

(Stage 7) Samples in Late Pleistocene Terrace Deposits.

Results from Laguna Beach (M 1018 and M 1019) and Newport Beach (M 1722, M 5898, and LACM 66-2) indicate that samples of probable Stage 7 age are mixed with samples of Stage 5 age on the first terrace of the San Joaquin Hills. Both Tivela and Polinices at Laguna Beach appear to be between 190,000 and 290,000 years in age, while Saxidomus and Protothaca from Laguna Beach appear 120,000 to 140,000 years in age. Saxidomus, Chione, and Protothaca from the area of LACM 66-2 and M 5898 appear to be 190,000 to 290,000 years in age, while Protothaca from M 1722 (and perhaps one Protothaca, sample 76-24, from LACM 66-2) appear to be 120,000 to 140,000 years in age. Deposits on Newport Mesa, at an elevation quite similar to that of localities LACM 66-2 and M 1722, also appear 120,000 to 140,000 years in age. There are several reasonable geological arguments that may serve as explanations for the apparent frequency of sample mixing at these localities:

- 1) Elevations of eustatic high sea levels inferred from the isotopic record are significantly lower for Stage 7 than they are for Stage 5e. In areas of low to moderate uplift rates (less than .20 m/1000 years) deposits correlative to these two high sea levels would be at roughly equal eleva-

tions today and difficult to distinguish (Shackleton and Opdyke, 1973).

- 2) Localities LACM 66-2, M 5898, and M 1722 (see Figure 2,j) are in a region where there is great possibility of second terrace material having been reworked into deposits of the first terrace. Evidence of reworking was noted by Hoskins (1957) at locality M 5898; and Vedder (unpubl.) has noted the presence of Pliocene fossils (from the underlying bedrock) in the beds at LACM 66-2. The area of these three localities is one where the second terrace is actually absent, apparently having been truncated by back-wearing of the sea-cliff during formation of the first terrace platform. The elevation of all three localities is quite similar, and is lower than that of M 1476, the only locality that is probably truly representative of the second terrace. Localities LACM 66-2 and M 1722 are no longer accessible for study, so samples with proper documentation cannot be collected for further study.
- 3) The Laguna Beach localities (M 1018 and M 1018 - see Figure 2,j) are in a region of the coast where only subtle morphological distinctions between the first and second terraces can be made, though both lie just to the seaward side (50 to 100 meters) of

the probable position of the shoreline angle of the first terrace. Hoskins (1957) noted that the appearance of the terrace deposit at M 1018 indicated "current scouring and thorough faunal mixing", though he did not specifically suggest that reworked material might be present. Hoskins also noted the presence of a large number of worn shells and shell fragments at M 1018, but none of the samples from Laguna Beach analyzed here were fragmented or appeared unusually worn. Very shallow water (approx. 3 meters) was inferred by Hoskins for the environment of deposition at M 1018. Though these characteristics are not, in themselves, proof of reworking, we consider them supporting evidence in light of the enantiomeric ratios observed in the Tivela and Polinices samples at Laguna Beach.

The validity of the relative age assignments for the Laguna Beach samples is supported by the results seen in the one Polinices sample from M 1476, a locality above the first terrace shoreline angle at Newport Beach, and mapped as second terrace because of its elevation relative to the first and third terraces in the area (Vedder et al., 1957; Vedder, 1975; Szabo and Vedder, 1971). The Polinices samples from M 1018 and M 1476 have very similar enantiomeric ratios, implying similar ages. The second terrace age for the Saxidomus, Protothaca, and Chione samples at LACM 66-2 is supported by results (Wehmiller, unpubl.) for

Saxidomus and Protothaca from the second terrace at San Clemente (15 km south of Laguna Beach), where the first and second terrace deposits are more clearly resolved than at Laguna Beach (Vedder et al., 1957). Preliminary results (Wehmiller, unpubl.) on Tivela from the first and second terrace at San Clemente yield somewhat ambiguous geological conclusions but do not contradict the Saxidomus-Protothaca Tivela generic relationship inferred from the results for these three genera from Newport Mesa and San Pedro. This generic relationship has also been documented at a locality near Del Mar, California (Wehmiller, in press). Therefore we conclude that the best available explanation of the Laguna Beach Tivela results is reworking, but some of our other observations on Tivela (see localities M 5902, M 1479) indicate that a better understanding of the racemization kinetics in Tivela is required before firm geological conclusions can be derived from this genus alone.

The inferred uplift rates for the Palos Verdes Hills (see Table 13) are approximately four times greater than those for the San Joaquin Hills. It appears that the three terraces on the San Joaquin Hills (up to ~ 100 m) represent approximately the same period of time as the twelve terraces on the Palos Verdes Hills (up to ~ 400 meters). The lack of detail in the terrace record on the San Joaquin Hills thus appears to be a consequence of lower uplift rates, as is the greater probability of samples of more than one age being found in the terrace deposits on a single platform. Since two major faults separate the Palos Verdes and San Joaquin Hills (Yerkes et al., 1965, and others) so it is not unreasonable to expect differing rates of uplift for these two areas.

e.) Pacific Beach, SDSU 1854

Locality SDSU 1854 at Pacific Beach also appears to be a clear example of mixing of samples of two different ages. Samples correlative with both Stages 5 and 7 of the isotopic record are present. The comparatively low elevation of locality SDSU 1854 (approx. 8 meters) suggests that uplift rates have not been rapid enough to resolve terraces formed during Stages 5 and 7. Additional samples of probable Stage 7 age have been found at several localities around Mission Bay, between two and three kilometers from SDSU 1854 (Wehmiller, Kern, and Lajoie, in prep.), so it appears that a local source of Stage 7 fossils was available during the time (Stage 5) of deposition of the terrace deposit at SDSU 1854.

f.) San Nicolas Island: Late and Middle Pleistocene Terraces

The major low (30-meter) terrace, designated the second terrace on San Nicolas Island appears to be correlative with Stage 5e of the isotopic record (Shackleton and Opdyke, 1973). The lowest terrace found in some areas of San Nicolas Island (Vedder and Norris, 1963) would then presumably be late Stage 5 in age. The enantiomeric ratios observed in samples from the 30-meter terrace, when used as calibration for the kinetic curves, suggest Middle Pleistocene ages of approximately 320,000 years for the fifth (120-meter) and 450,000 years for the tenth (240-meter) terraces. Probable correlation of the fifth terrace with Stage 9 of the isotopic record suggests that the less well-defined third and fourth terraces of San Nicolas Island are those associated with Stage 7 of the isotopic curve. If the age estimate for the 10th terrace is correct then several of the intermediate terraces (six through nine, perhaps) are correlative with the 70,000 years represented by Stage 11

of the isotopic record. Probably uplift rates greater than during the late Pleistocene (i.e., > .2 meters/1000 years) would have been required for the resolution of so many terraces.

A non-constant uplift rate (decreasing through time) is implied by our age estimates for the high terraces on San Nicolas Island (Table 13). Constant uplift rates extrapolated from the observations for the 30-meter terrace would predict ages of about 600,000 years and 1,200,000 years for the fifth and tenth terraces, respectively. Ages as great as these would require a revision of our kinetic model or of the assumed thermal history for these higher terraces. Neither range of age assignments is in conflict with faunal age estimates of Valentine and Lipps (1967). Paleomagnetic polarity determinations on these higher terrace deposits, if possible, might clarify these age assignments.

3.) Early(?) Pleistocene Localities

The Timms Point Silt at locality LACM 130-7 is the only deposit studied to which we might assign an early Pleistocene age based upon the amino acid enantiomeric ratios. A large amount of uncertainty is inherent in our age assignment for the Timms Point Silt, primarily due to uncertainties regarding the thermal history of this deposit. In light of results obtained on samples from the Ventura Basin (Wehmiller, unpubl.), we consider an early middle Pleistocene age for the Timms Point Silt at LACM 130-7 to be most probable.

As stated in Section VII, our results do not permit definite distinctions to be made between earliest Pleistocene and Pliocene samples, so we cannot improve upon the early(?) Pleistocene age estimate (Kennedy, 1973) for the Lindavista Formation in the San Diego area.

IX. CONCLUSIONS

The work described was designed as an evaluation of the applicability of using amino acid enantiomeric ratio determinations in stratigraphic and chronologic problems of uplifted and discontinuous marine terrace deposits. Apart from tropical islands with uplifted coral reefs and reliable radiometric control, the west coast of the United States provides one of the best geologic, climatic, and chronologic frameworks in which to test and apply these techniques.

Several molluscan genera have been evaluated by analysis of multiple individuals from several low terrace localities and, where possible, by analysis of samples with known stratigraphic relationships. Systematic differences in enantiomeric ratios among different genera do occur, though several cases of significant inversions in these relationships are also apparent. These inversions are indicative of either geological or geochemical complexities that remain to be evaluated. Of all the genera frequently analyzed, Saxidomus appears to yield the most reproducible results. Sample reliability seems to be related primarily to shell thickness and internal shell structure, since both of these characteristics affect the weathering (leaching) behavior of the shell samples.

Two different approaches have been taken in the interpretation of the analytical results:

- a.) Qualitative relative age assignments have been derived from similarities and differences in enantiomeric ratios for an entire suite of amino acids as observed in several genera from both dated and un-

dated localities, and

- b.) Kinetic model age assignments have been based upon only one amino acid leucine, and upon models derived from racemization kinetics as observed in calcareous foraminifera in deep-sea sediments.

The two approaches are complimentary, though the latter is essential for estimation of ages greater than about 200,000 years (at temperatures found along the northeastern Pacific coast) and for quantitative evaluation of latitudinal-temperature effects among samples of equal age. The former approach is particularly useful in the interpretation of samples from within the same temperature region, or in a single basin of deposition. Development of kinetic models based upon more than one amino acid should prove helpful in reducing uncertainties in the model age assignments.

The kinetic model itself is derived by extrapolation of racemization kinetics observed in foraminifera at low (deep-sea) temperatures to higher and more variable temperatures that are appropriate for the molluscan samples studied here. Model kinetics are adjusted for generic differences by calibration with results from Holocene and latest Pleistocene samples. Further calibration of the model has been possible because of the availability of reliable chronologic and paleoclimatic information for a few of the late Pleistocene localities (Point Loma Nestor Terrace, and Cayucos). The proposed model kinetics are distinctly non-linear (Wehmiller and Hare, 1971; Wehmiller and Belknap, in press), in contrast to the linear models used for the interpretation of Pleistocene molluscan samples from Florida (Mitterer, 1975). Linear

kinetic models, when tested within the geologic and paleoclimatic framework of the Pacific coast marine terraces, seem inappropriate for the interpretation of the samples studied in this work. Temperature sensitivities derived from laboratory pyrolysis experiments (Bada and Schroeder, 1972; Mitterer, 1975) seem appropriate for the development of geologically-controlled kinetic models (see also Wehmiller et al., 1976).

One group of molluscan genera, the "slow-racemizing" Protothaca, Chione, Tivela, and Saxidomus, appears to be of most value in comparison with the kinetic models derived from foraminifera. A qualitative chemical model of calcified protein diagenesis has been proposed as an explanation of this kinetic similarity. Kinetic models for the group of "fast-racemizing" genera have not been formally proposed, though some precedent does exist (King and Hare, 1972a) for their informal usage. The use of several genera in studies such as these is almost mandatory so that geological and kinetic information can be developed fully.

The kinetic model predicts ages for the higher terraces on San Nicolas Island and for the San Pedro Sand (at LACM 332) that are somewhat younger than previously assumed; revisions of these ages could be accomplished by re-evaluation of the temperature histories of the samples or by revision of the kinetic model itself. The latter option, however, would negate some of the apparent validity of the kinetic model that is apparent among the age assignments for some of the younger samples. These age assignments are evaluated within the framework of two important records of ice-volume/sea-level fluctuation: the eustatic record of Bloom et al. (1974), and the isotopic record of Shackleton and Opdyke (1973). Though correlation of model ages with the high sea levels

identified by these records is, in itself, not proof of the validity of the kinetic model, enough supporting information exists for many of the model age assignments so that we expect that future adjustments in the model will be minor.

Perhaps the strongest supporting evidence is both the qualitative and quantitative comparison of the results for the two terraces on Point Loma with those for the Goleta terrace. Kinetic model ages (calibrated to the Nestor Terrace on Point Loma) for the Bird Rock Terrace and for Goleta are 70,000 to 90,000 years and 30,000 to 50,000 years, respectively. Direct correlation with specific events of the eustatic sea-level curve (Bloom et al., 1974) are apparent. Correlations of these two terraces with any other events of the sea-level curve would require paleotemperature fluctuations that are inconsistent with available information (CLIMAP, 1976). Relatively rapid uplift rates for the Goleta platform are indicated by its apparent age, since it has probably been uplifted about 55 meters since its formation.

Additional supporting evidence for the model ages comes from the apparent association of "cool-water" faunas with all of the terraces identified in this work as being correlative with ice-volumes somewhat greater than at present (late Stage 5 and post-Stage 5). Deposits correlative with ice-volumes somewhat less than at present (i.e., Stage 5e of Shackleton and Opdyke, 1973) appear to contain "warm-water" faunal associations (primarily the Palos Verdes Sand and correlative deposits in the Los Angeles Basin).

We have adopted a terminology for the chronological division of the Pleistocene into late (ca. 10,000 yrs. to 130,000 yrs.), middle (130,000

yrs. to ca. 700,000 yrs.), and early (700,000 yrs. to 1.8 million years) segments. Though several of our kinetic model age assignments have significant uncertainties, it is not difficult to use the model for the assignment of either late, middle, or early Pleistocene age designations within this chronological framework. Middle Pleistocene (350,000 to 550,000 years) ages are estimated for the highest terraces on San Nicolas Island, Palos Verdes Hills (380 meters), and the San Joaquin Hills (90 meters), suggesting uplift rates for these areas that differ by as much as a factor of four. Regions of more rapid uplift appear to have preserved more of the details of the record of eustatic sea-level fluctuations. In regions of apparently lower uplift rates (localities LACM 66-2, M 1018 and M 1019, and SDSU 1854) the amino acid results have identified apparent mixing of terrace deposits of both late middle Pleistocene (Stage 7 equivalent) and late Pleistocene (Stage 5 equivalent) ages.

Our age estimate for the upper part of the San Pedro Sand of the Los Angeles Basin (350,000 to 450,000 years) places it in a period when the higher terraces of the Palos Verdes Hills were being formed. Though this age estimate has a wide range of uncertainty, a middle Pleistocene age is indicated by our results. Preliminary results (Wehmiller, unpubl.) on chronologically controlled middle Pleistocene samples from the western Ventura Basin strongly support this age assignment for the San Pedro Sand. The age estimate for the Timms Point Silt has a wide range of uncertainty because of the probable range of diagenetic temperatures involved, but an early middle Pleistocene age (< 700,000 years) is probable.

Many of the age assignments presented here are for localities that have been previously examined by uranium-series dating of molluscan samples. Though the accuracy of this technique has been questioned (Kaufman *et al.*, 1971), we have presented evidence here that is, in several cases, consistent with apparent relative and absolute ages derived from molluscan isotopic analyses. Specific examples are the samples from Santa Cruz (Bradley and Addicott, 1968), Goleta (Kaufman *et al.*, 1971), San Nicolas Island and Palos Verdes Hills (Szabo and Vedder, 1971), and Cape Blanco (Richards and Thurber, 1966).

Amino acid measurements have only recently been applied to chronologic problems of the Quaternary. Additional evaluation of the technique within new geological and diagenetic environments is necessary for the development of kinetic models. Variations in sample thermal histories can complicate both relative and absolute age assignments, and only within the framework of a large body of geologically controlled data, with some reliable radiometric control, can these thermal effects be quantified. The results presented here certainly indicate the role that such a geological framework can play in the evaluation of the amino acid technique, and demonstrate the role that amino acids can have in understanding this framework. Major uncertainties involve results that indicate either mixing of samples of different ages and/or complex racemization kinetics that produce apparent generic inversions. Though complex kinetics must always be considered a possibility, it is important to note that such inversions have not been observed in studies of different genera of foraminifera (King and Hare, 1972; King and Neville, 1977). Therefore it is clear that mixing of samples of different ages

must be given serious consideration in the interpretation of faunal and chronologic information from a given terrace deposit. Amino acid studies appear to have a unique ability to contribute to these interpretations.

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Table 1: Locality and Sample Information

<u>Location</u>	<u>Locality Numbers²</u>	<u>Elevation in meters³</u>	<u>Number of Samples</u>	<u>Existing Age Estimates</u>	<u>References</u>
Bainbridge Isl., Furlet Sound, Washington	LACM 5012	5	2	3,260 ± 80 C-14 years	This work
Orcas Island, Furlet Sound, Washington	LACM 5009	40	4	12,350 ± 400 C-14 years	Easterbrook (1969)
Cape Blanco, Oregon	M1450 LACK 3949	60 (70) 60 (70)	5 1	>37,000 yrs. >40,000 yrs. Late Pleistocene	Richards and Thurber (1966) Janda (1969) Addicott (1964a)
Trinidad Head, California	LACM 3939	2	2	Early to Middle Pleistocene	Kennedy (unpubl.)
Point Año Nuevo, California	M1690	10 (30)	10	68,000 to 100,000 yrs.	Bradley and Addicott (1969) Addicott (1966)
Santa Cruz, California	M1691	7 (20)	4	68,000 to 100,000 yrs.	Bradley and Addicott (1969) Addicott (1966)
Cayucos, California	M5922	6 (25)	9	130,000 ± 30,000 yrs. 140,000 ± 30,000 yrs.	Veeh and Valentine (1967) Valentine and Veeh (1969) Valentine (1958)

Table 1. continued (p. 2)

Location	Sample ID	Number of Sites	Age (yrs.)	Geological Period	Reference
Goleta, California	M5790	3 (15)	9	Late Pleistocene	Wright (1972)
Los Angeles, California	LACM 466	73	1	Pliocene	Natural History Museum of Los Angeles County Natland (1971)
	LACM 1219		1	Pliocene (Fernando Fm.)	
Palos Verdes Hills, California	M6720 (4th terrace)	90	1	Late Pleistocene	Woodring et al (1946) Marincovich (1976) Kennedy (1975) Fanale and Schaeffer (1965)
	LDGO 930E (4th terr.)	80	1	all terraces	
	LDGO 974A (5th terr.)	105	1	330,000 to 420,000 yrs.	
	LDGO 807C (12th terr.)	370	1		
San Pedro, California	M5909	20	7	Upper Pleistocene	Woodring et al (1946) Hoskins (1957) Kennedy (1975) Fanale and Schaeffer (1965) Szabo and Rosholt (1969)
	NACM 1210	25	1	Palos Verdes Sand	
	LACM 332	10	5	Lower Pleistocene San Pedro Sand	Woodring et al (1946) Kennedy (1975)
	LACM 130-7	10	2	Lower Pleistocene Timms Point Silt	Woodring et al (1946) Kennedy (1975)
Huntington Beach, California	M5902	1	6	Upper Pleistocene Lower Pleistocene	Valentine (1959) Poland et al (1956)

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Newport Mesa, California	M2074	22	9	Late Pleistocene; 70,000 to 150,000 yrs.	Kanakoff and Emerson (1959); Szabo and Vedder (1971); Hoskins (1957)
	M1477	6	4		
	M1479	8	4		
Newport Beach, California	M1722 (1st terrace)	17 (25)	1	Late Pleistocene; 70,000 to 150,000 yrs.	Kanakoff and Emerson (1959); Szabo and Vedder (1971); Hoskins (1957)
	LACK 66-2 (1st terr.)	20	4		
	M589B (1st terr.) [†]	18	1		
Corona del Mar, California	M1476 (2nd terrace)	35	1	>270,000 yrs.	Szabo and Vedder (1971)
	M3759 (3rd terrace)	90	3		
	M1481	27 (36)	2	70,000 to 150,000 yrs.	Szabo and Vedder (1971)
Laguna Beach, California	M1482	21 (36)	1		
	M1018	21 (40)	5	70,000 to 150,000 yrs.	Szabo and Vedder (1971)
	M1019	21 (40)	1		
Torrey Pines Park, California	LACK 2662	15 (20)	3	Upper Pleistocene	Valentine (1960)
Pacific Beach, California	SDSU 1854	8	2	Upper Pleistocene; Nestor Terrace	Kern (in press); Ku and Kern (1974)
Point Loma, San Diego, California	SDSU 2577		1		
	SDSU 2520	20	2		
	K6706	to	3	All six localities from the Nestor Terrace; locality SDSU 2577 dated at 120,000 ± 10,000 yrs. (Ku and Kern, 1974)	
	K6703	25	4		
	K6704 K6702		2 3		
SDSU 2523	6 (8)	3		Bird Rock Terrace; formerly Tia Juana Terrace (Ku and Kern, 1974); renamed by Kern (in press)	

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San Diego, California	SUSNH 0329	135	2	Early Pleistocene (?), Lindavista Fm.	Kennedy (1973)
	LACM 319	30	1	Pliocene San Diego Fm.	Hertlein and Grant (1972)
San Nicolas Isl., California	21653 (1st terr.)	15	1		
	21664 (2nd terr.)	21 (30)	1		Vedder and Norris (1963)
	21665 (2nd terr.)	24 (30)	2	87,000 to 120,000 (\pm 20,000) yrs.	Valentine and Veeh (1971); Szabo and Vedder (1971)
	21662 (5th terr.)	113 (120)	2		
	21663 (4th terr.)	179	1		
	21659 (9th terr.)	200	1		
	21654 (10th. terr.)	220 (240)	4		
	21655 (10th. terr.)	220 (240)	3	>200,000	Szabo and Vedder (1971)

Notes:

1. Complete locality description in Appendix I.
 2. Abbreviations for Locality Numbers:

- N- U.S. Geological Survey, Menlo Park, California, locality (San Nicolas Island localities are U.S. Geol. Survey Numbers; collections at Menlo Park)
- LACK- Los Angeles County Museum of Natural History, Invertebrate Paleontology Locality Number
- LDGO- Lamont-Doherty Geological Observatory, Palisades, New York (W.S. Broecker sample collection)
- SUSU- San Diego State University Locality Number (J. P. Kern sample collection)
- SUSNH- San Diego Soc. Natural History Locality Number

3. Elevations are those of the fossil locality; elevations in parentheses are those of inferred shoreline angle.
 4. Locality M589B very near loc. LACM 66-2 (within 300 meters) and not plotted in map (figure 2) of area. Enantiomeric ratio results indicate that the two localities can be interpreted as being identical in age.

Table 2: Temperature Data for Coastal Localities,
Puget Sound to San Diego

<u>LOCATION</u>	<u>LATITUDE</u>	<u>MEAN ANN. TEMP.</u>	<u>EFFECTIVE ANN. TEMP.*</u>	<u>COMMENTS</u>
Puget Sound, Wash.				
Anacortes	48.5 ⁰	10.5 ⁰ C.	11.9 ⁰ C.	Long-term record
Coupeville 1S	48.1	9.8	11.3	Long-term record
Mt. Vernon 3NW	48.4	9.8	11.3	1963-1965 record
Olea 2 SE	48.6	9.6	10.9	Long-term record
Sequim	48.0	9.9	11.4	Long-term record
Orcas Island	48.4	9.9	11.2	Inferred from above records
Bremerton	47.5	11.1	12.3	1963-1965 record
Seattle	47.6	11.4	13.3	Long-term record
Bainbridge Is.	47.5	11.1	12.5	Inferred from above records
Newport, Ore.	44.5	10.3	11.0	Long-term record
Bandon, Ore.	43.0	10.8	11.3	Long-term record
Cape Blanco, Ore.	42.8	~10	~10	Inferred from nearby localities; open coast locality.
Port Orford, Ore.	42.7	10.9	11.7	1975 record only
Brookings, Ore.	42.1	10.9	12.3	Long-term record
Crescent City, Cal.	41.8	11.6	12.2	Long-term record
Orick Creek St. Pk., Cal.	41.5	11.0	11.7	Long-term record
Eureka, Cal.	40.8	11.1	11.5	Long-term record
Trinidad Head, Cal.	41.1	11.1	11.6	Interpolated from Orick and Eureka records
Fort Bragg, Cal.	39.4	11.6	11.9	Long-term record
Half Moon Bay, Cal.	37.5	12.4	12.7	Long-term record
Point Año Nuevo, Cal.	37.1	13.0	13.5	Interpolation between Half Moon Bay and Santa Cruz
Santa Cruz, Cal.	36.9	13.7	14.3	Long-term record

Cayucos, Cal.	35.4	13.3	13.5	Estimated from short-term records for Morro Bay and Pismo Beach, Cal.
Santa Barbara, Cal.	34.45	15.5	16.1	Long-term record
Santa Barbara Airport	34.45	14.9	15.5	Long-term record
Goleta, Cal.	34.45	15.2	15.8	Inferred from above records for Santa Barbara
Oxnard, Cal.	34.2	15.3	15.7	Long-term record
Santa Monica Pier, Cal.	34.0	16.1	16.4	Long-term record
Torrance, Cal.	33.7	16.4	17.0	Long-term record, inland station
San Pedro, Cal.	33.7	16.9	17.7	Interpolated between Torrance and Long Beach records
Long Beach, Cal.	33.7	17.4	18.4	Long-term record
Newport Beach Harbor, Cal.	33.6	15.9	16.5	Long-term record
Laguna Beach, Cal.	33.5	15.6	16.3	Long-term record
Oceanside, Cal.	33.2	15.7	16.2	Long-term record
San Diego Airport, Cal.	32.7	17.1	17.8	Long-term record, inland station
Point Loma, Cal.	32.7	16	16	Open coastal locality, estimated from Oceanside records
Chula Vista, Cal.	32.6	15.6	16.2	Long-term record
Southern California Channel Islands:				
Avalon Pleasure Pier,	33.3	15.6	16.1	Long-term record
Santa Catalina Is.	34.1	13.7	14.0	Long-term record from Felton (1965)
San Miguel Is.				
San Nicolas Is.	33.3	14.8	15.2	1971-1974 records

Relevant Soil Temperature Data

Mt. Vernon 3NW, Washington	6" depth in soil:	Mean Ann. Temp. 11.1° C. Eff. Ann. Temp. 13.0° C.	(Records for 1963-1965; mean ann. air temp. during same period, 9.8° C.)
Riverside Exp. Sta., California	12" depth in soil:	Mean Ann. Temp. 17.7° C. Eff. Ann. Temp. 21.0° C.	(Records for 1964, 1966-1968; mean annual air temperature during same period, 17.7° C.)
	18" depth in soil: (irrigated)	Mean Ann. Temp. 16.9° C. Eff. Ann. Temp. 18.3° C.	

Data has been synthesized from Felton (1965) and Climatological Records for Washington, Oregon, and California, published by U.S. Department of Commerce.

Long-term records are those derived from 1975 mean monthly temperatures, corrected for "departure from normal" data for respective recording stations.

*Effective annual temperatures are calculated from mean monthly temperature data according to procedures outlined in text.

TABLE 3. Enantiomeric Ratios for Samples with Local Stratigraphic or Chronologic Control

SAMPLE	LOCALITY	ELEV., m.	LEU	GLU	VAL	ALA	PRO	PHE	ASP	SER	SER/LEU	%CAL.
<u>Bainbridge Island, Puget Sound</u> 3,260 C-14 yrs. (\pm 80 yrs.)												
<u>Saxidomus giganteus</u>												
76-83	LACM 5012	4	.053	.071	.035	.10	.09	.093	nd	.33	1.35	hd
<u>Protothaca staminea</u>												
76-82	LACM 5012	4	.043	.055	.026	.091	.055	.043	nd	.26	2.51	nd
<u>Orcas Island, Puget Sound</u> 12,350 C-14 yrs. (\pm 400 yrs.)												
<u>Saxidomus giganteus</u>												
75-76	LACM 5009	15	.14	.10	.06	.15	.21	.10	nd	.45	1.6	.1
75-77	LACM 5009	15	.13	.10	.06	.21	.24	.13	nd	.53	1.8	nd
		mean	.135	.10	.06	.18	.225	.115	-	-	-	-
<u>Protothaca staminea</u>												
DFB-33	LACM 5009	15	.09	.08	.045	.12	.13	.09	nd	.30	2.3	nd
76-78	LACM 5009	15	.08	.08	.043	.18	.12	.09	nd	.27	2.1	nd
		mean	.08	.08	.044	.15	.125	.09	-	-	-	-
<u>San Nicolas Island</u>												
<u>Saxidomus nuttalli</u>												
JW-5	21664	21	.45	.40	.34	.75	.53	.51	.60	.50	.19	0
JW-3	21662	113	.63	.57	.45	.84	.85	.62	.63	.54	.05	nd
JW-4	21654	220	.74	.67	.65	.87	.79	.76	.68	-	.00	0
JW-2	21655	220	.67	.66	.68	.94	.84	.79	.62	-	.00	0
<u>Enilucina californica</u>												
75-27	21665	24	.58	.53	.39	.78	.58	.62	.73	.6	.02	0
75-26	21662	113	.83	.79	.77	1.04	.84	.85	.87	.5	.02	.5
75-25	21655	220	.70	.76	.76	.99	.77	.82	.79	-	.00	.5
75-25A	"	"	.88	.76	.74	.98	.95	.95	nd	-	.00	"
75-66	21654	220	.69	.79	.72	.95	.82	.79	nd	.37	.06	<1
<u>Protothaca staminea</u>												
75-24	21655	220	.46	.54	.45	.80	.64	.45	.54	.05	.13	0
JW-9	21654	220	.69	.74	.69	.96	.77	.86	nd	.15	.02	0

<u>Tegula funebris</u>												
JW-11	21665	24	.69	.61	.41	.93	.84	.82	.70	-	0	11.0
JW-16	21663	178	.90	.85	.87	.91	.91	.92	.76	-	0	0
JW-12	21654	220	.93	.95	.96	1.02	.97	1.06	.88	-	0	3.8
<u>Diadora aspera</u>												
50-24	21653	20	.20	.30	.18	.40	.48	.24	.38	.18	.17	0
50-27	21659	200	.09	.10	.08	.16	.12	.08	.09	.06	.49	1.7
San Pedro Area Palos Verdes Sand, Upper Pleistocene												
<u>Saxidomus nuttalli</u>												
76-16	LACM 1210		.53	.42	.34	.84	.64	.54	nd	.67	.12	nd
75-52	M5908		.53	.42	.37	.83	.66	.58	nd	.70	.12	0
75-53	M5909		.54	.42	.34	.87	.67	.58	nd	.72	.19	nd
	mean		.533	.42	.35	.85	.66	.57				
<u>Protothaca staminea</u>												
75-54	M5908		.48	.39	.32	.75	.54	.56	nd	.59	.25	0
<u>Macoma nasuta</u>												
76-1	M5909		.67	.55	.44	.83	.81	.80	nd	.75	.07	0
San Pedro Sand, Lower Pleistocene												
<u>Saxidomus nuttalli</u>												
76-6	LACM 332		.60	.49	.41	.93	.70	.69	nd	.76	.06	0
76-7	LACM 332		.63	.50	.48	.94	.74	.67	nd	.56	.07	nd
	mean		.615	.495	.445	.935	.72	.68				
<u>Protothaca staminea</u>												
76-23	LACM 332		.64	.59	.56	.93	.71	.74	nd	.72	.05	0
76-23a	LACM 332		.61	.55	.51	.94	.67	nd	nd	.56	.15	nd
	mean		.625	.57	.535	.935	.69	-				
<u>Macoma nasuta</u>												
76-59a	LACM 332		.79	.71	.77	.94	.85	.95	nd	-	<.01	nd

Timms Point Silt, Lower Pleistocene

Saxidomus nuttalli

76-9	LACM 130-7	.69	.54	.52	.94	.80	.70	nd	.47	.06	<.5
76-9	LACM 130-7	.75	.58	.57	.93	.90	.73	.80	.90	.08	nd
	mean	.72	.56	.545	.935	.85	.715				

Palos Verdes Hills, upper terraces

Tegula gallina

75-76	LDGO-930E	80	.67	.57	.42	.87	.91	.89	.39	.09	nd
75-62	LDGO-874A	105	.84	.68	.63	.93	.95	1.0	.40	.01	nd
75-61	LDGO-807C	370	.94	.81	.85	1.02	.98	1.02	-	0	nd

Epilucina californica

76-73	M6720	85	.66	.59	.46	.87	.67	.73	-	0	nd
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Newport Beach-Corona del Mar Area

Tegula funebris

75-60A	M2074	22	.66	.55	.36	.81	.93	.86	.39	.10	nd
75-71	M2074	22	.71	.58	.35	.82	.90	.91	.46	.03	nd
74-24	M2074	22	.64	.51	.33	.75	.85	.77	.38	.11	.5
74-23	M3759	90	.95	.83	.79	.98	.97	1.01	.40	.02	1.4

Epilucina californica

75-19	M1481	27	.64	.55	.44	.85	.74	.73	-	.00	nd
75-51	M1491	27	.70	.54	.46	.89	.79	.83	.70	.02	<.2
75-50	M1482	21	.62	.53	.45	.81	.70	.72	.50	.06	nd
75-19	M3759	90	.90	.80	.81	.95	.93	.95	-	.00	<.5

Pollinices reclusianus

50-14	M1477	6	.57	.41	.13	.66	.73	.43	.11	.28	nd
50-17	M1476	35	.65	.56	nd	.77	.75	.49	nd	nd	0
50-18	M3759	90	.45	.51	nd	.46	.63	.35	nd	nd	nd

Pliocene/Early Pleistocene Localities

Lindavista Formation, Early Pleistocene (?)
San Diego, Calif.

Tivela stultorum

75-20	SDSNH-0329	135	.96	1.0	1.02	.95	.97	.82	.00	0
75-20A	SDSNH-0329	135	1.01	.96	.97	1.05	.95	.98	.00	0

Fernando Formation, Pliocene
Los Angeles, Calif.

Saxidomus nuttalli

76-18	LACM 1219	.90	.77	.88	.99	.95	.98	nd	.00	nd
76-34	LACM 466	.91	.78	.90	1.01	.90	.98	nd	.00	0

San Diego Formation, Pliocene
San Diego, Calif.

DFB-32	LACM 319	.93	.92	.96	.98	.91	.97	nd	.00	nd
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Amino acid abbreviations:

LEU = leucine
GLU = glutamic acid
VAL = valine
ALA = alanine
PRO = proline
PHE = phenylalanine
ASP = aspartic acid
SER = serine

nd = not determined
% CAL. = % calcite in sample

a) Samples that are bracketed represent duplicate analyses of same individual.

TABLE 4: Enantiomeric Ratios for Samples from Low Terrace Localities along the Coast

SAMPLE	LOCALITY	SPECIES	LEU	GLU	VAL	ALA	PRO	PHE	ASP	SER	SER/LEU	%CAL.
<u>Cape Blanco, Oregon</u>												
76-9	M1450	S. g.	.26	.22	.19	.36	.37	.30	.40	-	.01	0
76-10	M1450	S. g.	.27	.22	.20	.43	.37	.30	.36	.45	.17	nd
DFB-36	LACM 3948	S. g.	.28	.22	.21	.43	.41	.29	nd	.52	.30	0
		mean	.27	.22	.20	.41	.38	.30				
DFB-34	LACM 2641	P. s.	.31	.24	.21	.46	.36	.37	nd	.64	1.10	nd
76-27	LACM 2641	P. s.	.30	.24	.23	.48	.37	.36	nd	.60	.76	nd
		mean	.305	.24	.22	.47	.365	.365				
DFB-19	M1450	M. i.	.35	.27	.26	(.48)	.48	.40	nd	.60	.21	nd
<u>Trinidad Head, Calif.</u>												
75-29	LACM 3939	S. g.	.64	.55	.51	.89	.74	.65	.82	.50	.08	nd
DFB-37	LACM 3939	S. g.	.60	.52	.52	.85	.70	.68	nd	.52	.30	nd
		mean	.62	.535	.515	.87	.72	.665				
<u>Point Año Nuevo, Calif.</u>												
74-2	M1690	S. g.	.45	.34	.26	.64	.56	.54	.54	.60	.15	0
50-6	M1690	S. g.	.45	.32	.26	.63	.49	.52	.51	.39	.10	nd
[75-11	M1690	S. g.	.46	.34	.31	.62	.59	.55	.48	.73	.20	0
75-11A	"	S. g.	.45	.35	.32	.66	.56	.58	nd	.73	.20	"
K75-1	M1690	S. g.	.45	.32	(.30)	.62	.63	.56	.53	.66	.14	0
DFB-2	M1690	S. g.	.44	.30	.30	.64	nd	.53	nd	.43	.20	nd
		mean	.449	.325	.29	.634	.56	.54				

SAMPLE	LOCALITY	SPECIES	LEU	GLU	VAL	ALA	PRO	PHE	ASP	SER	SER/LEU	%CAL.
<u>Cape Blanco, Oregon</u>												
76-9	M1450	S. g.	.26	.22	.19	.36	.37	.30	.40	-	.01	0
76-10	M1450	S. g.	.27	.22	.20	.43	.37	.30	.36	.45	.17	nd
DFB-36	LACM 3948	S. g.	.28	.22	.21	.43	.41	.29	nd	.52	.30	0
		mean	.27	.22	.20	.41	.38	.30				
DFB-34	JACM 2641	P. s.	.31	.24	.21	.46	.36	.37	nd	.64	1.10	nd
76-27	LACM 2641	P. s.	.30	.24	.23	.48	.37	.36	nd	.60	.76	nd
		mean	.305	.24	.22	.47	.365	.365				
DFB-19	M1450	M. i.	.35	.27	.26	(.48)	.48	.40	nd	.60	.21	nd
<u>Trinidad Head, Calif.</u>												
75-29	LACM 3939	S. g.	.64	.55	.51	.89	.74	.65	.82	.50	.08	nd
DFB-37	LACM 3939	S. g.	.60	.52	.52	.85	.70	.68	nd	.52	.30	nd
		mean	.62	.535	.515	.87	.72	.665				
<u>Point Año Nuevo, Calif.</u>												
74-2	M1690	S. g.	.45	.34	.26	.64	.56	.54	.54	.60	.15	0
50-6	M1690	S. g.	.45	.32	.26	.63	.49	.52	.51	.39	.10	nd
75-11	M1690	S. g.	.46	.34	.31	.62	.59	.55	.48	.73	.20	0
75-11A	"	S. g.	.45	.35	.32	.66	.56	.58	nd	.73	.20	"
K75-1	M1690	S. g.	.45	.32	(.30)	.62	.63	.56	.53	.66	.14	0
DFB-2	M1690	S. g.	.44	.30	.30	.64	nd	.53	nd	.43	.20	nd
		mean	.449	.325	.29	.634	.56	.54				

74-1	M1690	P. s.	.44	.36	.30	.75	.47	.60	.67	.70	.36	2.5
75-12	M1690	P. s.	.39	.31	.30	.74	.48	.55	.62	.64	.63	nd
75-13	M1690	P. s.	.38	.31	.29	.70	.44	.49	.63	.75	.49	0
		mean ^{a)}	.385	.31	.295	.72	.46	.52	.625			
50-5	M1690	M. i.	.51	.40	.30	.59	.56	.56	.66	.25	.20	nd
DFB-18	M1690	M. i.	.47	.36	.35	.60	.55	.60	nd	.52	.11	<.5
		mean	.49	.38	.325	.60	.56	.58				

Santa Cruz, Calif.

74-6	M1691	S. g.	.44	.33	.29	.65	.62	.55	.52	.63	.14	0
74-7	M1691	S. g.	.41	.34	.27	.66	.51	.46	.52	.40	.38	0
		mean	.425	.335	.28	.655	.56	.48	.60			
74-4	M1691	P. s.	.36	.29	.24	.63	.43	.42	.63	.60	.31	0
74-5	M1691	P. s.	.39	.29	.25	.69	.42	.54	.57	.54	.28	0
		mean	.375	.29	.245	.66	.425	.48	.60			

Guaycos, Calif.

74-9	M5922	P. s.	.43	.37	.27	.63	.55	.54	.72	.67	.13	0
75-16	M5922	P. s.	.40	.36	.27	.63	.53	.45	.66	.50	.07	<.1
75-30	M5922	P. s.	.41	.36	.26	.67	.54	.50	.57	.63	.26	0
		mean	.413	.363	.267	.643	.54	.50	.65			
75-75	M5922	M. i.	.49	.39	.28	.62	.58	.62	nd	.74	.08	nd
DFB-17	M5922	M. i.	.47	.39	.28	.60	.63	.60	nd	.50	.02	<.5
		mean	.48	.39	.28	.61	.60	.61				
75-17	M5922	E. c.	.55	.44	.33	.69	.70	.64	.74	-	.00	0
DFB-9	M5922	E. c.	.55	.46	.37	.67	.68	.69	nd	.40	.03	nd
		mean	.55	.45	.35	.68	.69	.67				
75-15	M5922	T. f.	.60	.48	.32	.84	.91	.87	.65	.41	.11	nd
DFB-9	M5922	T. f.	.58	.44	.34	.81	.87	.77	nd	.43	.15	nd
		mean	.59	.46	.33	.83	.89	.82				

Goleta, Calif.

74-10	M5790	S. g.	.34	.29	.20	.52	.47	.34	.51	.57	.38	0
50-31	M5790	S. g.	.32	.25	.21	.49	.43	.36	.47	.59	.13	0
50-31A		S. g.	.35	.28	.22	.54	.52	.39	.47	.59	.13	"
		mean	.338	.278	.208	.518	.473	.358	.49			
JW-1	M5790	P. s.	.28	.22	.18	.53	.32	.34	.50	.60	.32	0
75-41	M5790	P. s.	.26	.22	.18	.48	.32	.30	nd	.53	.35	<.5
74-9	M5790	P. s.	.41	.32	.24	.49	.48	.46	.61	.63	.60	0
		mean b)	.27	.22	.18	.50	.32	.32				
75-69	M5790	M. n.	.45	.31	.29	.55	.63	.53	nd	.57	.11	.5
76-3	M5790	M. n.	.43	.31	.26	.52	.65	nd	nd	.57	.03	nd
		mean	.44	.31	.275	.54	.64					
50-30	M5790	D. a.	.03	.05	.02	.05	.04	.03	.07	.19	.07	0

San Pedro, Calif. Palos Verdes Sand

75-52	M5908	S. n.	.53	.42	.37	.93	.66	.58	nd	.70	.12	0
75-53	M5908	S. n.	.54	.42	.34	.87	.67	.58	nd	.72	.19	nd
76-16	LACM 1210	S. n.	.53	.42	.34	.84	.64	.54	nd	.67	.12	nd
		mean	.533	.42	.35	.847	.657	.567				
75-54	M5908	P. s.	.48	.39	.32	.75	.54	.56	nd	.59	.25	0
76-1	M5908	M. n.	.67	.55	.44	.83	.81	.80	nd	.75	.07	0
76-2	M5908	T. s.	.49	.41	.35	.77	.61	.58	nd	.50	.14	nd
75-55	M5908	Ch. u.	.49	.40	.34	.83	.57	.57	nd	.61	.19	nd
75-56	M5908	Ch. u.	.51	.43	.38	.85	.61	.57	nd	.57	.21	nd
		mean	.50	.415	.36	.84	.59	.57				.5

Newport Beach, Calif.

74-15	M2074	S. n.	.48	.39	.28	.71	.59	.57	.55	.73	.12	0
75-22	M2074	S. n.	.51	.42	.30	.75	.63	.51	nd	.66	.11	0
JW-7	M2074	S. n.	.54	.45	.34	.87	.64	.52	.50	.52	.17	0
		mean	.51	.42	.307	.777	.62	.533				
75-14	M1479	S. n.	.64	.51	.44	.91	.77	.67	.60	.58	.19	0
75-43	M1479	S. n.	.60	.48	.44	.91	.75	.67	.60	.66	.09	0
		mean	.62	.495	.44	.91	.76	.67	.60			
76-20	LACM: 66-2	S. n.	.63	.50	.43	.88	.79	.67	nd	.68	.15	0
76-25	LACM: 66-2	S. n.	.62	.48	.42	.85	.76	.64	nd	.63	.07	nd
		mean	.625	.49	.425	.865	.775	.655				
74-11	M1722	P. s.	.45	.40	.32	.75	.47	nd	.65	.54	.18	0
74-12	M2074	P. s.	.44	.40	.29	.75	.49	.55	.65	-	.00	<.5
		mean	.445	.40	.305	.75	.48	-	.65			
76-24	LACK 66-2	P. s.	.50	.42	.36	.78	.56	.59	nd	.47	.18	nd
76-43	LACK 66-2	P. t.	.54	.48	.43	.78	.67	.66	nd	.60	.10	nd
		mean	.52	.45	.395	.78	.60	.63				
[75-47	M1477	M. n.	.59	.49	.36	.77	.71	.77	nd	.50	.04	<.9
75-47X			.61	.49	.39	.77	.73	.73	nd	.85	.05	
		mean	.60	.49	.375	.77	.72	.75				
75-49	M1479	M. n.	.68	.57	.48	.84	.82	.88	nd	.85	.08	<.8
75-44	M2074	T. s.	.47	.41	.32	.79	.59	.57	nd	.48	.13	nd
75-14	M2074	T. s.	.46	.39	.28	.80	.58	.60	.61	.61	.11	0
74-13	M1477	T. s.	.44	.40	.28	.73	.63	.53	.57	.50	.15	0
		mean	.457	.40	.294	.773	.60	.567				
76-46	M1479	T. s.	.65	.53	.52	.93	.77	.84	nd	.40	.32	nd
75-42	M589A	Ch. u.	.57	.48	.415	.84	.68	.68	nd	.57	.17	<.5
74-24	M2074	T. f.	.64	.51	.33	.75	.85	.77	.72	.38	.11	<.5
75-60A	M2074	T. f.	.66	.55	.36	.81	.93	.86	nd	.39	.10	nd
75-71	M2074	T. f.	.71	.58	.35	.82	.90	.91	nd	.46	.03	nd
		mean	.67	.547	.347	.79	.89	.85				
50-13	M1477	D. a.	.54	.56	.14	nd	.73	.60	.67	nd	nd	nd
50-14	M1477	P. r.	.58	.41	.13	.66	.73	.45	.55	.11	.28	nd

Torrey Pines State Park, Calif.

75-1	LACM 2662	S. n.	.44	.35	.71	.52	.46	nd	.63	.23	0
76-5	LACM 2662	S. n.	.44	.37	.72	.53	.47	nd	.67	.24	nd
		mean									
75-59	LACM 2662	P. s.	.49	.36	.715	.525	.465	nd	.66	.17	nd

Pacific Beach, Calif.

75-39	SDSU 1854	Ch. c.	.55	.425	.81	.63	(.72)	nd	.55	.16	nd
76-47	SDSU 1854	P. s.	.575	.47	.80	.63	.66	nd	.70	.16	nd
76-89	SDSU 1854	P. s.	.48	.42	.74	.52	.52	nd	.50	.10	nd
76-102	SDSU 1854	P. s.	.45	.39	.75	.51	.53	nd	.67	.15	nd

Point Loma, Calif., Nestor Terrace

76-59	SDSU 2520	S. n.	.48	.40	.73	.57	.47	nd	.18	.60	nd
75-31	M6703	P. s.	.44	.36	.66	.48	.42	.64	.48	.34	nd
76-10	M6706	P. s.	.49	.41	.71	.58	.50	nd	.69	.09	0
76-14	SDSU 2521	P. s.	.44	.39	.68	.47	.47	nd	.60	.12	0
76-40	M6702	P. s.	.46	.41	.73	.44	.50	nd	.42	.16	nd
76-41	M6702	P. s.	.45	.40	.76	.45	nd	nd	.80	.15	nd
		mean	.456	.394	.708	.486	.473				

75-2	M6706	E. c.	.62	.49	.73	.76	.67	.76	-	.00	0
75-2a	M6706	E. c.	.64	.49	.73	.72	.68	.76	-	.00	0
75-3a	M6706	E. c.	.68	.51	.75	.77	.76	.77	-	.00	0
75-3b	M6703	E. c.	.62	.50	.73	.71	.64	.74	-	.00	0
75-32a	SDSU 2577	E. c.	.71	.49	.85	.79	.74	nd	.90	.03	nd
75-40	SDSU 2577	E. c.	.60	.47	.77	.70	.67	nd	-	.00	nd
76-39	M6702	E. c.	.64	.53	.75	.74	.67	nd	-	.01	nd
		mean	.646	.497	.768	.742	.691				

76-15	SDSU 2520	Ch. c.	.44	.39	.71	.53	.51	nd	.61	.20	0
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75-34	M6704	G. c.	.59	.50	.79	.72	.63	.67	-	.00	nd
75-9	M6703	T. f.	.59	.47	.83	.92	.83	.62	-	.00	.5
75-33	M6703	T. f.	.55	.43	.77	.86	.75	.52	.40	.21	nd
76-11	M6704	T. f.	.60	.45	.74	.87	.77	nd	.38	.12	nd
		mean	.58	.45	.78	.88	.78				

Point Loma, Calif.: Bird Rock Terrace

76-22	SDSU 2523	P. s.	.39	.36	.27	.52	.39	.40	.58	.56	.12	0
76-22a	SDSU 2523	P. s.	.37	.33	.24	.52	.38	.38	.56	.53	.25	nd
		mean	.38	.345	.255	.52	.385	.39				
76-21	SDSU 2523	G. c.	.53	.47	.32	.66	.65	.56	nd	.85	.13	nd

Notes for Table 4

Amino acid identifications as given in Table 3

Species abbreviations:

C. c.	=	<u>Cuminea californica</u>
Ch. u.	=	<u>Chione undatella</u>
Ch. c.	=	<u>Chione californiensis</u>
D. a.	=	<u>Diodora aspera</u>
E. c.	=	<u>Epilycina californica</u>
M. i.	=	<u>Macoma inguinata</u>
M. n.	=	<u>Macoma nasuta</u>
P. r.	=	<u>Polinices reclusianus</u>
P. s.	=	<u>Protothaca staminea</u>
P. t.	=	<u>Protothaca tennerima</u>
S. f.	=	<u>Saxidomus giganteus</u>
S. n.	=	<u>Saxidomus nuttalli</u>
T. f.	=	<u>Tegea funebris</u>
T. s.	=	<u>Tivela stultorum</u>

Bracketed samples represent duplicate analyses of same individual.
Numbers in parentheses indicate tentative values.

- a) Sample 74-1 non included in mean value calculation because of calcite abundance.
- b) Sample 74-9 no included in mean value calculation because it is thought to have been reworked from an older deposit.

Table 5: Relative Errors Observed in Different Genera.

GENUS	AMINO ACID (% Error)				
	LEU	GLU	VAL	ALA	PRO PHE
<u>Saxidomus</u>					
Foimt Año Nuevo - M1690: Five Individuals					
mean	.449	.325	nd	.634	.564 .543
std. dev. (%)	1.2	5.5		1.4	10.3 3.1
Newport Beach - M2074: Three Individuals					
mean	.51	.42	.307	.777	.62 .533
std. dev. (%)	5.8	7.1	7.1	10.5	4.0 6.0
San Pedro - M5908 and LACM 1210: Three Individuals					
mean	.533	.42	.35	.847	.657 .567
std. dev. (%)	0.9	0.0	4.8	2.5	2.1 5.9
<u>Protothaca</u>					
Foimt Año Nuevo - M1690: Two Individuals					
mean	.385	.31	.295	.72	.46 .52
range (%)	1.3	0.0	1.7	2.8	4.3 5.8
Santa Cruz - M1691: Two Individuals					
mean	.375	.29	.245	.66	.425 .48
range (%)	4.0	0.0	2.0	4.5	1.2 12.5
Cayucos - M5922: Three Individuals					
mean	.413	.363	.267	.643	.540 .496
std. dev. (%)	3.6	1.7	2.2	3.6	1.9 9.0

San Pedro Sand - LACM 332: Two Individuals
 mean .625 .57 .445 .935 .72 .68
 range 2.4 3.6 7.8 0.5 2.8 1.5
 (%)

Point Loma, Nestor Terrace: Five Individuals (four localities)
 mean .455 .394 .297 .708 .486 .47
 std. dev. 4.6 5.3 4.4 5.6 11.3 8.5
 (%)

Point Loma, Bird Rock Terrace - SDSU 2523: Two Individuals
 mean .38 .345 .255 .52 .385 .39
 range 2.6 4.3 5.9 0.0 1.3 2.5
 (%)

Newport Beach - M2074 and M1477: Three Individuals
 mean .457 .39 .293 .77 .602 .567
 std. dev. 3.3 2.5 6.8 5.2 4.2 6.2
 (%)

San Pedro - M5908: Two Individuals
 mean .50 .415 .36 .84 .59 .57
 range 2.0 3.6 5.6 2.3 3.3 0.0
 (%)

Newport Beach - M2074: Three Individuals
 mean .667 .543 .340 .793 .893 .85
 std. dev. 6.0 6.4 2.9 4.7 4.5 8.4
 (%)

Point Loma, Nestor Terrace: Three Individuals (two localities)
 mean .58 .45 .34 .793 .883 .783
 std. dev. 4.5 4.4 2.6 4.0 3.6 5.4
 (%)

Tiveia

Chlone

Tesula

Epilucina

Point Loma, Nestor Terrace: Five Individuals (four localities)

mean	.646	.497	.413	.769	.742	.691
std. dev. (%)	6.1	4.4	7.5	6.3	4.8	4.3

Corona del Mar - M1481 and M1482: Three Individuals

mean	.653	.54	.45	.85	.747	.76
std. dev. (%)	5.2	1.9	2.2	5.0	5.4	6.6

Macoma

Point Año Nuevo - M1690: Two Individuals

mean	.49	.38	.325	.595	.555	.58
range (%)	4.1	5.3	7.7	.9	.9	3.5

Cayucos - M5922: Two Individuals

mean	.48	.39	.28	.61	.605	.61
range (%)	2.1	0.0	0.0	1.6	4.1	1.6

Goleta - M5790: Two Individuals

mean	.44	.31	.275	.54	.64	nd
range (%)	2.3	0.0	5.5	2.8	1.6	-

1. Mean values and standard deviation expressed as percent of mean.

TABLE 6 Apparent Relative Ages,
Southern Temperature Region
Localities in Relation to
Marine Isotopic Record Stage 5¹.

<p>Early Stage 5</p> <p>Point Loma, Nestor Terrace Pacific Beach, Nestor Terrace (SDSU 1854: two samples of early stage 5 age, two of pre-stage 5 age).</p>	<p>Point Loma, Nestor Terrace Newport Mesa (M2074, M1477) Laguna Beach (M1018: <u>Saxidomus</u> and <u>Protothaca</u>) Corona del Mar (M1481 and M1482) Newport Beach, First Terrace (M1722: <u>Protothaca</u>) Torrey Pines (LACM 2662: <u>Protothaca</u>) San Pedro, Palos Verdes Sand (M5908, LACM 1210) Palos Verdes Hills, Fourth Terrace (M6720, LDGO 830E)</p>
<p>Late Stage 5</p>	<p>Point Loma, Bird Rock Terrace Torrey Pines (LACM 2662: <u>Saxidomus</u>)</p>
<p>Uncertain Stage 5</p>	<p>San Nicolas Island, 30-meter terrace (USGS loc. 21664). <u>Saxidomus</u> and <u>Epilucina</u> both suggest late stage 5 age if temperatures equivalent to those of Point Loma; cooler temperatures would imply early stage 5 age.</p>
<p>Post- Stage 5</p>	<p>Goleta (M5790)</p>
<p>Pre- Stage 5</p>	<p>Newport Mesa (M1479) Huntington Beach (M5902) Newport Beach (LACM 66-2, M5898: all samples except one <u>Protothaca</u> that appears equivalent to early stage 5). San Pedro, San Pedro Sand (LACM 332) San Pedro, Timms Point Silt (LACM 130-7) San Nicolas Island, higher terraces (most samples) Corona del Mar, 90-meter terrace (M3759) Corona del Mar, 35-meter terrace (M1476) Laguna Beach (M1018 and M1019; <u>Tivela</u> and <u>Polinices</u>) Palos Verdes Hills, fifth and higher terraces.</p>

1. Isotope stage 5 of Shackleton and Opdyke, 1973.

TABLE 7: Apparent Relative Ages,
Central Temperature Region
Localities in Relation to
Marine Isotopic Record Stage 5

	U-Series age on corals of 150,000-140,000 years.
Early Stage 5	Cayucos (M5922); age defined by/ (Veeh and Valentine, 1967). Point Año Nuevo (M1690); comparison of <u>Macoma</u> with Cayucos, <u>Saxidomus</u> with Santa Cruz
Late Stage 5	Santa Cruz (M1691); comparison based upon <u>Protothaca</u> only, Santa Cruz vs. Cayucos Point Año Nuevo (M1690); possible comparison of <u>Protothaca</u> from Cayucos and Pt. Año Nuevo

1. Marine isotope stage 5 of
Shackleton and Opdyke, 1973.

Table 8: Endothimeric Ratios in Molluscs from Holocene and Latest Pleistocene Localities in Puget Sound. Apparent First-Order Rate Constants, Relative Rate Constants, and Effective Temperature Differences

Locality	$k_{(leu)}$ (yrs^{-1})	$k_{(ileu)}$ (yrs^{-1})	T_{KIN} , °C.	$k_{(calc)}/k_{(obs)}$
LACN 5012, Bainbridge Isl. 12,260 ± 90 yrs. (C-14) Mean Ann. Air Temp., 11.1° C				
<u>Protothaca</u>	1.01 x 10 ⁻⁵	1.12 x 10 ⁻⁵	13.45	.67
<u>Saxidomus</u>	1.32 x 10 ⁻⁵	1.44 x 10 ⁻⁵	14.99	.52
LACN 5009, Orcas Isl. 12,350 ± 400 yrs. (C-14) Mean Ann. Air Temp., 9.8° C.				
<u>Protothaca</u>	.56 x 10 ⁻⁵	.61 x 10 ⁻⁵	9.93	.78 ^{c)}
<u>Saxidomus</u>	1.02 x 10 ⁻⁵	1.10 x 10 ⁻⁵	13.37	.44 ^{c)}

Prot. mean = .73
Sax. mean = .48

Protothaca Temp. Diff. = 3.52°

Saxidomus Temp. Diff. = 1.62°

mean Temp. Diff. = 2.6 ± .9° C.

Apparent Effective Temperature, Orcas Isl. = 11.1° - 2.6° = 8.5 ± .9° C.

- Notes:
- a) calculated assuming (D/L)leucine = 0.93 (D-alloisoleucine/L-isoleucine)
 - b) k_{calc} = rate constant for isoleucine from equation 1 (text) for appropriate air temperature
 k_{obs} = rate constant for isoleucine as estimated from leucine data and assumption stated in note a).
 - c) k_{calc} = that derived from equation 1 (text) for 8.5° C.

Table 9: Numerical Data for the Calculation of Leucine Kinetic Model Curves

$(X_E - X)/X_E$	Time, yrs.	Isoleucine Model Curves: Time Required to Reach Same Value of $(X_E - X)/X_E$ (in foraminifera) at elevated temperatures of:							Leucine $(X_E - X)/X_E$ values for conversion factors ^{b)} of:
		10°	12°	15°	17°	19°	22°		
0.90	75,000	22059	15717	9557	6980	4987	3095	0.90	0.95
0.70	135,000	39705	28290	17204	12395	8976	5572	.797	.787
0.50	300,000	98235	62866	38231	27523	19947	12391	.694	.690
0.40	1,100,000	323529	230511	140180	100917	73138	45399	.486	.465
0.30	2,100,000	617647	440067	267618	192661	139627	86669	.379	.355
								.272	.247

Equivalent Temperatures ($\pm 1^\circ$) for:

Protothaca

8° 10° 13° 15° 17° 20°

Saxidomus

6° 8° 11° 13° 15° 18°

- Notes:
- a) Derived from curve for most extensively racemized data from Wehmiller and Hare (1971)
 - b) Conversion factors are defined as (D-leucine/L-leucine)/(D-alloisoleu/L-isoleu). Two possible values are shown for the purposes of defining the probable range of uncertainty in this conversion.

Table 10: Aspartic Acid/Leucine Ratios for Molluscan Genera as Determined by Gas Chromatography

<u>Genus</u>	<u>ASP/LEU (mean)</u>	<u>(range)</u>	<u>Number of samples measured</u>
<u>Tegula</u>	2.6	1.7-3.2	6
<u>Macoma</u>	1.6	0.7-2.2	6
<u>Epilucina</u>	1.4	1.2-1.6	6
<u>Cumingia</u>	1.7	1.5-1.9	2
<u>Protothaca</u>	6.2	3.2-8.0	12
<u>Tivela</u>	10.0	8.5-12.0	4
<u>Saxidomus</u>	10.2 5.7 ^{a)}	8.8-12.5 5.5-5.9 ^{a)}	8 2 ^{a)}
<u>Chione</u>	4.8	4.3-5.2	4

Note: a) These two Saxidomus samples are from the San Pedro Sand (LACM 332) and are assigned a Middle Pleistocene age based upon kinetic models described in this work. Decreasing trends in ASP/LEU ratios with increasing sample age were not observed in other genera, so age distinctions for these other genera are not made in presentation of data in this table.

Table 11: Effective Diagenetic Temperatures for Samples of Selected Ages as Derived from Model Temperature Histories Shown in Figure 16.

Sample Age, Years	Effective Diagenetic Temperature, Expressed as Reduction Below Present (Mean Annual Air or Effective Annual Air) Temperatures			
	Model 1	Model 2	Model 3	Model 4
125,000	1.9° C.	2.9° C.	4.35° C.	3.00° C.
80,000	2.4	3.9	5.4	4.0
40,000	2.2	3.3	4.7	3.8

Table 12: Kinetic Model Age Assignments

<u>Locality</u>	<u>Model Age, 10³ yrs.</u>	<u>Comments</u>
San Nicolas Island:		
30-meter terrace	120 ± 20	Calibration site: older of two U-series dates appears correct in light of amino acid data.
120-meter terrace	320 + 60 - 40	
240-meter terrace	450 ± 100	
Point Loma:		
Nestor Terrace	120 ± 10	Calibration site
Bird Rock Terrace	90 ± 10	
Pacific Beach, SDSU 1854 2 older samples → 2 younger samples →	220 ± 30 120 ± 10	Effective diagenetic temp. equal to that of Nestor Terr. assumed. Possible mixing of samples of slightly different ages.
Torrey Pines LACM 2662	90 ± 15 to 130 ± 15	
Newport Beach M2074 M1477 M1722	120 to 140	Effective temperatures approximately 0.5° warmer than Nestor Terrace assumed.
Laguna Beach M1018 } M1019 }	120 to 140 250 ± 40	<u>Protothaca</u> and <u>Saxidomus</u> <u>Tivela</u> and <u>Folinices</u>
San Pedro, Palos Verdes Sand	120 to 140	Effective temperatures approximately 1.0° warmer than Nestor Terrace assumed.
Santa Cruz	90 ± 10	
Cayucos	135 ± 15	Calibration site: mean of two U-series dates
Point Año Nuevo	110 ± 30	Temperature uncertainty precludes better age estimate
Goleta	40 ± 10	
Cape Blanco	± 20	Inversion of <u>Saxidomus</u> and <u>Protothaca</u> relationship precludes better age estimate

Similarity with results for same genus from Nestor Terrace, Point Loma, calibration site

Table 12, continued

Trinidad Head	500 ± 100	Effective temperature 2° cooler than Point Año Nuevo assumed.
San Pedro Sand (LACM 332)	350 to 450	Effective temperatures 2° - 3° cooler than Palos Verdes Sand assumed.
Huntington Beach (M5902)	350 to 450	Similarity of ratios to those from LACM 332
Newport Mesa (M1479)	350 to 450	Similarity of ratios to those from LACM 332
Timms Point Silt (LACM 130-7)	1,000 ± 200	Effective temperatures 5° to 7° cooler than Palos Verdes Sand assumed.
Newport Beach (LACM 66-2)	240 ± 50	Effective temperatures equal to M2074 assumed
Palos Verdes Hills 12th terrace	450 ± 100	Similarity of <u>Tegula</u> data with that of San Nicolas Island (upper terraces). <u>Tegula</u> data
San Joaquin Hills 3rd Terrace	450 ± 100	Similarity of <u>Tegula</u> and <u>Epilucina</u> with San Nicolas Island results for these two genera.

Table 13: Long-term Average Uplift Rates for Selected Localities.^{a, b}

Locality	Age, 10 ³ yrs.	Elevation of Shoreline Angle at present, meters	Elevation of Shoreline Angle when formed, meters	Uplift Rate, m/1000 yr.
Cape Blanco	50 ± 20	70	-40 if 40,000 yrs. -20 if 60,000 yrs.	2.75 1.5
Santa Cruz	90 ± 10	20	-10	.34 ± .04
Cayucos	135 ± 15	20	0?	.15 ± .03
Goleta	40 ± 10	15	-40	1.4 ± .4
San Pedro (First Terrace)	120 to 140	~30	+ 6	.19 ± .02
Palos Verdes Hills				
Fourth Terrace	120 to 140	~80	+6	.6 ± .1
Twelfth Terrace	450 ± 100	380	0?	.9 ± .25
Newport Beach				
First Terrace and Newport Mesa	120 to 140	~25	+ 6	.15 ± .03
Second Terrace (Corona del Mar)	240 ± 50	~35	0?	.15 ± .04
Third Terrace (Corona del Mar)	450 ± 100	90	0?	.20 ± .05
Point Loma				
Nestor Terrace	120 ± 10	~25	+ 6	.16 ± .05
Bird Rock Terrace	80 ± 10	~8	- 10	.225 ± .05

Table 13, continued

San Nicolas Island					
30-meter Terrace	120 ± 20	30	+ 6	.2 ± .03	
120-meter Terrace	320 ± 60	120	0?	.37 ± .06	
240-meter Terrace	450 ± 100	240	0?	.55 ± .12	

Note: a) Sea-level curve of Bloom et al (1974) used as reference for elevation of shoreline angle at time of formation.

b) Age assignments taken from Table 12.

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- " 2b: Cape Blanco, Oregon
- " 2c: Trinidad Head, California
- " 2d: Point Año Nuevo, California
- " 2e: Santa Cruz, California
- " 2f: Cayucos, California
- " 2g: Goleta, California
- " 2h: Palos Verdes Hills and San Pedro, California
- " 2i: Huntington Beach, California
- " 2j: Newport Mesa; Newport Beach, Corona del Mar, and Laguna Beach, California
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- Figure 2l: Pacific Beach, California
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Figure 14: Leucine Kinetic Model Curves

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Figure 17: Proposed Kinetic Models for Glutamic Acid, Valine, Alanine, Proline, and Phenylalanine racemization in Protathaca

Figure 18: Kinetic Model Age Assignments Compared With Marine Isotopic Record

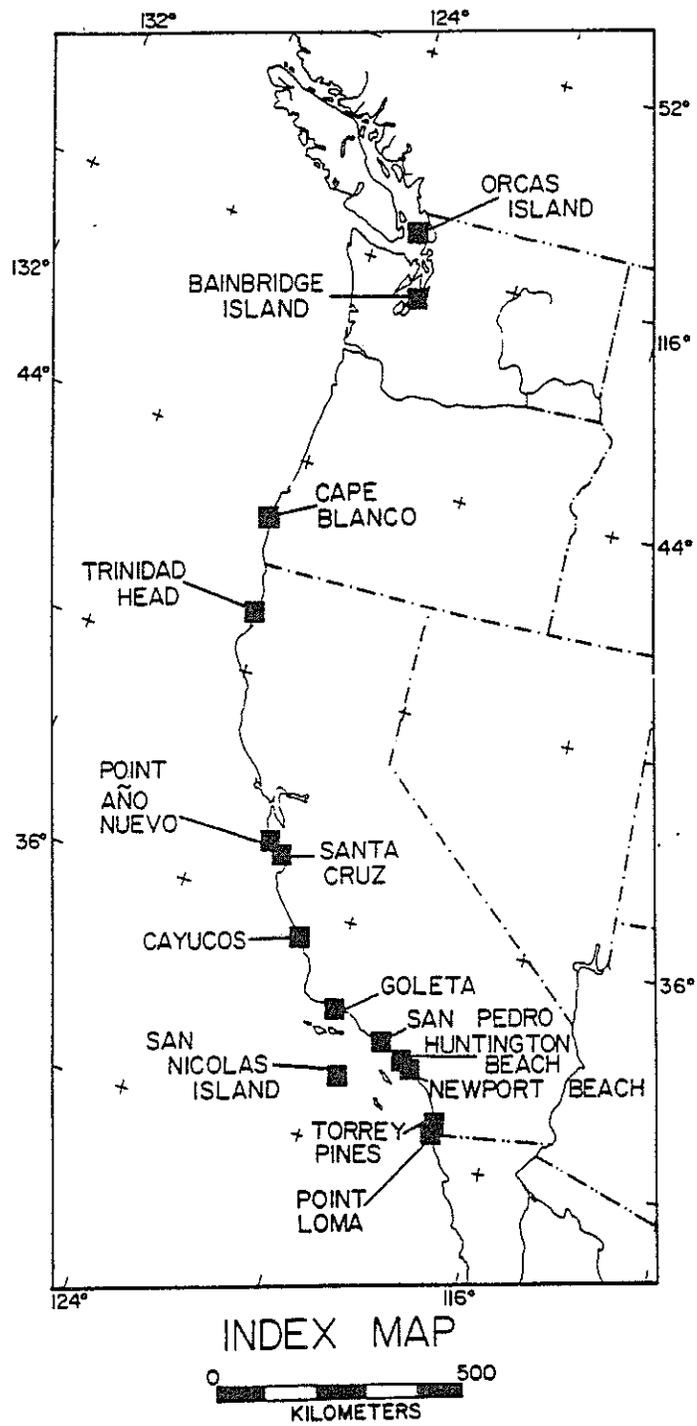


Figure 1: Index map of sample localities. See figures 2a-2n and Appendix for more detailed location descriptions.

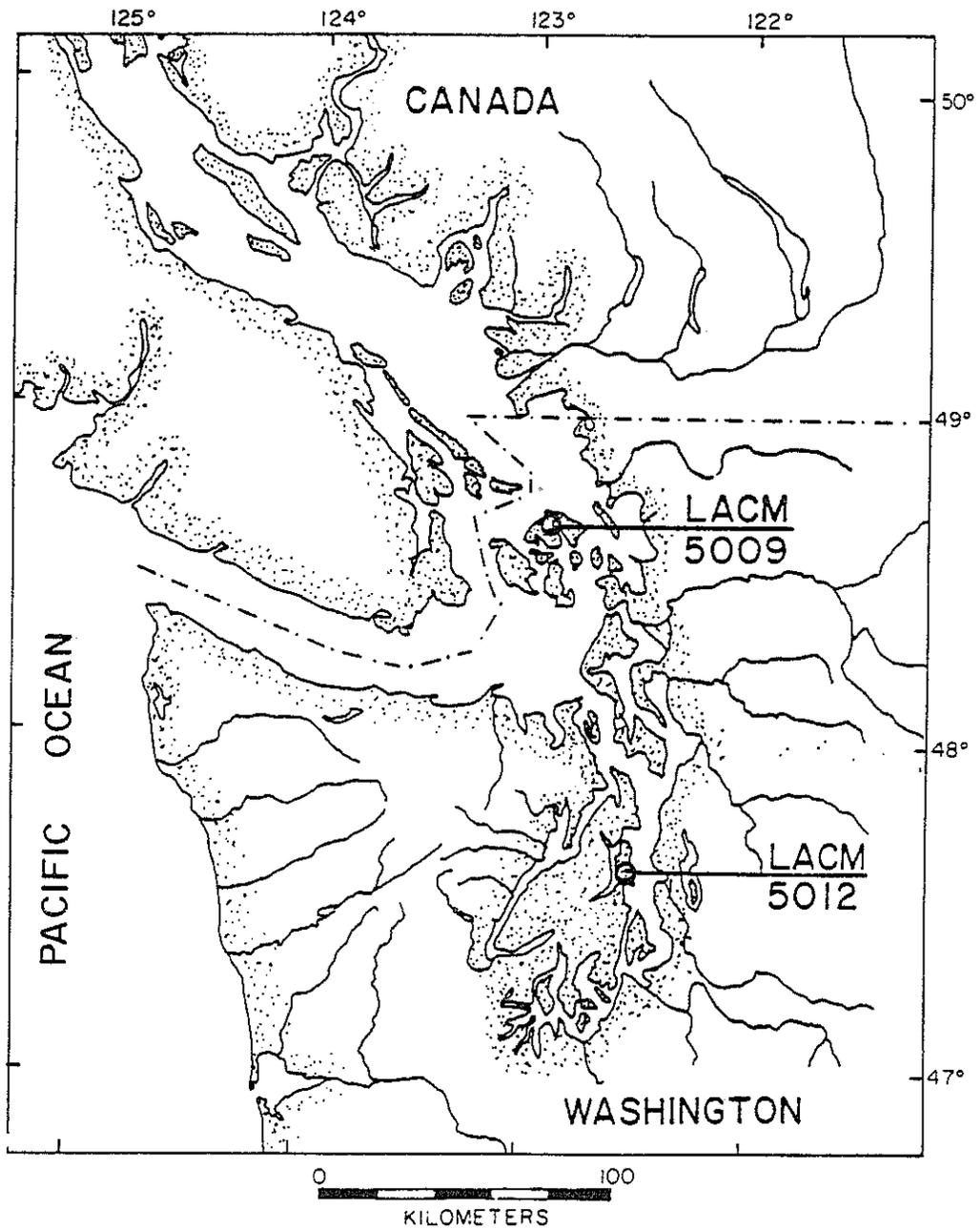


Figure 2a: Puget Sound, Washington. Abbreviations used for locality designations in Figures 2a-2n are explained in footnote 2 of Table 1.

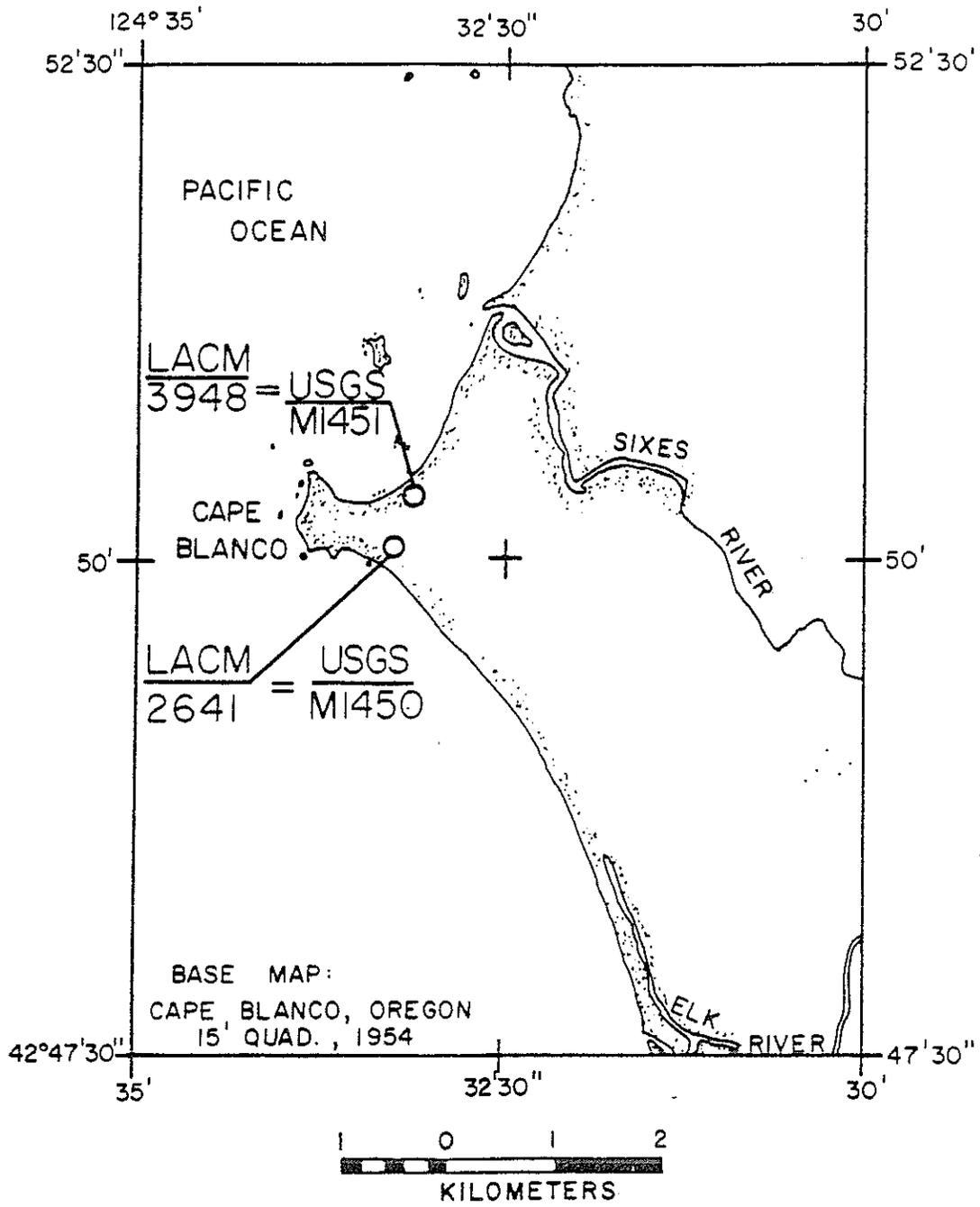


Figure 2b: Cape Blanco, Oregon.

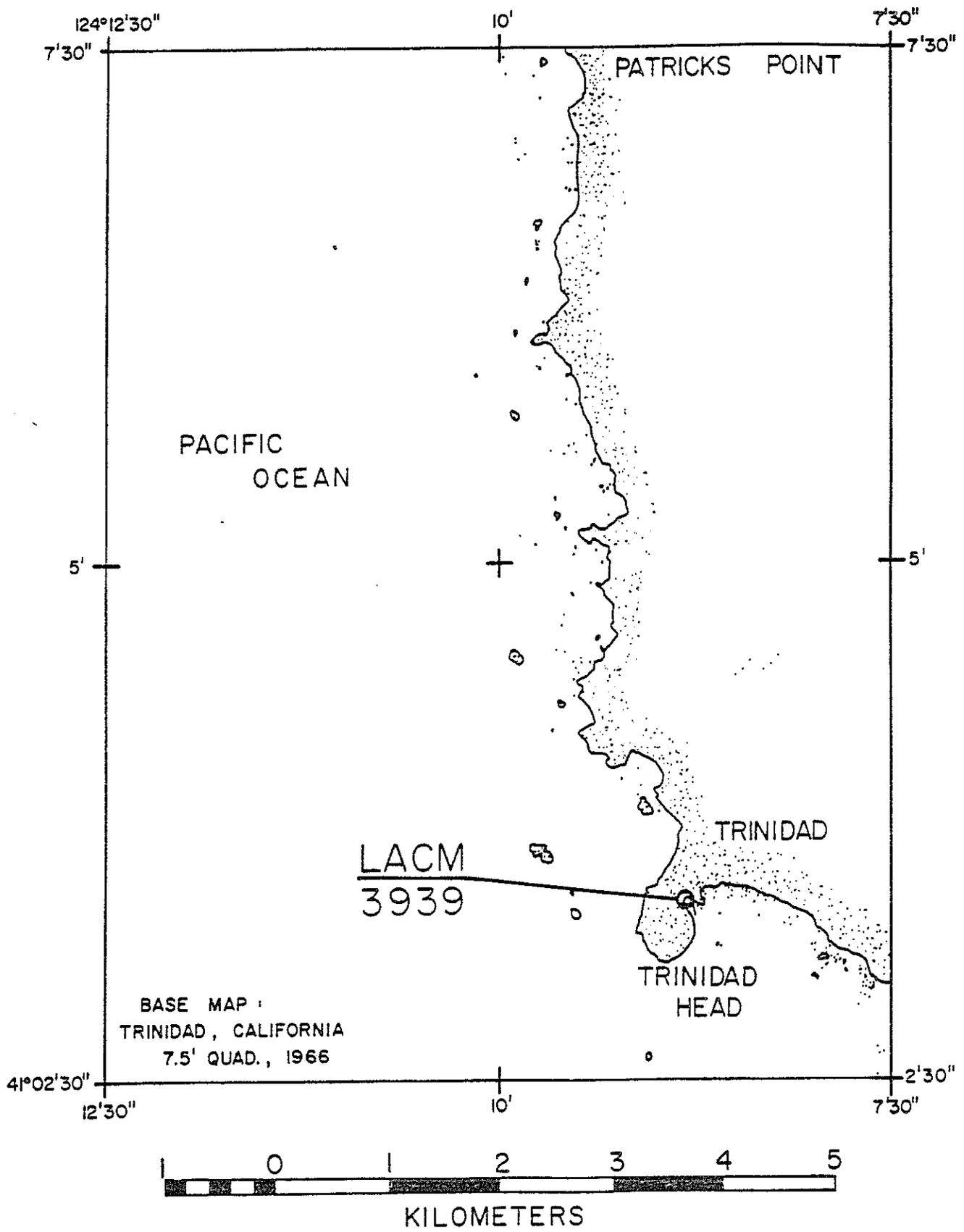


Figure 2c: Trinidad Head, California.

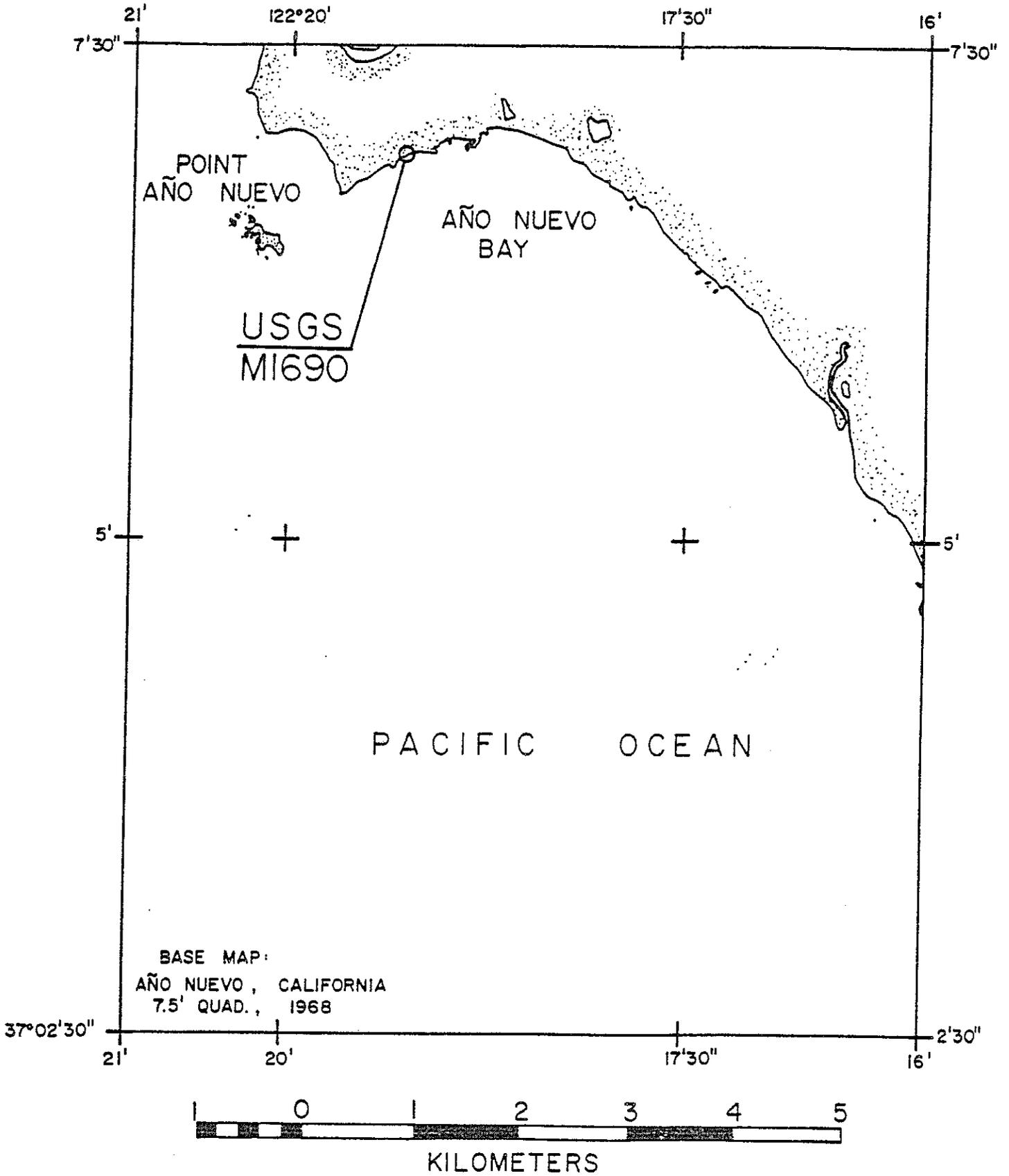


Figure 2d: Point Año Nuevo, California.

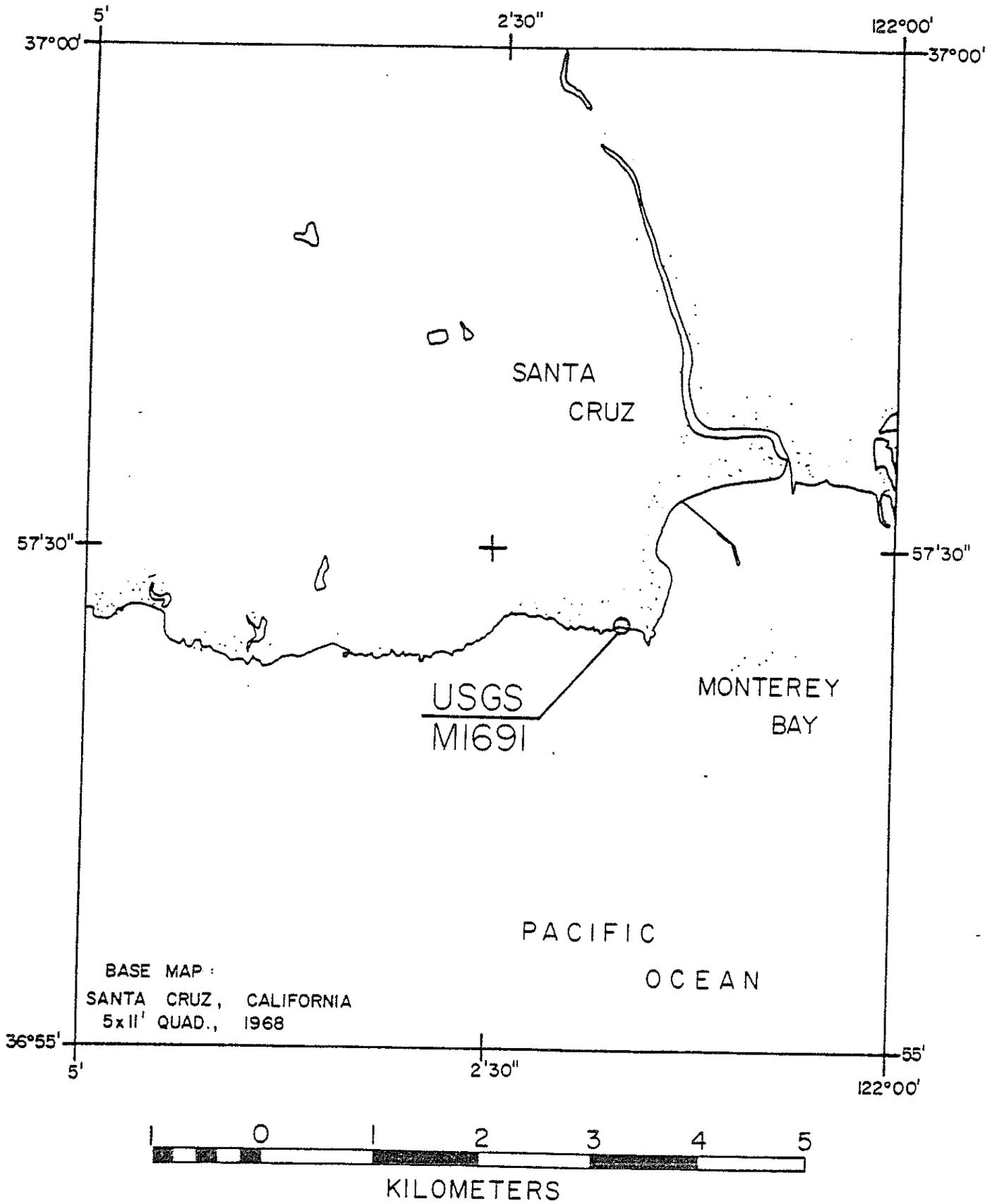


Figure 2e: Santa Cruz, California.

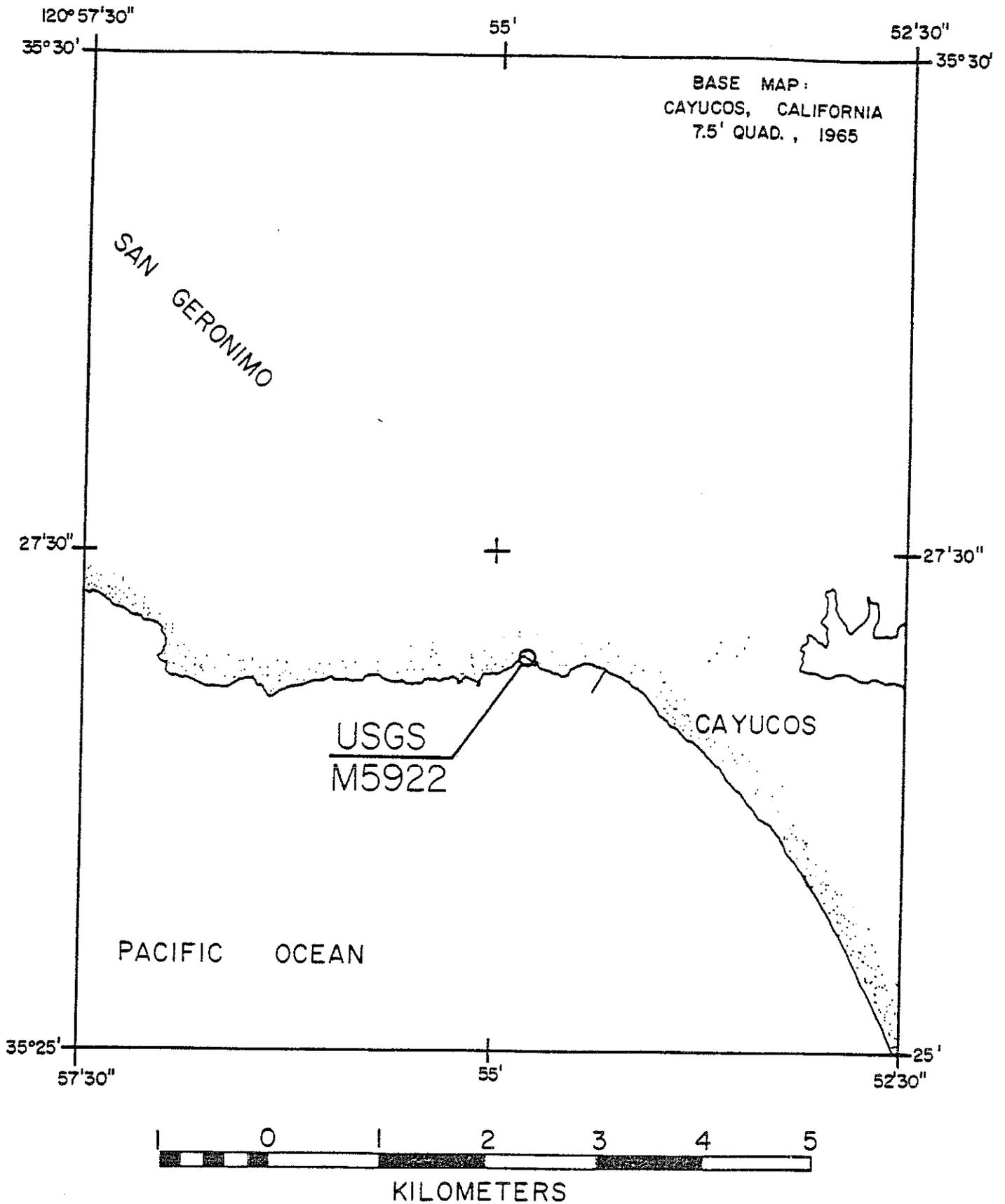


Figure 2f: Cayucos, California.

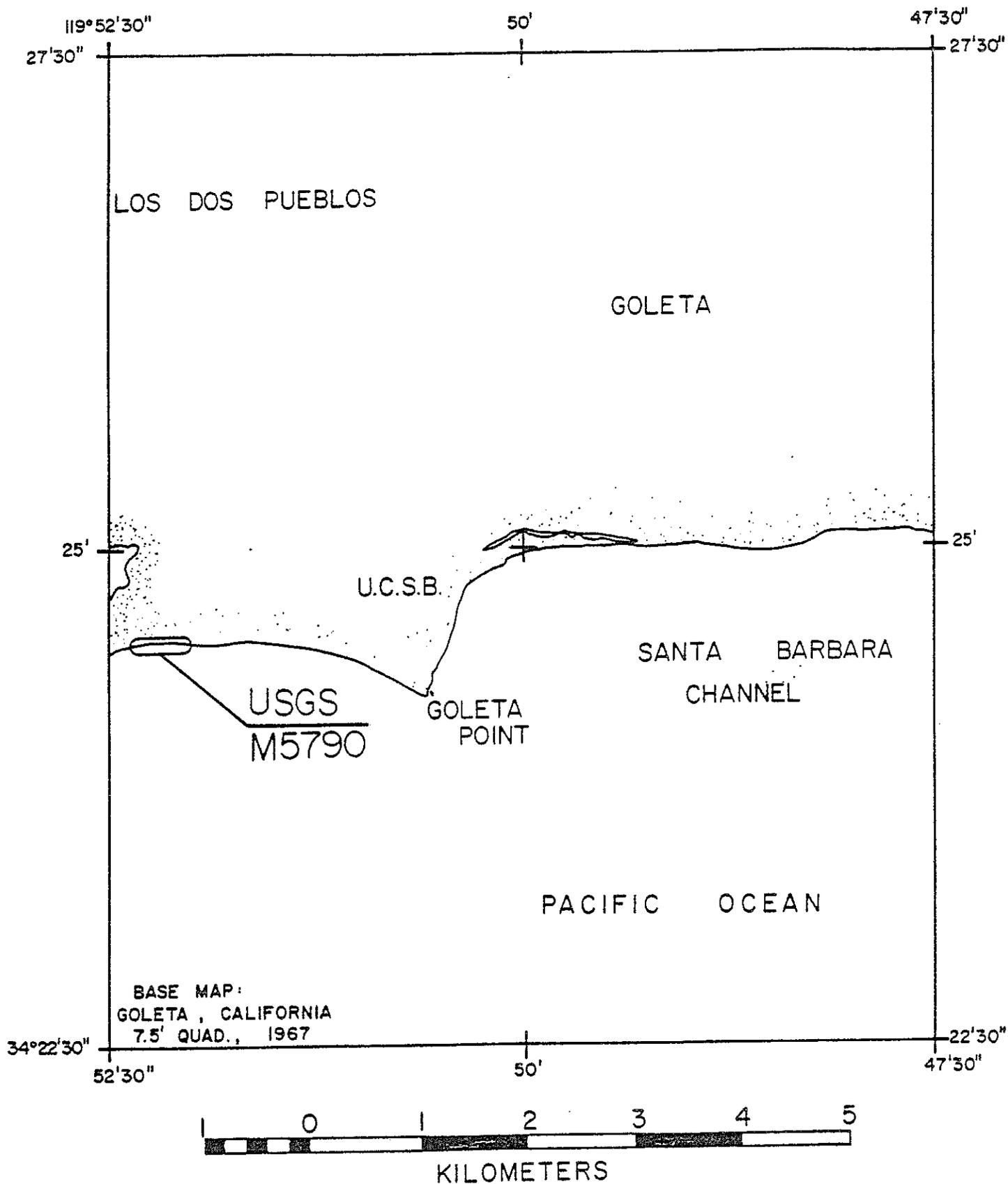


Figure 2g: Goleta, California..

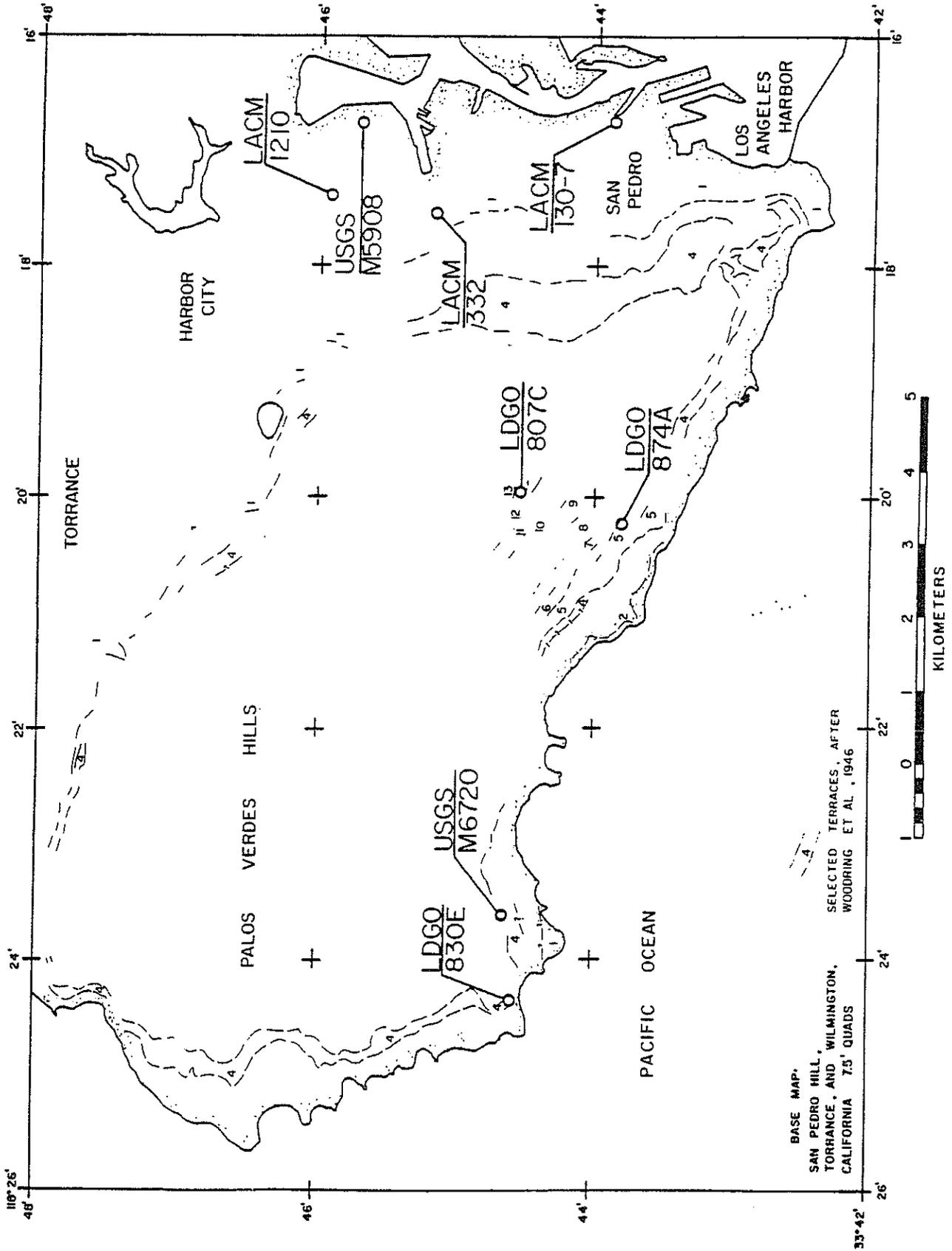


Figure 2h: Palos Verdes Hills and San Pedro, California

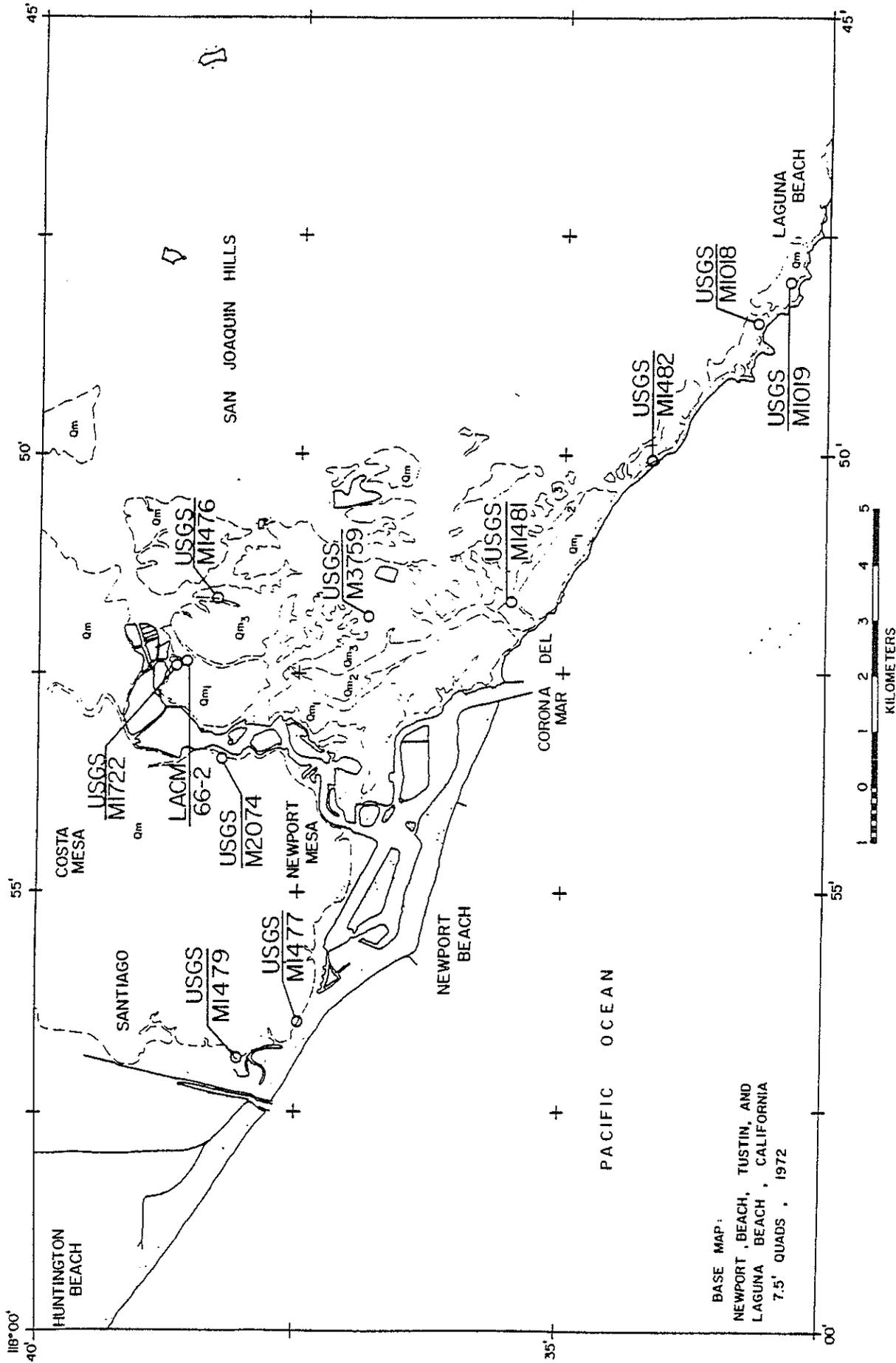


Figure 2j: Newport Mesa, Newport Beach, Corona del Mar, and Laguna Beach, California.

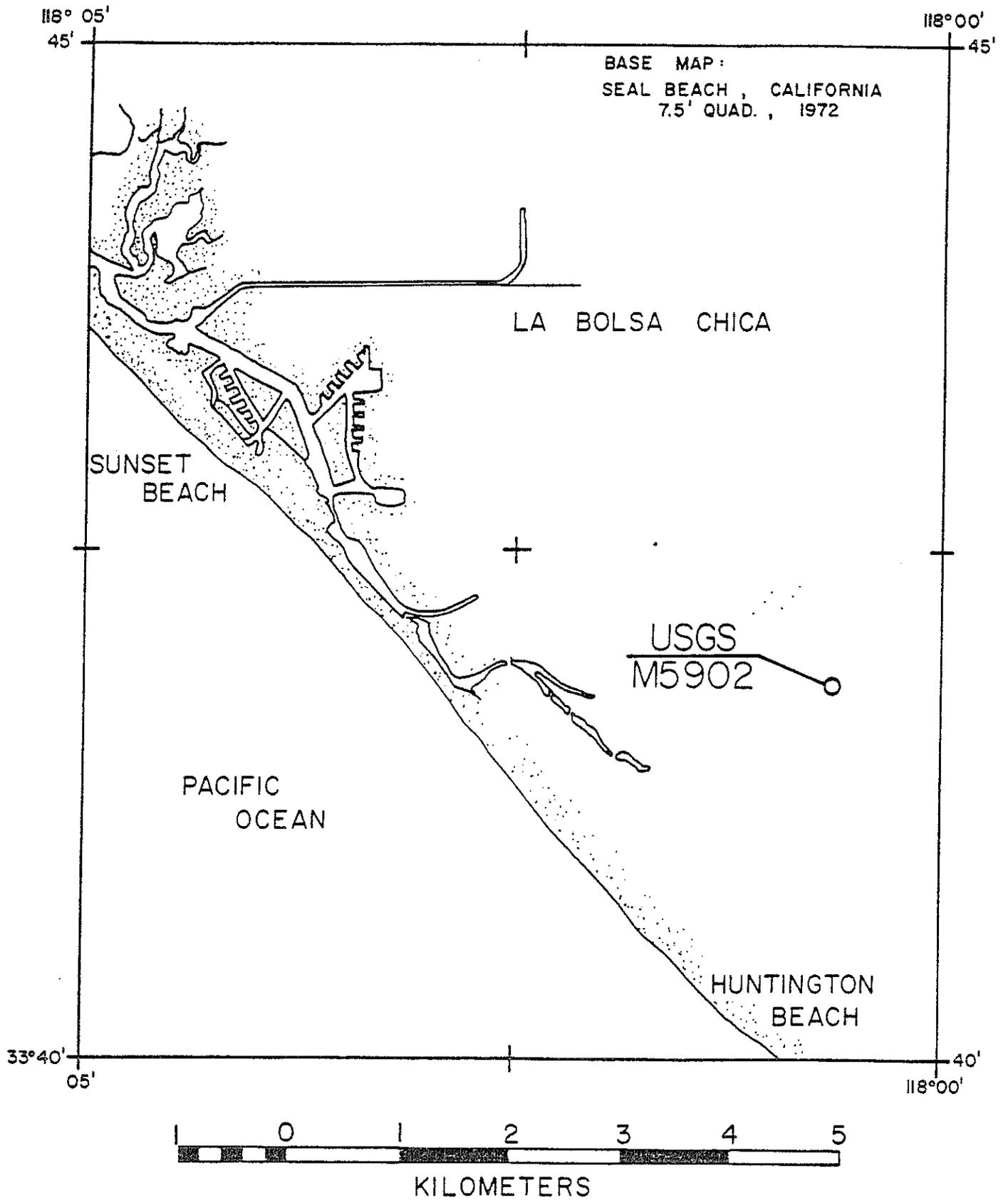


Figure 2i: Huntington Beach, California.

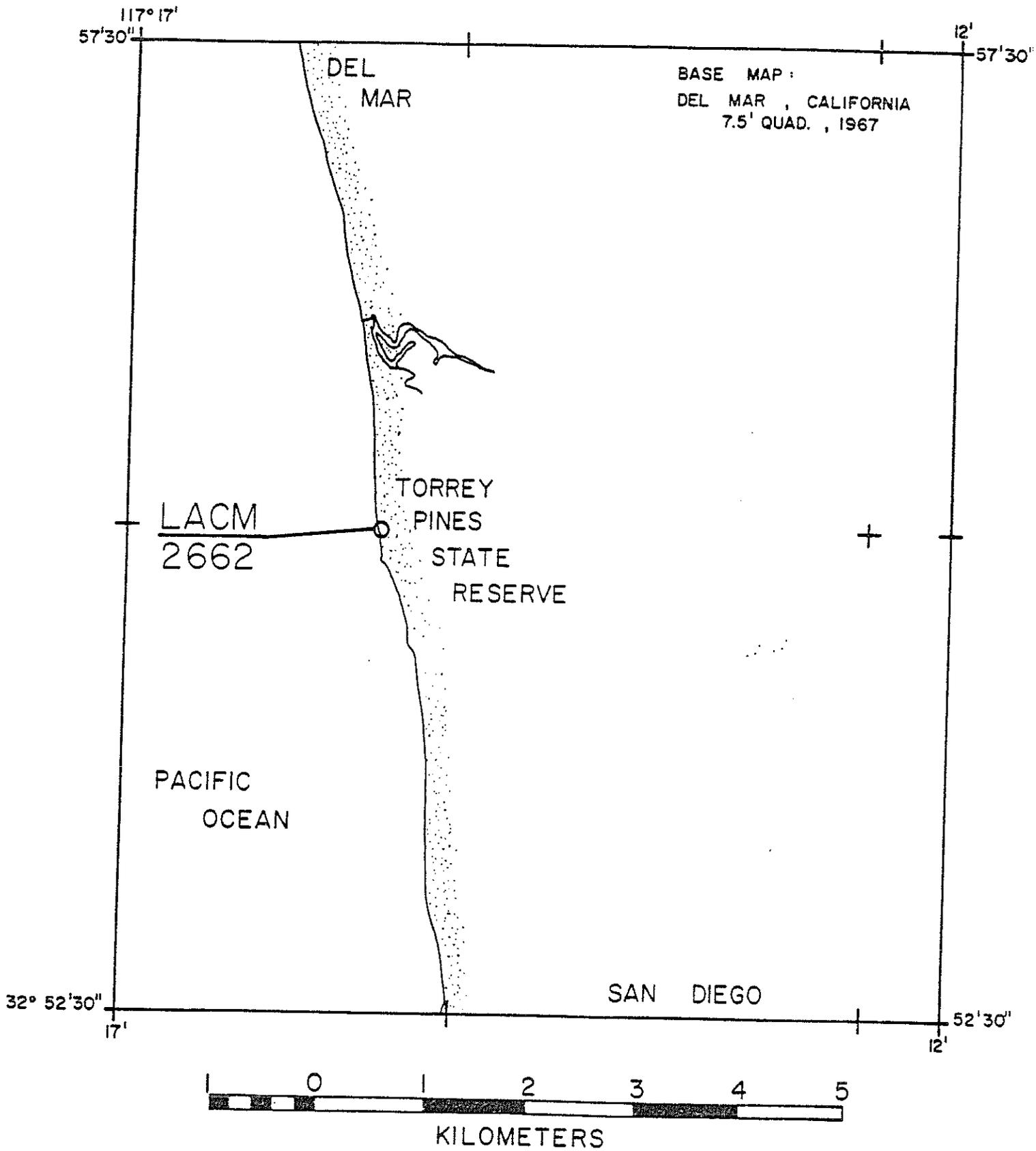


Figure 2k: Torrey Pines Park, California.

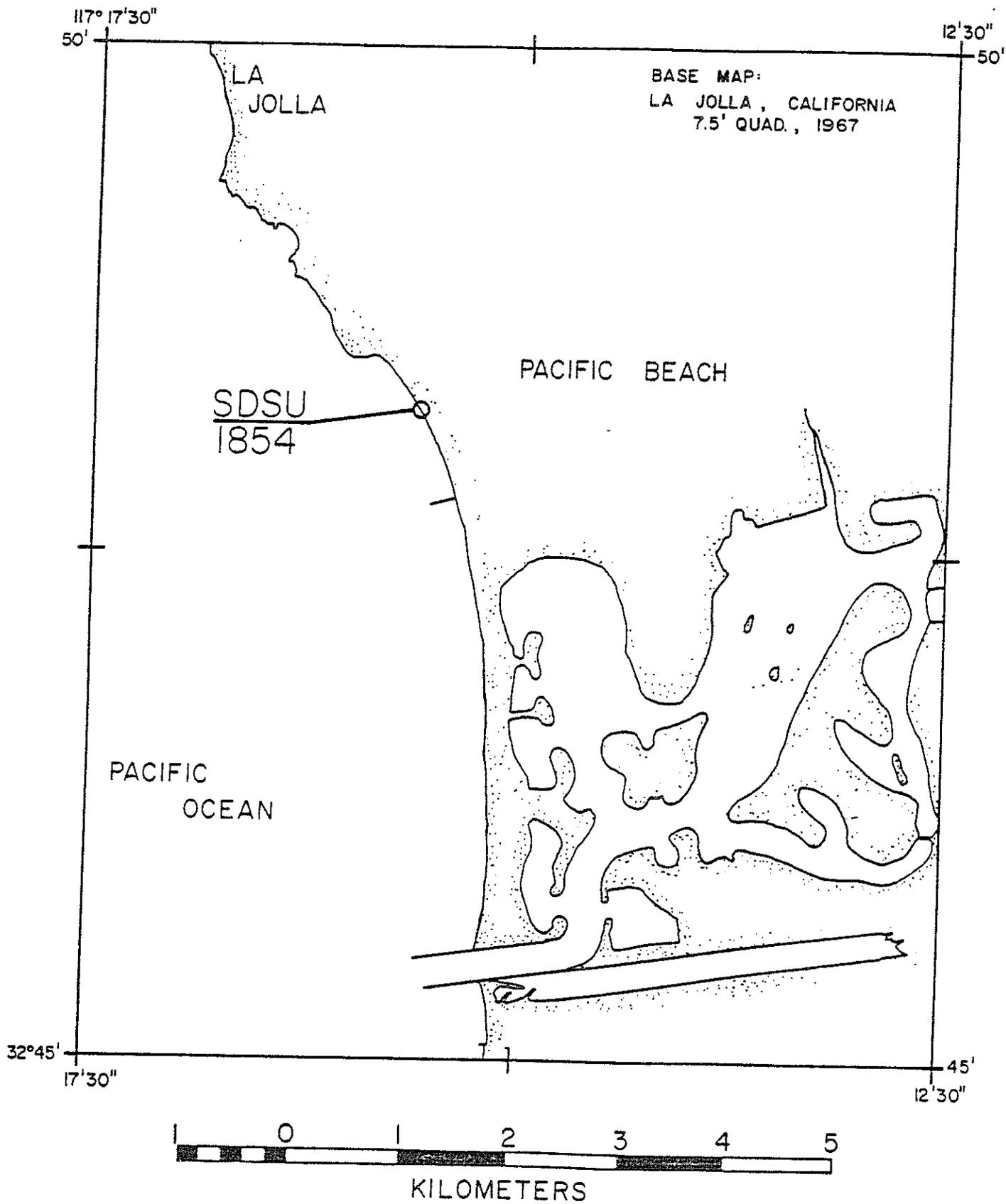


Figure 21: Pacific Beach, California.

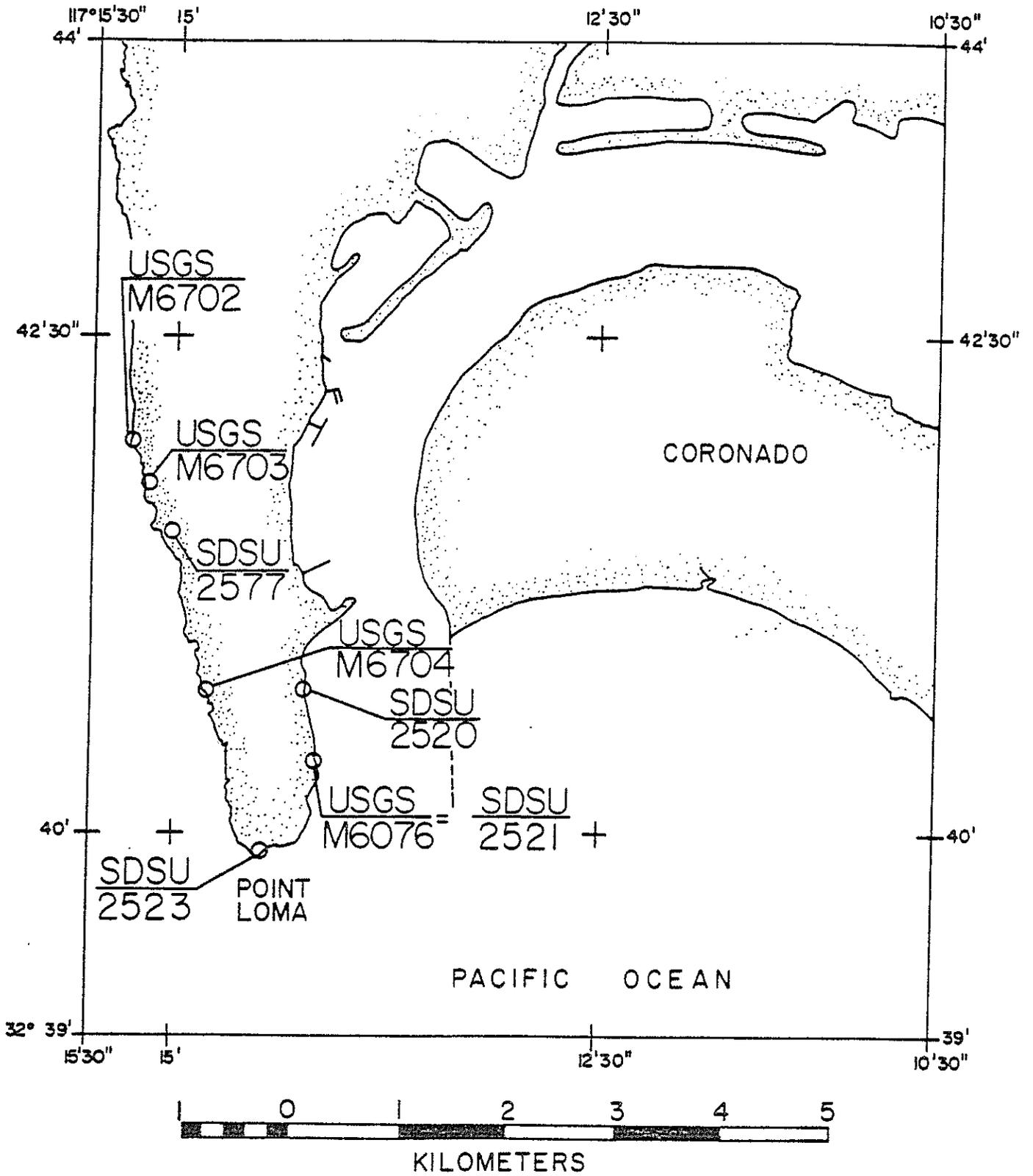


Figure 2m: Point Loma, California.

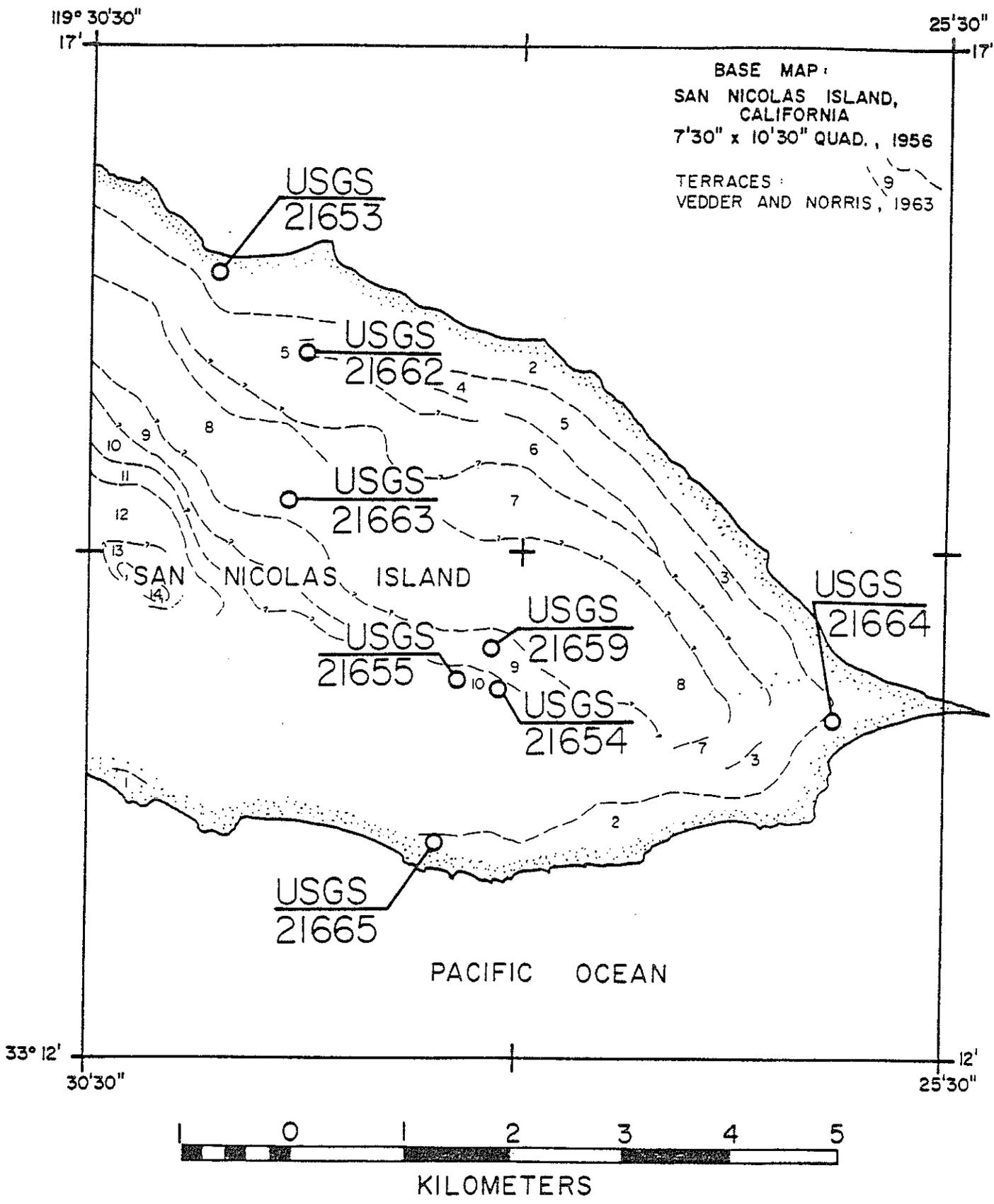


Figure 2n: San Nicolas Island, California (eastern half).

D/L RATIOS
 VERTICAL TERRACE FLIGHT
 SAN NICOLAS ISLAND

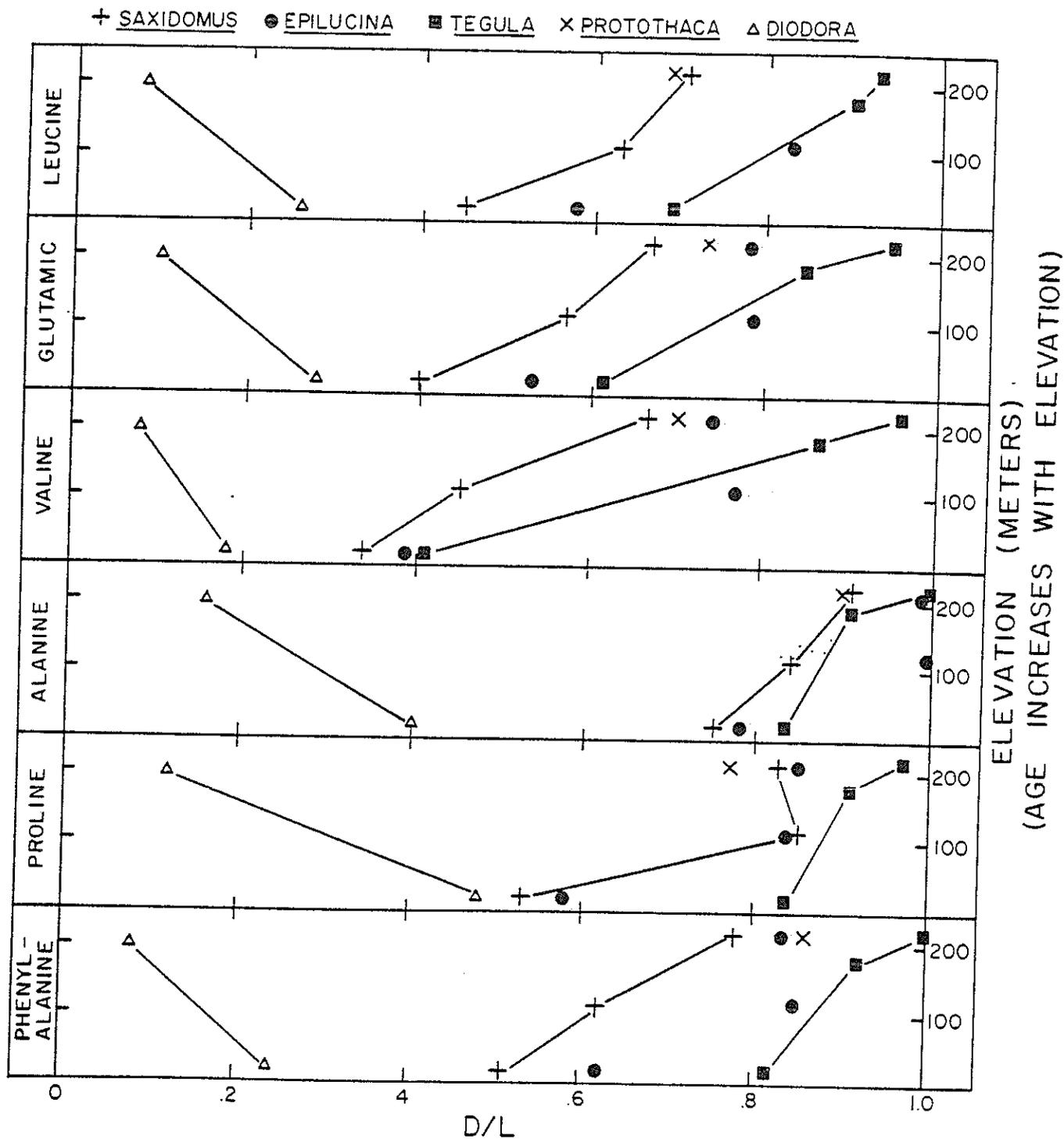


Figure 3a: Enantiomeric ratios on a vertical terrace flight on San Nicolas Island. Note that D/L ratios in *Diodora* do not increase with age indicating this genus is not reliable for amino acid dating purposes.

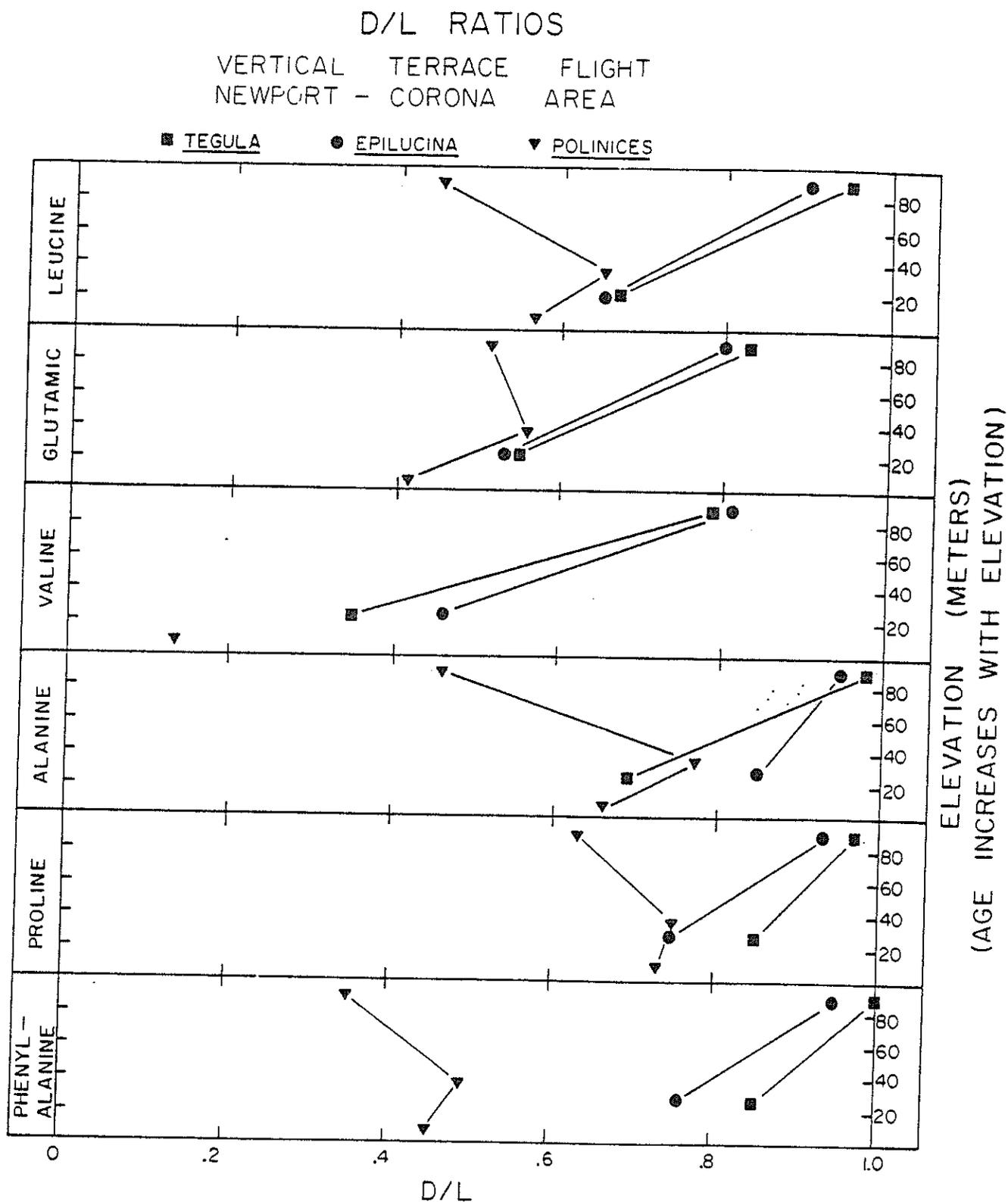


Figure 3b: Enantiomeric ratios, vertical terrace flight, Newport Beach, Corona del Mar. Note that D/L ratios in Polinices do not increase with age indicating this genus is not reliable for amino acid dating purposes.

D/L RATIOS
VERTICAL TERRACE FLIGHT
PALOS VERDES HILLS

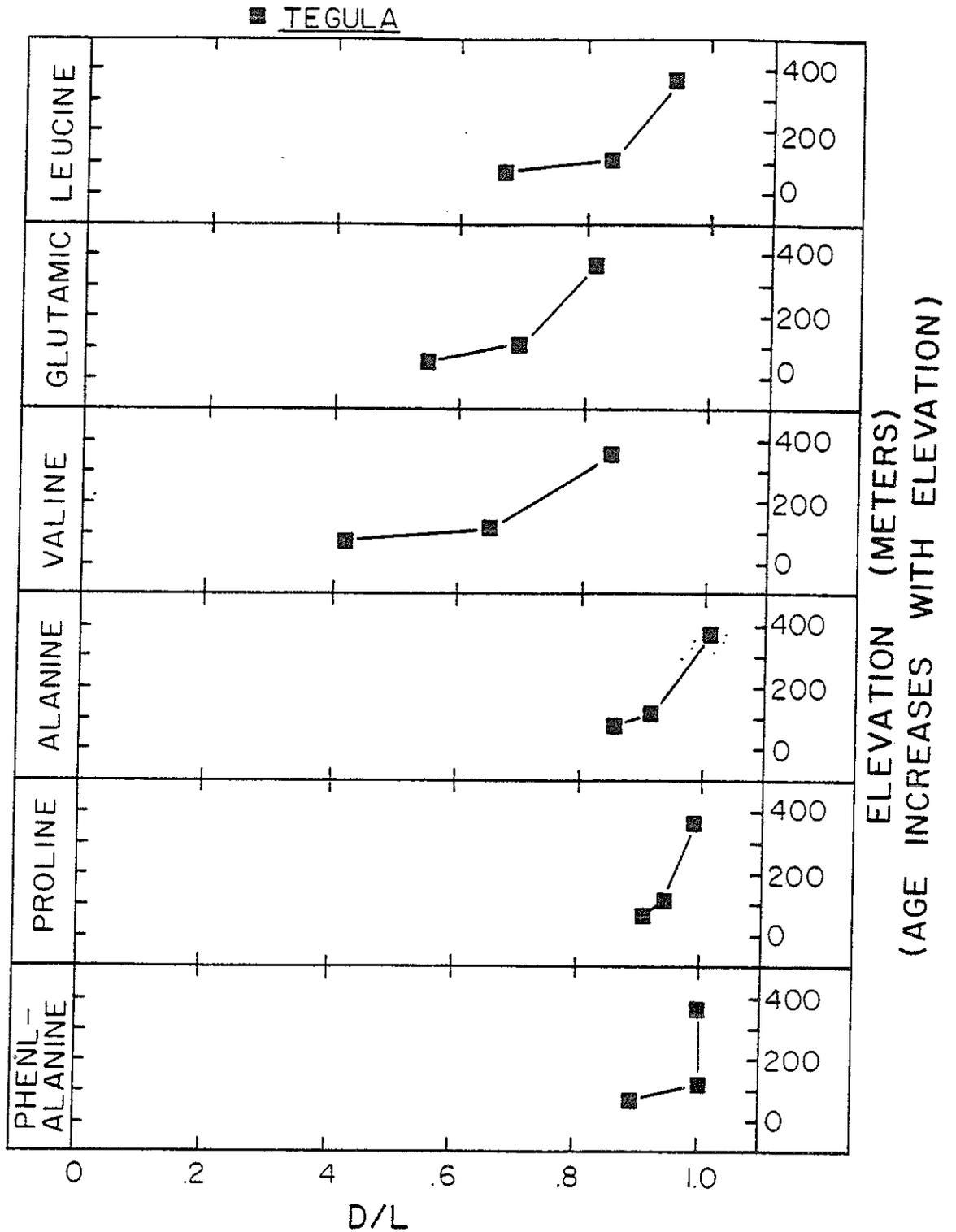


Figure 3c: Enantiomeric ratios, vertical terrace flight, Palos Verdes Hills, Tegula, unlike the other two gastropods analysed, polinices and diodora (see figures 3a and 3b), yields internally consistent results and therefore may be reliable for dating purposes. Data from Hare, 1974, written communication.

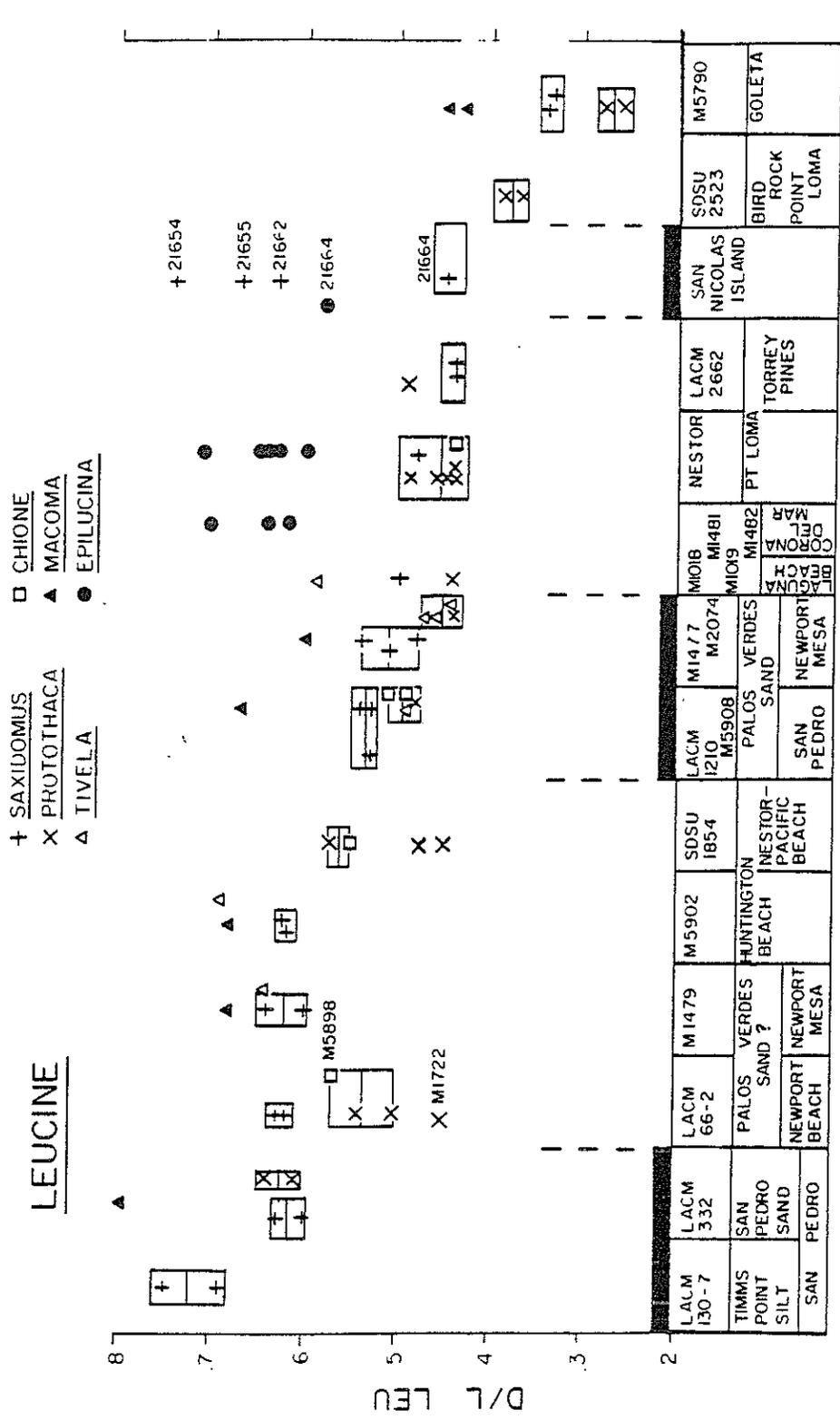


Figure 4: Leucine enantiomeric ratios, southern region localities. Localities listed from left to right in order of generally decreasing D/L ratios indicating decreasing ages. For Figures 4-7 the term "Palos Verdes Sand" is used in describing several localities in the Newport Beach area; as seen in these figures, samples from these Newport Beach localities show ratios quite similar to those from the Palos Verdes Sand in San Pedro in most cases. In some cases (localities M1479 and LACM 66-2) there are major discrepancies which are fully discussed in the text. Symbols used in Figure 4 for different genera are used in all subsequent figures.

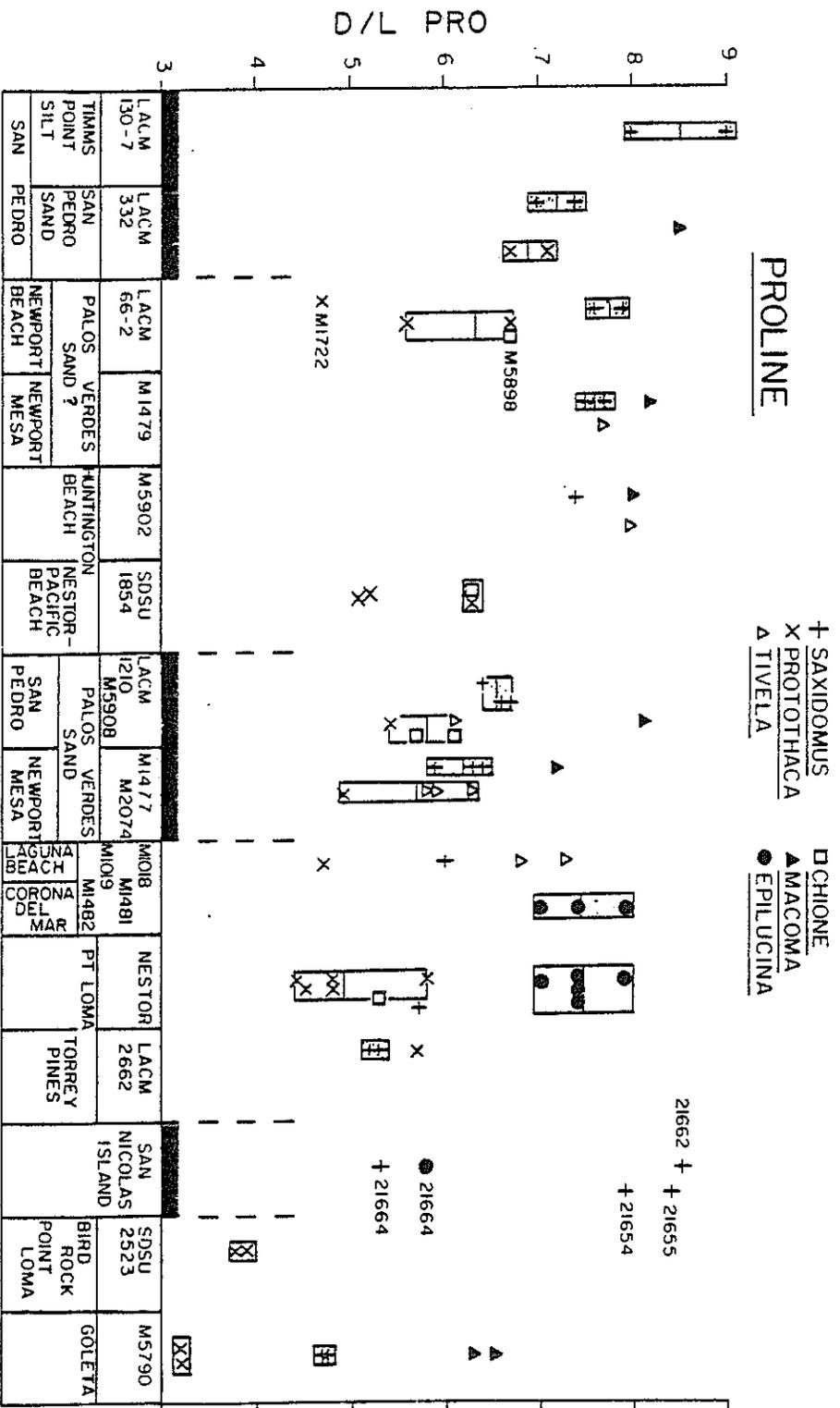


Figure 7: Proline enantiomeric ratios, southern region localities. Localities are listed from left to right in order of generally decreasing D/L ratios indicating decreasing ages.

LEUCINE

† SAXIDOMUS ▲ MACOMA PVS= PALOS VERDES SAND
 X PROTOTHACA □ CHIONE SPS= SAN PEDRO SAND
 Δ TIVELA TPS= TIMMS POINT SILT

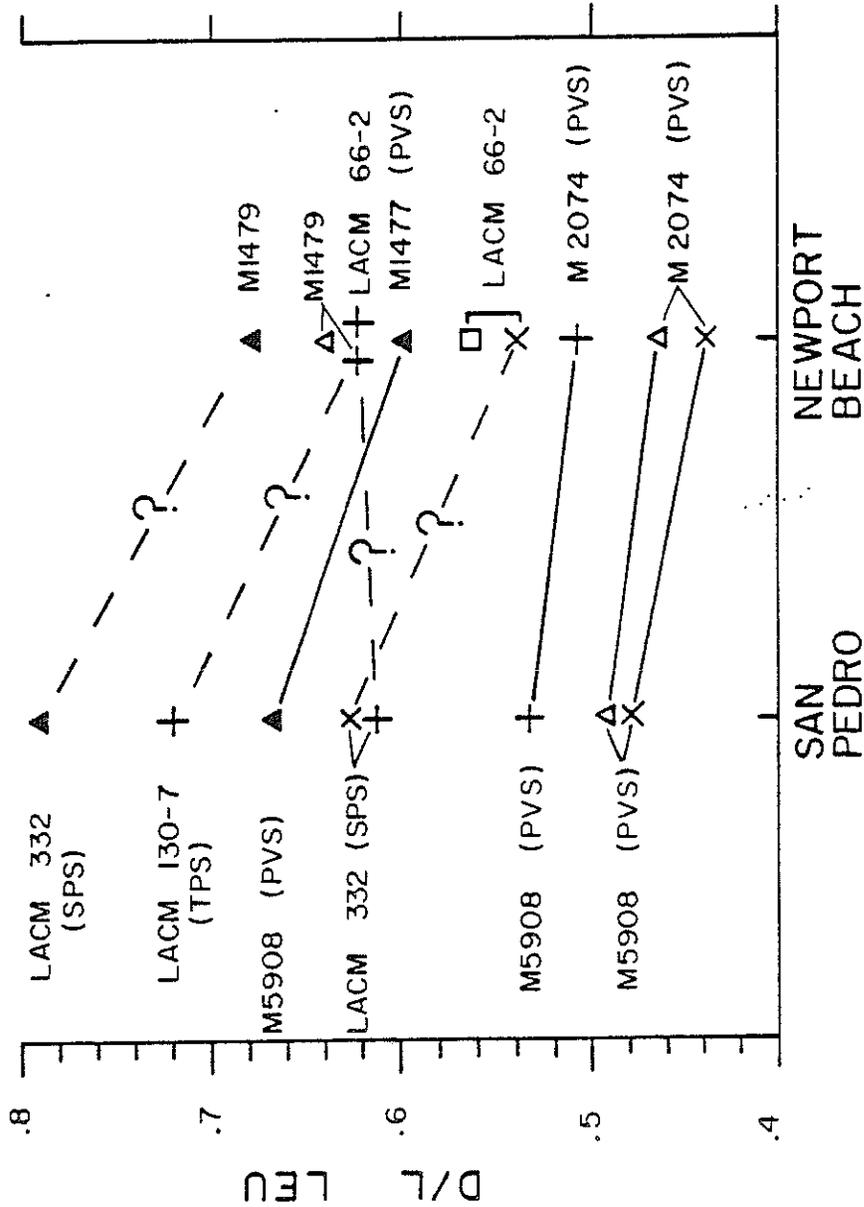


Figure 8: Leucine enantiomeric ratios, San Pedro and Newport Beach samples.

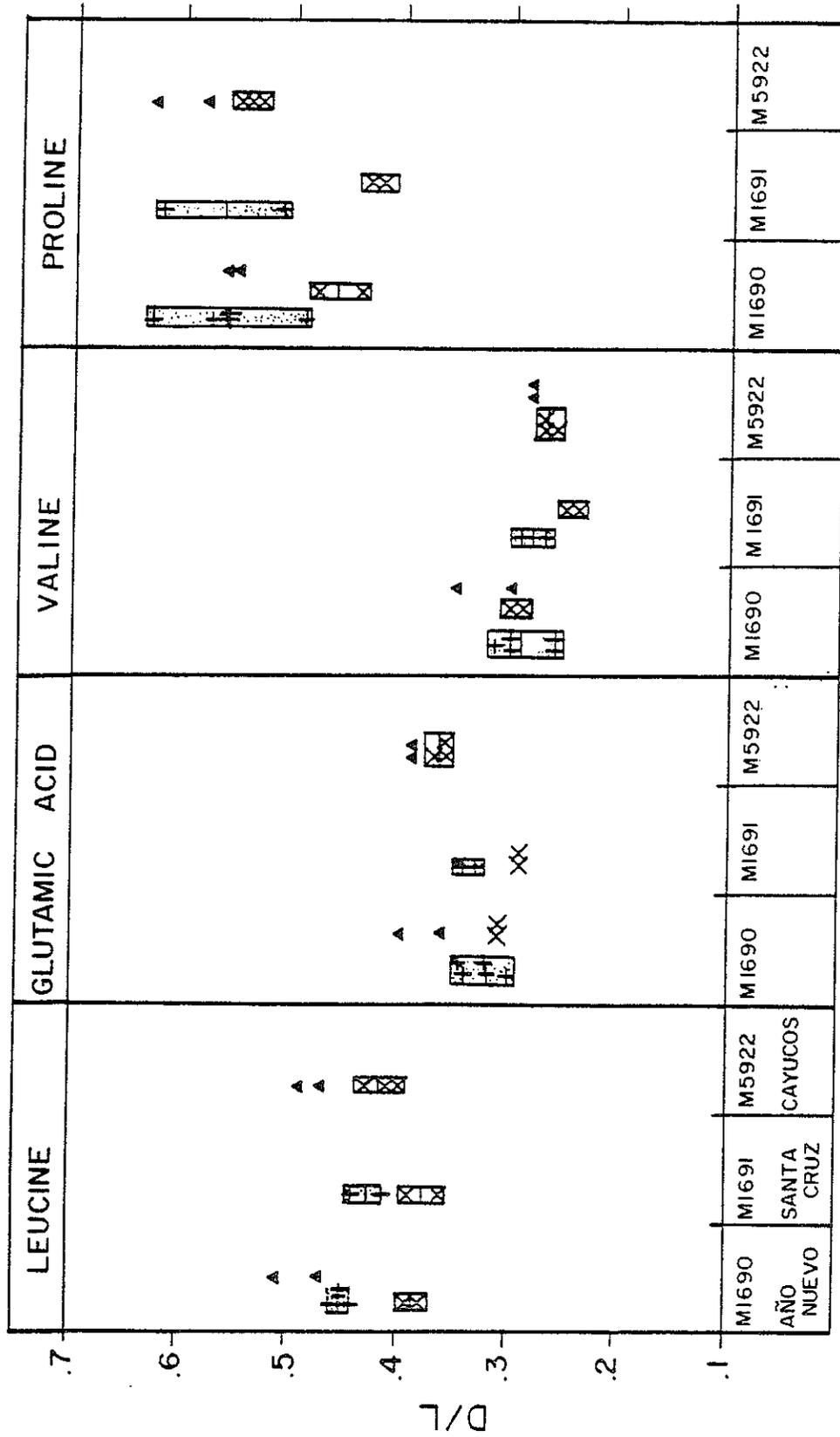


Figure 9: Leucine, glutamic acid, valine and proline enantiomeric ratios in central region samples.
See Figure 4 for identification of symbols used for different genera.

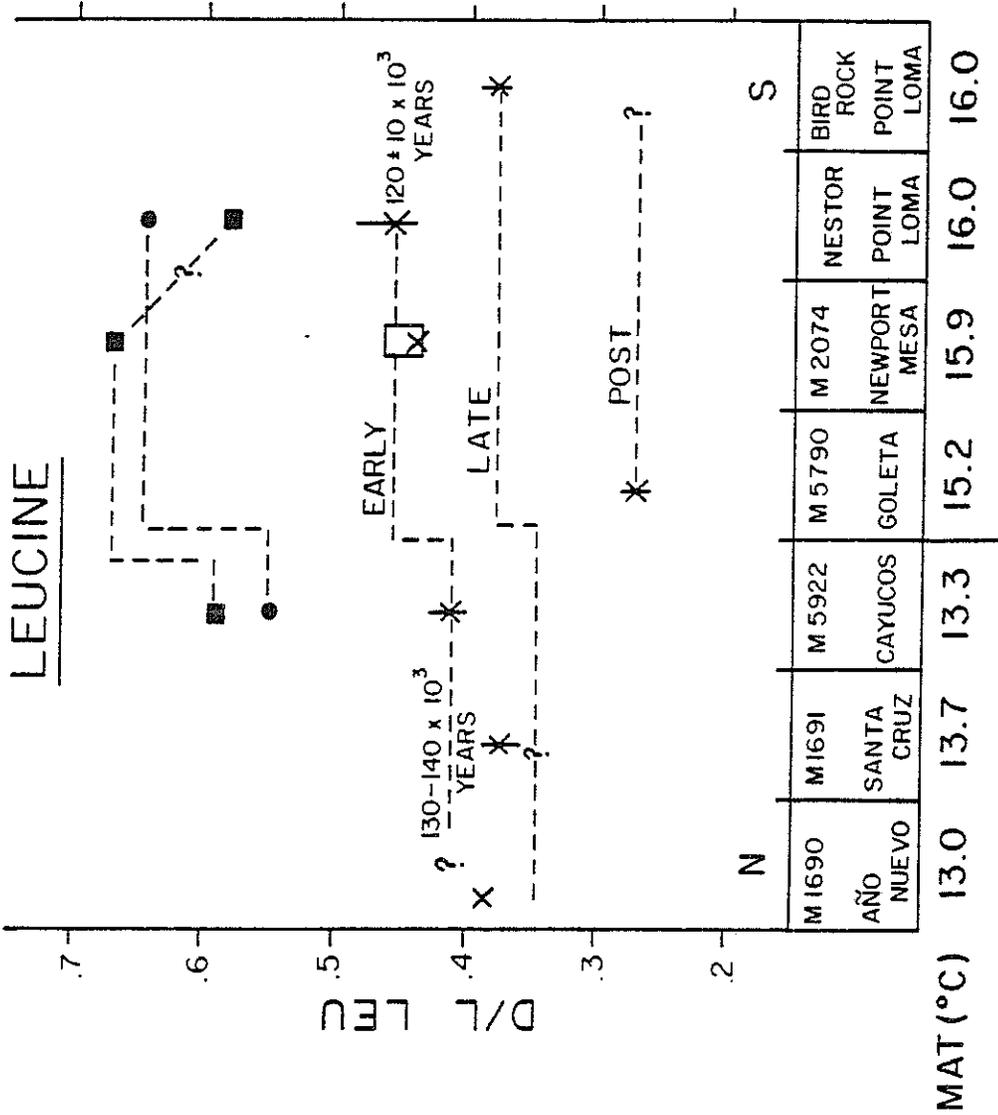


Figure 10: Comparison of leucine enantiomeric ratios from the central and southern temperature regions. The 130-140 x 10³ year age is a uranium series date on corals from Cayucos (Veeh and Valentine, 1967) and the 120 ± 10 x 10³ year age is a uranium series age on corals from the Nestor terrace at Point Loma (Ku and Kern, 1974). Early, late and post refer to marine isotope stage 5 of Shackleton and Opdyke, 1973. MAT is the present mean annual air temperature (°C) for each locality listed from north to south across the horizontal axis. See Figure 4 for genera represented by different symbols. MAT is present mean annual air temperatures.

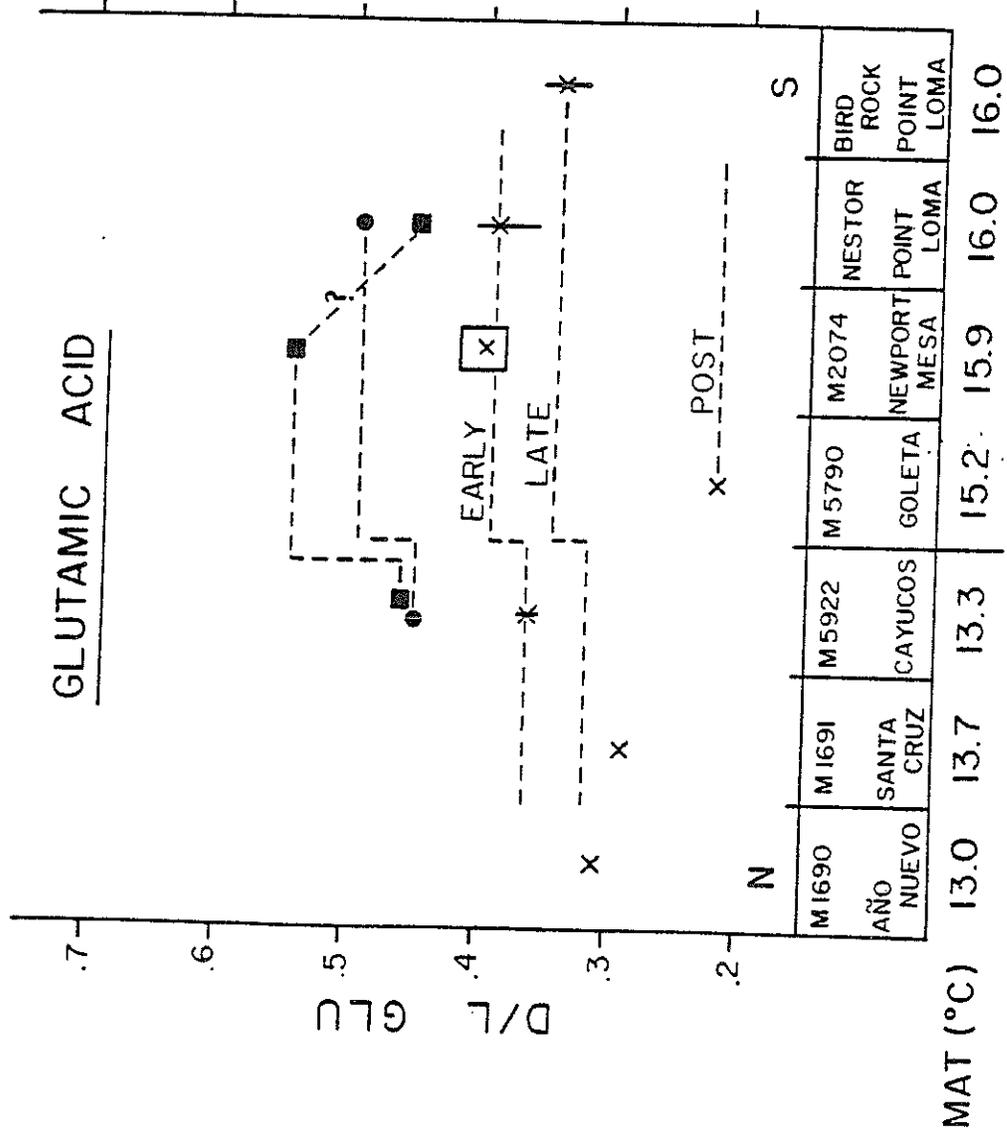


Figure 11: Comparison of glutamic acid enantiomeric ratios from central and southern temperature regions. See Figure 10 for age control of horizontal lines. Early, late, and post refer to marine isotope stage 5 of Shackleton and Opdyke, 1973. See Figure 4 for general represented by different symbols. MAT is present mean annual air temperature.

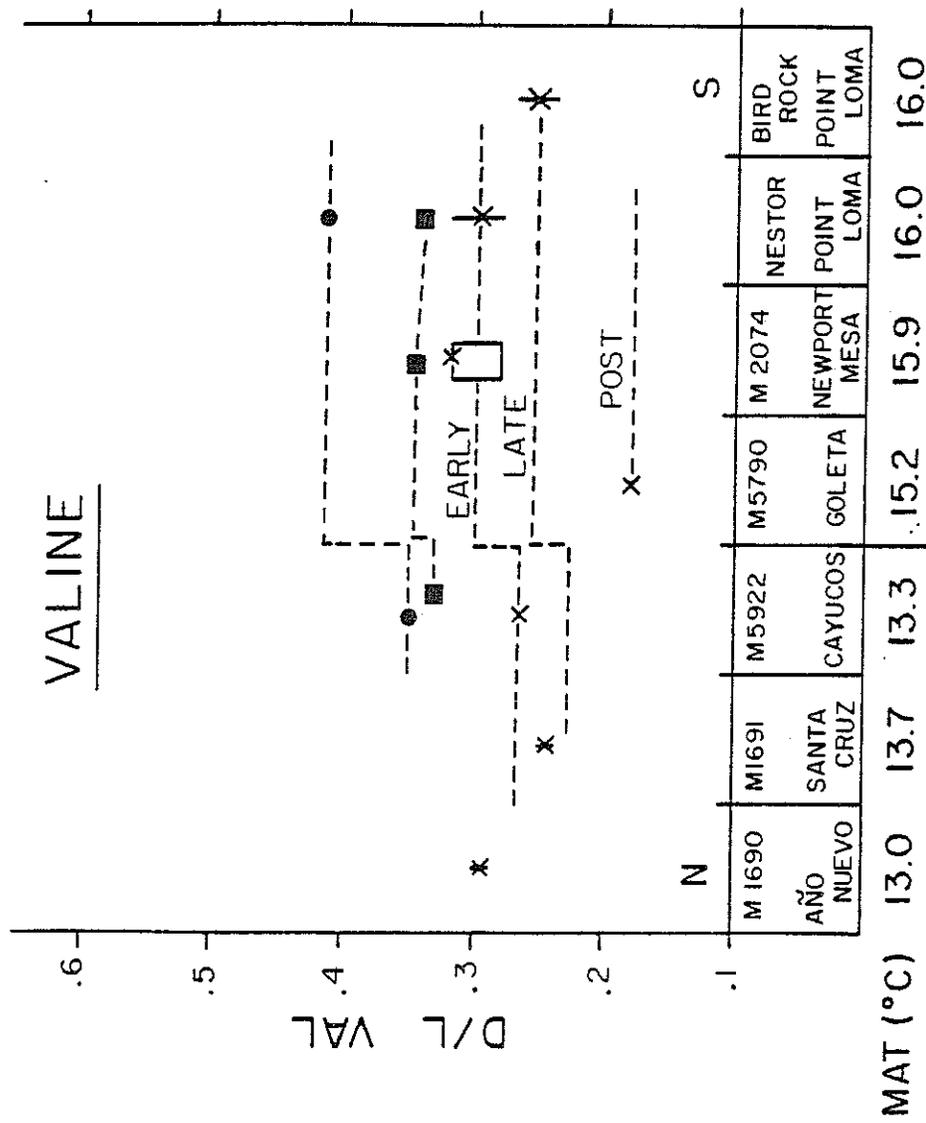


Figure 12: Comparison of valine enantiomeric ratios from the central and southern temperature regions. See Figure 10 for age control of horizontal lines. Early, late and post refer to marine isotope stage 5 of Shackleton and Opdyke, 1973. See Figure 4 for genera represented by different symbols. MAT is mean annual air temperature.

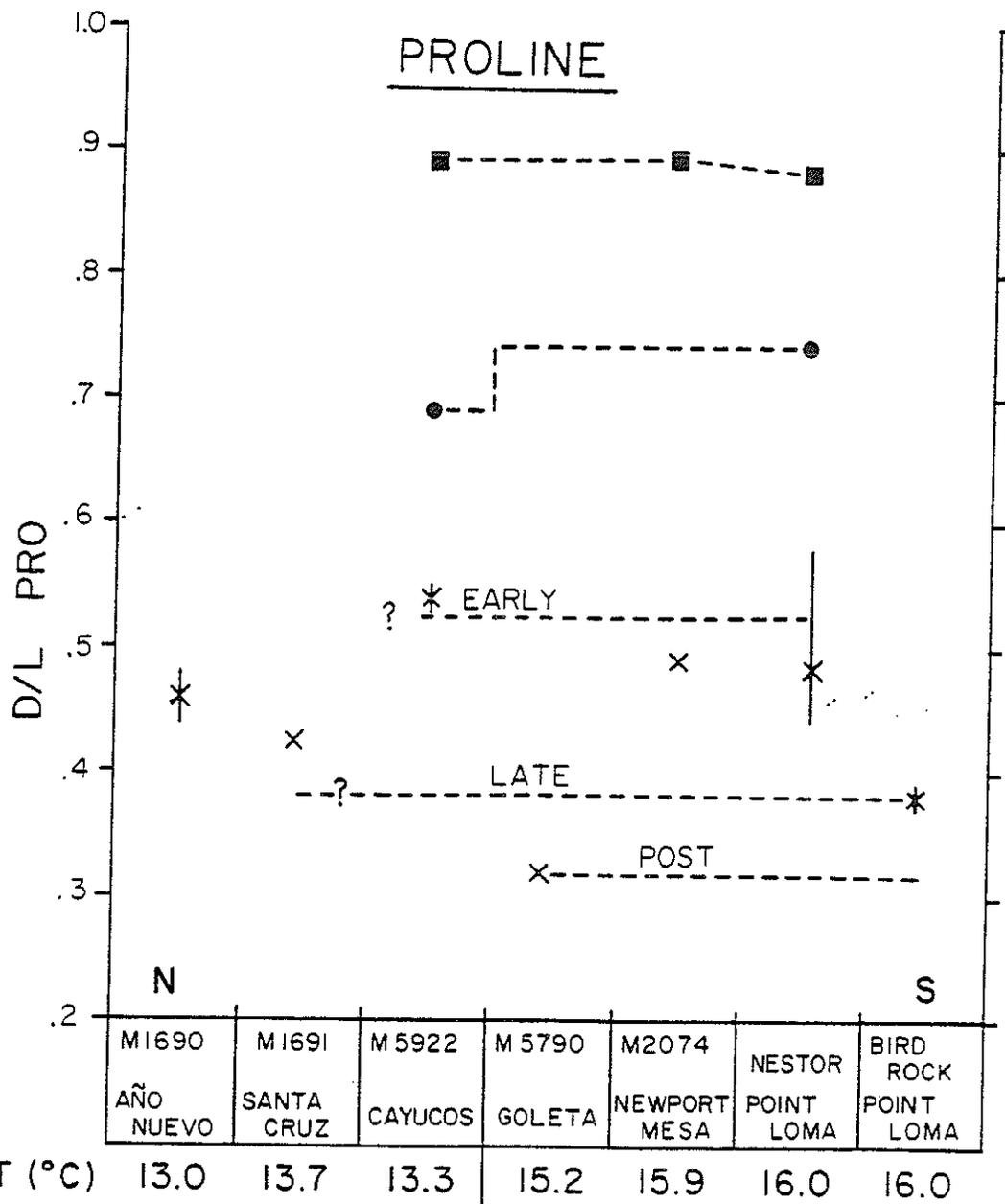


Figure 13: Comparison of proline enantiomeric ratios from the central and southern temperature regions. See Figure 10 for age control on horizontal lines. Early, late and post refer to marine isotope stage 5 of Shackleton and Opdyke, 1973. See Figure 4 for genera represented by different symbols. MAT is present mean annual air temperature.

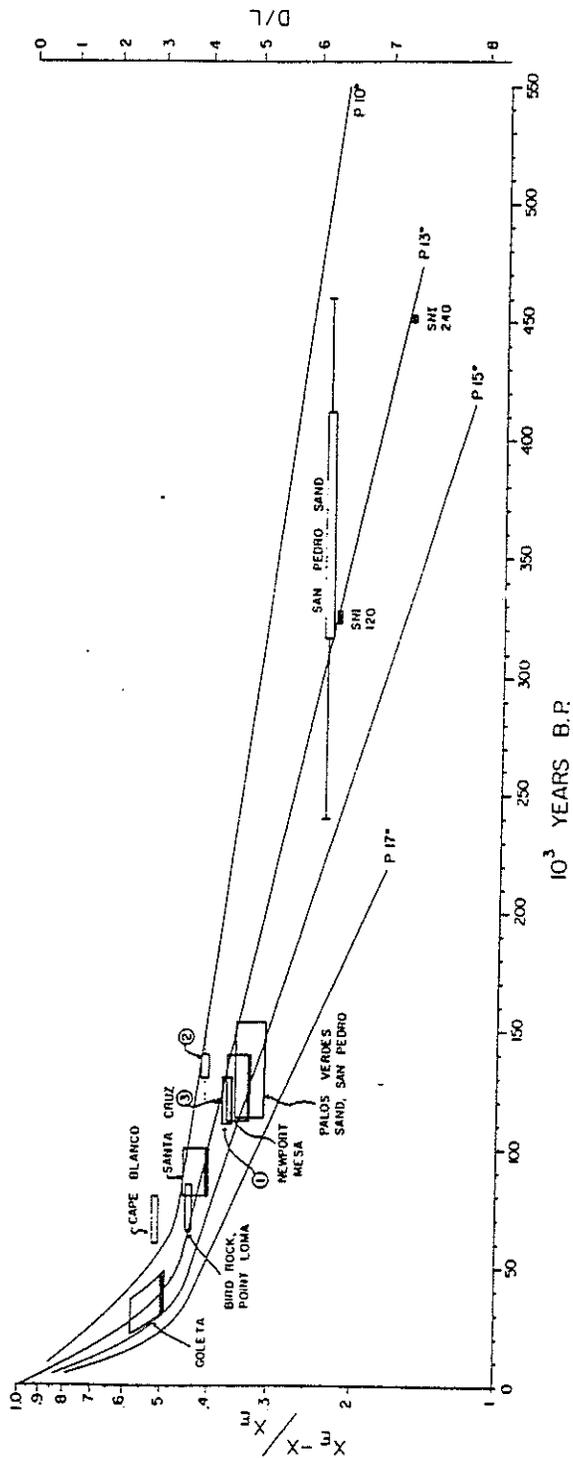


Figure 14:

Leucine kinetic model curves, calculated from data in Table 9. Curves derived for Protothaca only: temperatures are so indicated (P 10⁰, P 15⁰, etc.). The shaded bars that form the lower limit of each data range represent the mean values of the leucine enantiomeric ratios for Saxidomus. The upper limit of each data range represents the mean values of the leucine enantiomeric ratios for Protothaca. Saxidomus results from Cape Blanco and the San Pedro Sand are omitted only for clarity. Calibration localities used in this kinetic model are as follows:

- 1) Nestor Terrace, Point Loma, California, 120,000 ± 10,000 years (Ku and Kem, 1974)
- 2) Cayucos, California, 130,000 - 140,000 ± 30,000 years (Veeh and Valentine, 1967).
- 3) 30-meter terrace, San Nicolas Island, California, 120,000 ± 20,000 years (Valentine and Veeh, 1969).

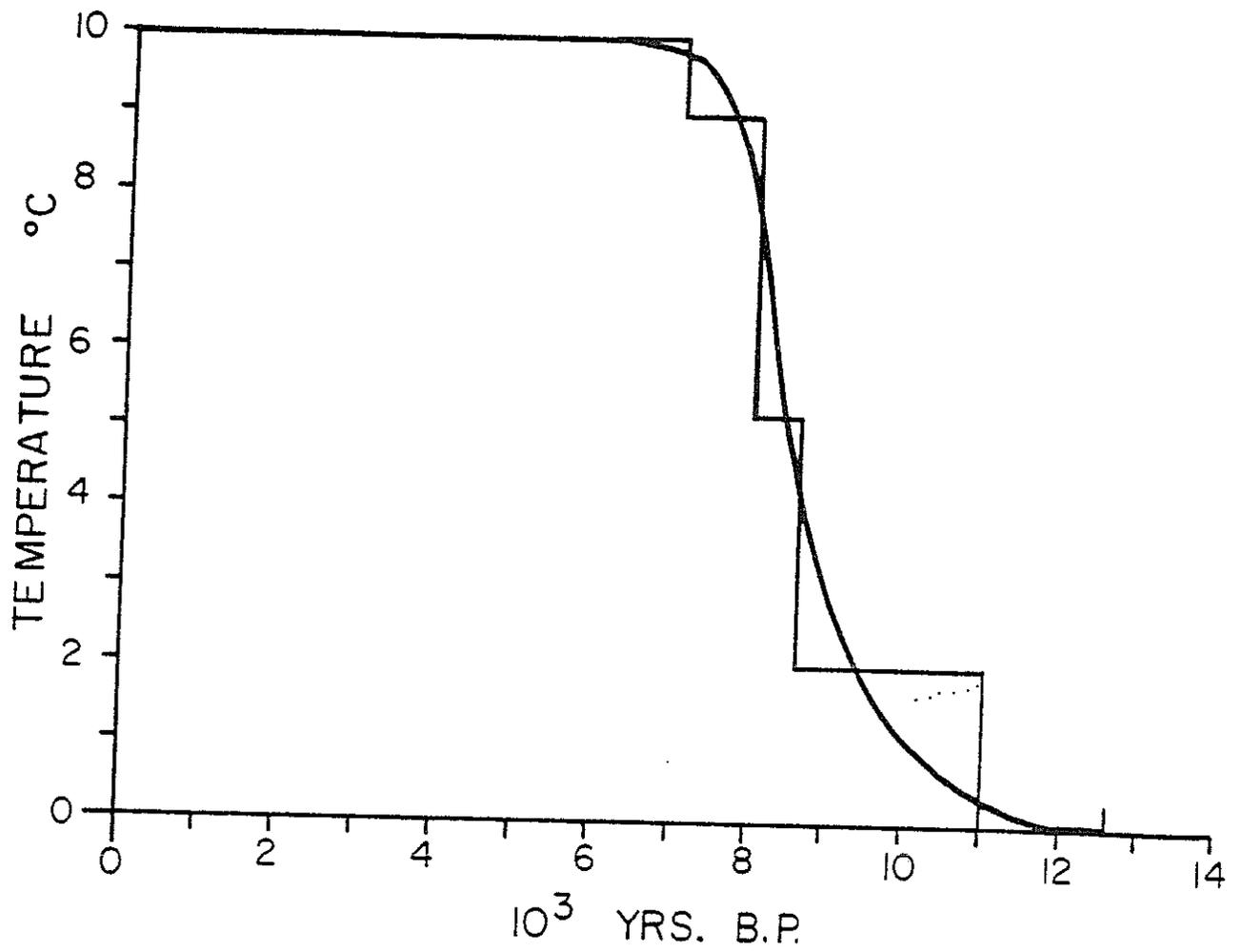


Figure 15: Possible temperature history for Orcas Island samples, as inferred from data summarized in Table 8.

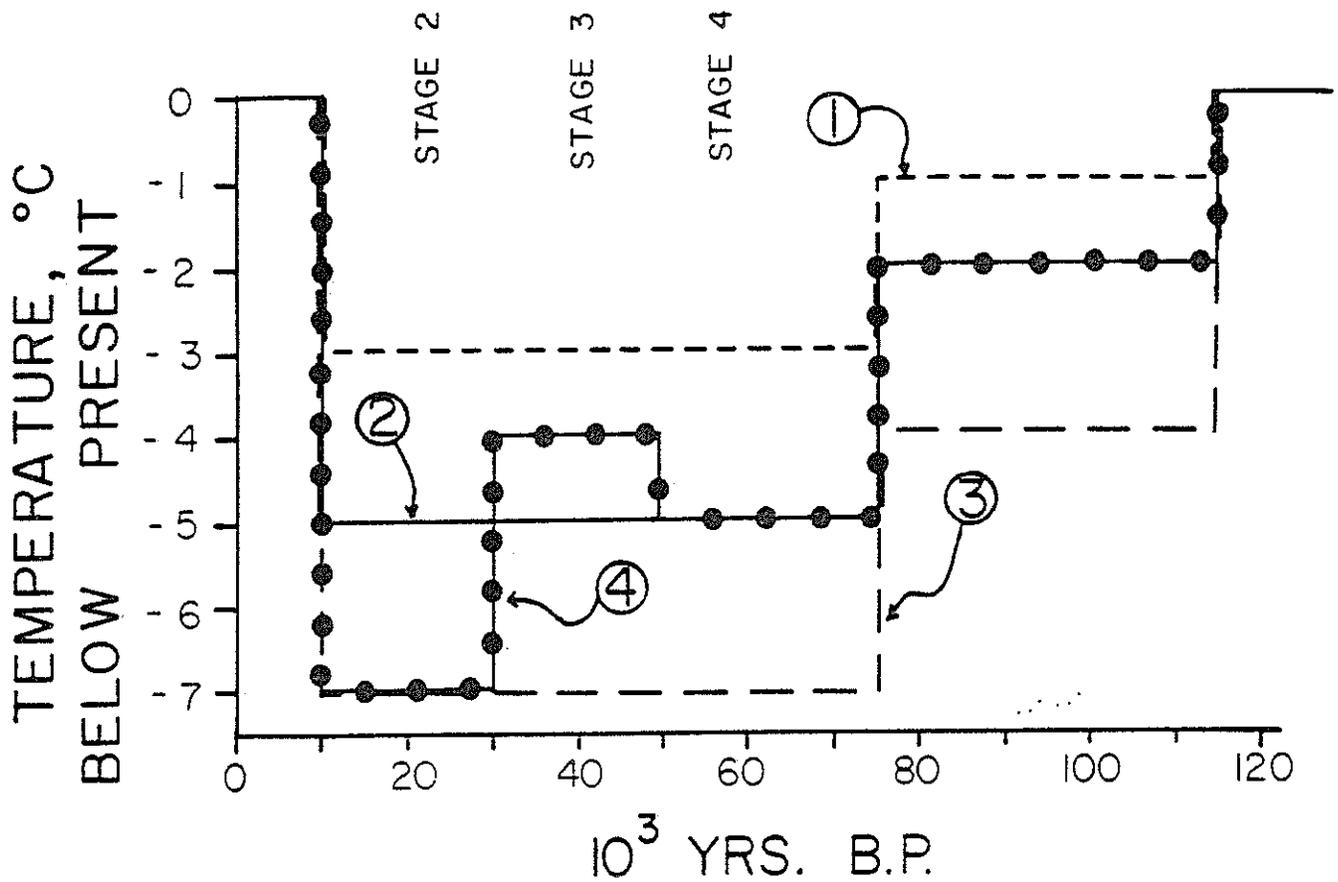


Figure 16: Temperature models for the estimation of effective diagenetic histories of late Pleistocene samples. See Table 11. Stages 2,3, and 4 refer to marine isotope stages of Shackleton and Opdyke, 1973.

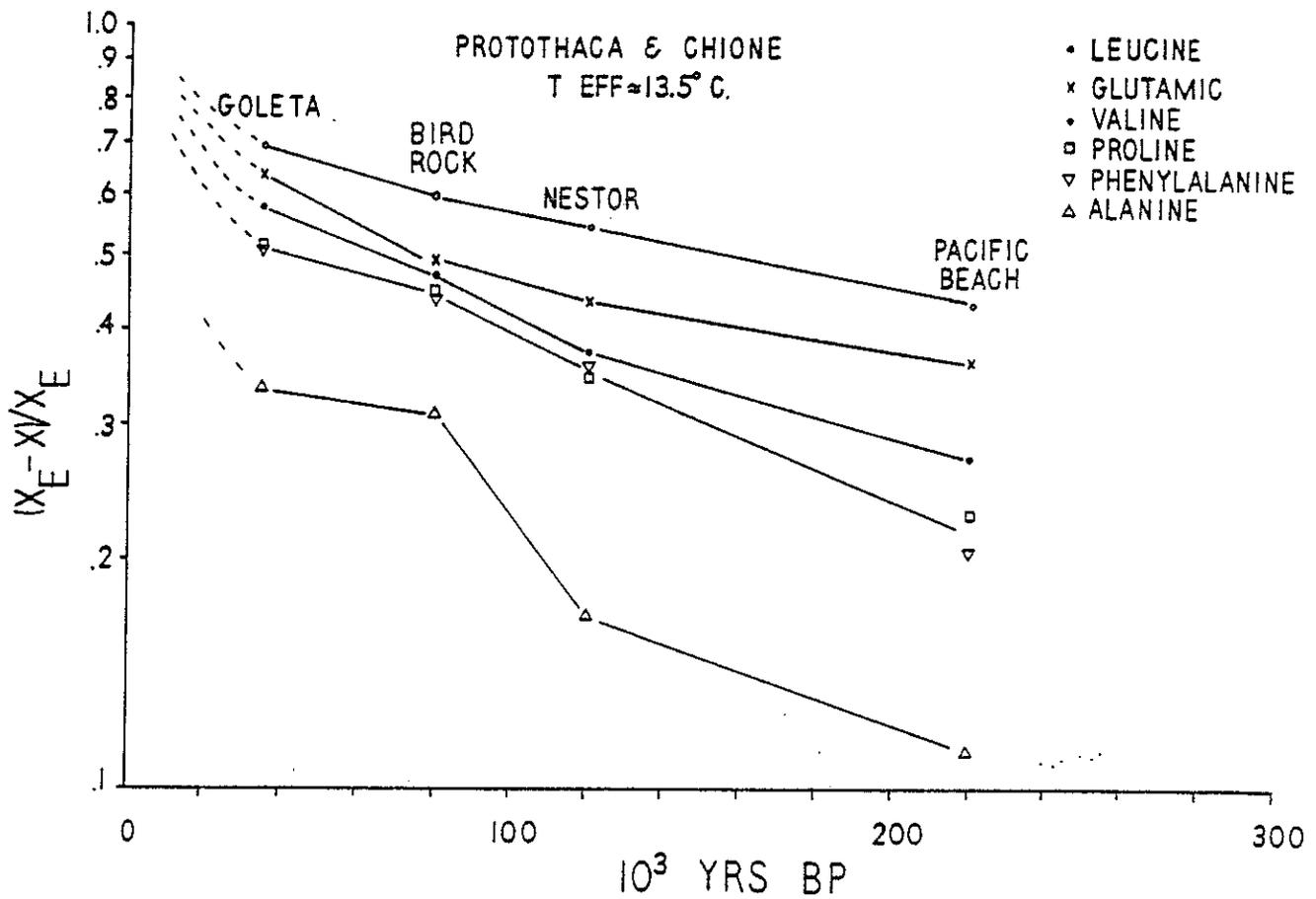


Figure 17: Proposed kinetic models for glutamic acid, valine, alanine, proline, and phenylalanine racemization in *Protothaca* and *Chione*. Ages assigned are those derived from leucine kinetic model; only samples from Goleta, Pacific Beach, and Point Loma (Nestor and Bird Rock terraces) are considered.

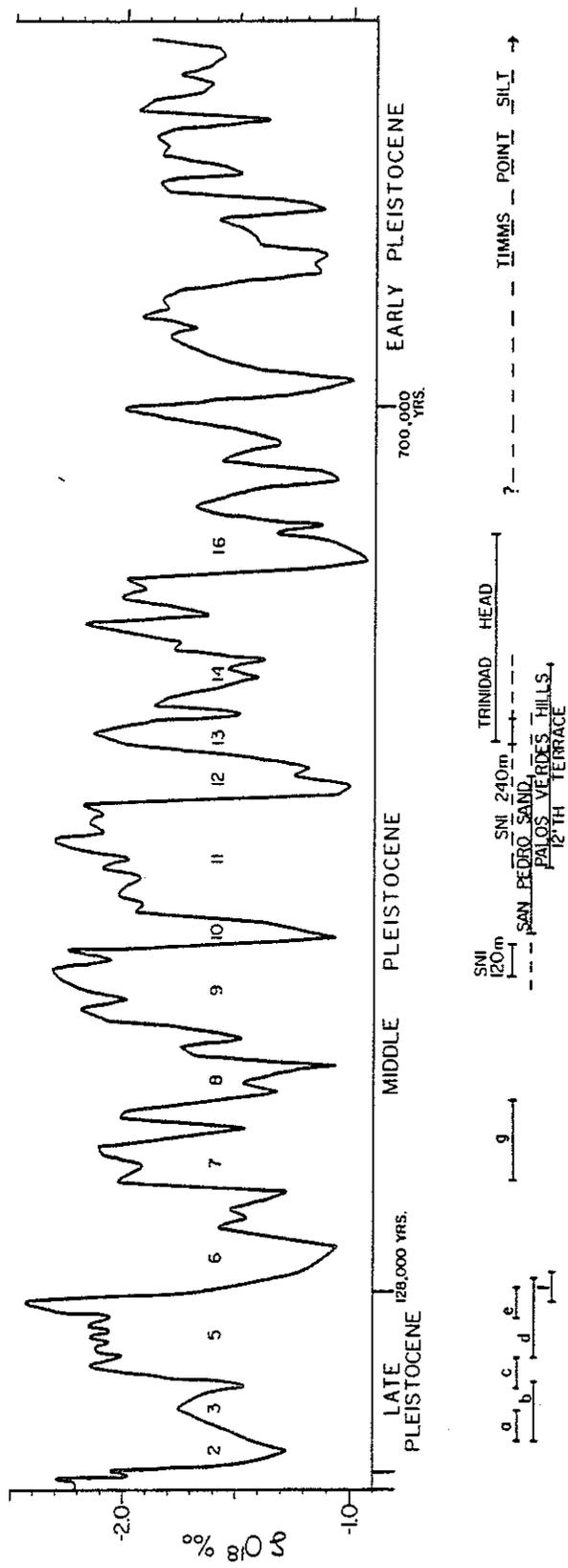


Figure 18: Kinetic model age assignments for localities discussed in this work compared with the marine isotopic record of Shackleton and Opdyke (1973) and Butzer's (1974) nomenclature for the chronologic division of the Pleistocene

Abbreviations:

- a) Goleta
- b) Cape Balno
- c) Bird Rock Terrace, Point Loma and Santa Cruz
- d) Point Ano Nuevo
- e) Nestor Terrace, Point Loma
- f) Palos Verdes Sand (San Pedro)
- Newport Mesa and First Terrace at Newport Beach and Laguna Beach (Cayucos also probably in this time span)
- g) Pacific Beach, Laguna Beach samples, LACM-66-2 (Newport Beach) samples
- SNI San Nicolas Island

APPENDIX
DESCRIPTION OF FOSSIL
LOCALITIES

LOCALITY* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTED BY	OTHER INFORMATION ON LOCALITY
LACH 5009	Orcas Island Puget Sound, Washington	40	Orcas Island 15' Quad. (1957). NE 1/4 NE 1/4 SE 1/4 sec. 22, T. 37N., R. 2 W., WBM. In drain- age channel below farm pond, east side of Orcas-Easy Sound road, near East Sound. (town). Everson Glaciomarine Drift (Easterbrook, 1969)	G. L. Kennedy in 1975	Near Locality W-1215 of Easterbrook, 1969
LACH 5012	Bainbridge Island, Puget Sound, Washington	66	Bremerton East 7.5' Quad. (1953). 340m W. and 1120 M N. of Lat. 47°35'N., Long. 122°30'W. In marine deposit on south side Blakely Harbor	G. L. Kennedy in 1975	500m E. of M6543 dated at 3260±80 14C years (H. Gower, written communication, 1976)
M1450 LAUM 2641	Cape Blanco, Oregon	60	Cape Blanco 15' Quad. (1954). South east side Cape Blanco. SE 1/4 NE 1/4 of Projected section 2 T. 32 S., R. 16 W, W.B.M. In Natural Amphitheater, South of Access Road to Cape Blanco Lighthouse. At base of Marine deposits on pioneer terrace (Janda, 1971).	LACH-2641 by G. L. Kennedy and G. G. Sphon in 1972; M1450 by R. Janda and K. R. Lajoie in 1969	Fauna listed by Addicott, 1964
LACH 3948	Cape Blanco, Oregon	60	Cape Blanco 15' Quad. (1954). 9/m S. of NW corner Sec. 1 T. 32S., R. 16 W. W.B.M. on N.E. side of Cape Blanco along S. flank of Gulley trending NW toward NW corner of sec. 1. At base of Marine deposits on pioneer terrace (Janda, 1971)	G. L. Kennedy in 1973	Fauna listed by Addicott, 1964, locality M1451

LOCALITY* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTED BY	OTHER INFORMATION ON LOCALITY
LACH 3939	Trinidad Head, California	2	Trinidad 7.5' Quad (1966). 854m W. and 198m S. of SE corner SEC. 23, T. 8 N., R. 1 W., H.B.M. At Head of small cover between Trinidad Head and Little Head.	G. L. Kennedy, in 1973	Locality not Pre- viously described; mapped as Upper Pliocene marine by Strand, 1964
M1690	Point, Año Nuevo, California	10	Año Nuevo 7.5' Quad. (1955). 1,525m N56°W of Tower on Año Nuevo Island. Near top of sea cliff on south side of Point Año Nuevo at base of Marine Terrace deposit.	W. O. Addicott in 1962. J.F. Wehmiller and K. R. Lajjole in 1974	Locality H56-32 (M5925) Hoskins, 1957 Fauna described by Addicott, 1966
M1691	Santa Cruz, California	7	Santa Cruz 7.5' Quad (1954). In sea cliff on small point 760m S. and 990 m E. of Lat. 36°57'30"N., Long. 122°02'30"W. At base of Marine deposit most likely in Davenport terrace (Bradley and Griggs, 1975).	W. O. Addicott in 1962	Locality H56-31 (M5924) of Hoskins, 1957 Fauna described by Addicott, 1966
M5922	Cayucos, California	6	Cayucos 15' Quad. (1943). 3,415m N. of Lat. 35°25'00"N., Long. 120°55'00"W. In sea cuff at base of Marine Terrace Deposit.	C. W. Hoskins in 1956. J. W. Valentine, Mid-1950's J. F. Wehmiller and D. F. Beklnap in 1975	Locality H56-29 (M5922) of Hoskins, 1957. Fauna by Valentine, 1958.

LOCALITY* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
M5790	Goleta, California	3-6	Goleta and Dos Pueblos 7.5' Quads. (1950 and 1951). 610 m E. and 153m W. of Long. 119°52'30" along south-facing sea cliff at base of Marine Terrace Deposit.	R. W. Wright in 1970	Fauna listed Wright, 1972
M5908	San Pedro, California	5	Torrance 7.5' Quad. (1951). 1,400 m N. and 1,145 m E. of Lat. 33°45'00" N., Long. 118°17'30" W. Palos Verdes Sand (Woodring and others, 1946). Locality No Longer exists.	C. W. Hoskins in 1956.	Locality 121 (PLT. 1) Woodring and others, 1946. H56-15 (M5908) of Hoskins, 1957.
LACH 1210	San Pedro, California	~25	Torrance 7.5' Quad. (1964). 335m E. and 1,495 m N. of Lat. 33°45'00' N., Long. 118°17'30" W. In road cut on south side of Union Oil Co. refinery. Palos Verdes Sand (Woodring and others 1946).	E. C. Wilson, and others, in 1969	Locality 96 of Kennedy, 1975
LACH 332	San Pedro, California	6	Torrance 7.5' Quad. (1964). 120 m W. and 305 m N. of Lat. 33°45'00" N., Long. 118°17'30" W. San Pedro Sand (Woodring and Others, 1946). Site now covered by Freeway.	R. D. Reimer, in 1963	Locality 86 of Kennedy, 1975
LACH 130-7	San Pedro, California	~10	San Pedro 7.5' Quad (1964). 2,590m W. and 2,090 m S. of NE. corner of Map. In NE. Facing embankment of Timms Point. Type locality of Timms Point silt (Clark, 1931	G. P. Kanakoff, and others, in 1947	33d? Locality 32a-3d of Woodring and others, 1946 (PLT. 14). Loc. 60 of Kennedy, 1975

LOCALITY* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
M5790	Goleta, California	3-6	Goleta and Dos Pueblos 7.5' Quads. (1950 and 1951). 610 m E. and 153m W. of Long. 119°52'30" along south-facing sea cliff at base of Marine Terrace Deposit.	R. W. Wright in 1970	Fauna listed Wright, 1972
M5908	San Pedro, California	5	Torrance 7.5' Quad. (1951). 1,400 m N. and 1,145 m E. of Lat. 33°45'00" N., Long. 118°17'30" W. Palos Verdes Sand (Woodring and others, 1946). Locality No Longer exists.	C. W. Hoskins in 1956.	Locality 121 (PLT. D) Woodring and others, 1946. H56-15 (M5908) of Hoskins, 1957.
LACM 1210	San Pedro, California	~25	Torrance 7.5' Quad. (1964). 335m E. and 1,495 m N. of Lat. 33°45'00" N., Long. 118°17'30" W. In road cut on south side of Union Oil Co. refinery. Palos Verdes Sand (Woodring and others 1946).	E. C. Wilson, and others, in 1969	Locality 96 of Kennedy, 1975
LACM 332	San Pedro, California	6	Torrance 7.5' Quad. (1964). 120 m W. and 305 m N. of Lat. 33°45'00" N., Long. 118°17'30" W. San Pedro Sand (Woodring and Others, 1946). Site now covered by freeway.	R. D. Redmer, in 1963	Locality 86 of Kennedy, 1975
LACM 130-7	San Pedro, California	~10	San Pedro 7.5' Quad (1964). 2,590m W. and 2,090 m S. of NE. corner of Map. In NE. Facing embankment of Timms Point. Type locality of Timms Point silt (Clark, 1931	G. P. Kanakoff, and others, in 1947	33d7 Locality 32a-3d of Woodring and others, 1946 (PLT. 14). Loc. 60 of Kennedy, 1975

LOCALITY* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
M6720	Palos Verdes Hills, California	75	Redondo Beach 7.5' Quad. (1963). 1330m N. and 1785m W of LAT. 33°44'00" N., LONG. 118° 22'30"W. In Low road cut on N. side Palos Verdes Drive South across from BM 235. Terrace & (Woodring and Others, 1946).	J. F. Wehmiller, G. L. Kennedy and K. R. Lajoie in 1976.	Locality not previously described.
LDGO 830E	Palos Verdes Hills, California	80	Redondo Beach 7.5' Quad. (1963). 1,160 m W and 825m S of LAT. 33°45'00"N., LONG. 118°25'00" W. In road cut on north side of Palos Verdes Drive South between Point Vicente and Marineland. Terrace 4 (Woodring and Others, 1946).	W. S. Broecker in 1964	Locality 84 (PLT. 22) of Woodring and Others, 1946
LDGO 874A	Palos Verdes Hills California.	105	San Pedro 7.5' Quad (1964). within 50m Radius of Point 2580m E. and 1555m S of LAT. 33°45'N. LONG. 118°22'30" W. In road cut at end of Dauntless Dr. near intersection with Conqueror Dr. Terrace 5 (Woodring and others, 1946).	W.S. Broecker in 1964	Locality mapped by G. Cleveland, California Division of Mines and Geology (W.S. Broecker, written communicat- ion, 1975)
LDGO 8070	Palos Verdes Hills, California	370	San Pedro 7.5' QUAD (1964). 105m E. and 855m S of LAT. 33°45' N., LONG. 118°20'W. In road cut on north side of Crest Drive. Terrace 12 (Woodring and Others, 1946).	W. S. Broecker in 1964	Locality 75 (PLT. 22) of Woodring and Others, 1946

LOCALITY* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
LACM 466	Los Angeles, California	70-80	Hollywood 7.5' Quad. (1966) 810m and 460m W of 118°15'00" W., 34°02'30"N. ± 200' NW-SE. Building excavation for Crocker National Bank Plaza, south side of Sixth Street between Hope St. and Grand Ave., downtown Los Angeles. Pliocene, Fernando Fm. site no longer exposed.	G. P. Kanakoff in 1966	Locality not previously described.
LACM 1219	Los Angeles, California	~73	Hollywood 7.5' Quad. (1966). within 50m radius of Point 460m W. and 1160m N. of LAT. 34°2'30"N., LONG. 118°15' W. In southern corner of Atlantic-Richfield Plaza excavation immediately N. of intersection of Sixth and Flower Streets, downtown Los Angeles. Deposit 18m below street level. Pliocene Fernando FM. Site no longer exposed.	P. I. LaFollette and others in 1969-1970	Locality described by Natland, 1971
M5902	Huntington Beach, California	1	Seal Beach 7.5' Quad. (1965). 1145m S. and 990m W. of LAT. 33°42'30"N., LONG. 118°W. Locality in Old Quarry now converted to Park, Fossil Bed exposed along shore of pond. San Pedro sand exposed in bottom of Quarry. (Poland, Piper and others, 1956).	C. W. Hoskins in 1956	Locality H56-9 (H5902) of Hoskins, 1957. Localities UCLA-3655, 3656, and 3657 of Valentine, 1959. Locality 14 (FIG.6) of Valentine, 1961.

LOCALITY* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
M1722	Newport Beach, California	17	Tustin 7.5' Quad. (1965). About 1985m N. and 200m E. of lat. 33°37'30" N., long. 117°52'30" W. Exposures in Gully system Draining Northward into salt ponds in Upper Newport Bay. Site no longer exposed; gulleys filled for subdivision. Terrace 1 (Vedder and Others, 1975). Palos Verdes Sand (Poland, Piper and Others, 1956).	M. Rogers	Locality F595 (M1077) of Vedder and Others, 1957
LACH 66-2	Newport Beach, California	[65 to 77 feet]	Tustin 7.5' Quad. (1965). LAT 33°38'37" N., Long. 117°52'37"W. Exposure in erosion channel draining northward toward salt ponds in Upper Newport Bay. Site no longer exposed. Palos Verdes Sand (Ksmakoff and Emerson, 1959)	G. P. Kanakoff, and others 1940's and 1950's.	
M5898	Newport Beach, California	20	Tustin 7.5' Quad. (1965). 2365m N. and 765m E. on SW Corner of Map. On same Terrace But 610m NE of locality M1722. Terrace 1 (Vedder and Others, 1975). Palos Verdes Sand (Poland, Piper and Others, 1956).	C. W. Hoskins in 1956	Locality H56-5 (H5898) of Hoskins, 1957
M1476	Newport Beach, California	35	Tustin 7.5' Quad. (1965). 550m NW and 305m NE of South Corner of Irvine Block 57. In road cut E. side McArthur Blvd. Terrace 2 (Seabo and Vedder, 1971). Site destroyed by Road Excavation.	J. G. Vedder in 1958	Locality NB-S-9 of Seabo and Vedder, 1971

LOCATION * NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
M3759	Newport Beach, California	90	Laguna Beach 7.5' Quad. (1965) 680m SW. and 280m SE. on N. Corner of Irvine Block 96. In new (1966) Roadcut on Terrace 3 (Seabo and Vedder, 1971; Vedder and Others, 1973). Locality covered by Subdivision.	J. G. Vedder in 1966.	Locality NB-S-10 of Seabo and Vedder, 1971
M2074	Newport Beach, California	25	Newport Beach 7.5' Quad (1965). 1040 m NW and 31 m NE of S. Corner of Irvine Block 52. In excavation for Housing Subdivision on W. side of Upper Newport Bay-Palos Verdes Sand (Poland, Piper and Others, 1956). Terrace 1 (Vedder and others, 1975). Locality covered by subdivision.	J. G. Vedder in 1972	Locality F599 (M2074) of Vedder and Others, 1975.
M1477	Newport Beach, California	6	Newport Beach 7.5' Quad. (1965) 345m W. and 400m S. of NE. corner Sec. 29, T. 6 S., R. 10 W. In SW facing sea cliff on N. side of Highway 101 ALT. Palos Verdes Sand (Poland and Piper, 1956).	J. G. Vedder in 1958	Locality NB-S-3 of Seabo and Vedder 1971. Locality F604-lower (M1477) of Vedder and others, 1975
M1479	Newport Beach, California	8	Newport Beach 7.5' Quad. (1951). 640m N. and 990m W. of NE corner of Sec. 29, T. 6 S., R. 10 W.	J. G. Vedder in 1956	Locality NB-S-6 of Seabo and Vedder, 1971. Locality F601 (M1479) of Vedder and Others, 1975.

LOCATION * NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
M1481	Corona Del Mar, California	27	Laguna Beach 7.5' Quad. (1965) 580m NW. and 405m SW. of South Corner of Irvine Block 96. In Foundation Trench for apartment house on N. side Pacific Coast Highway (1) Terrace 1 (Vedder and Others, 1975). No longer exposed.	J. G. Vedder and G. E. Vedder in 1959	Locality F585A (M1481) of Vedder and Others, 1975
M1482	Corona Del Mar, California	21	Laguna Beach 7.5' Quad. (1965). 1525m S. and 120m W. of LAT. 33°35'N., LONG. 117°50'W In SW. Facing Sea Cliff between Crystal Cove and Reef Point. Terrace 1 (Vedder and Others, 1957 and 1975).	J. G. Vedder in 1959	Locality F585 (M1482) of Vedder and Others, 1957 and 1975.
M1018	Laguna Beach, California	24	Laguna Beach 7.5' Quad. (1965). 1,295m N. and 1,540m W. of LAT. 33°32'30", LONG. 117°47'30" W. In road cut N. side Pacific Coast Highway (1) Now covered by slope Wash. Terrace 1 (Vedder and others, 1957 and 1975).	J. G. Vedder in 1953 and 1957	Locality F586 (M1018) of Vedder and Others 1957, and 1975.
M1019	Laguna Beach, California	21	Laguna Beach 7.5' Quad. (1965) 685m N. and 825, W. of LAT. 33°32'30", LONG. 117°47'30". Terrace 1 (Vedder and Others, 1957 and 1975).	J. G. Vedder	Locality F587 (M1019) of Vedder and Others, 1957 and 1975.
LACH 2662	Torrey Pines, California	15	Del Mar 7.5' Quad. (1967). 31m S. and 715m W. of LAT. 32°55' N. LONG. 117°15'W. In Sea Cliff of Torrey Pines State Park.	G. L. Kennedy in 1965	Fauna described by Valentine, 1960

LOCATION * NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
SDSU 1854	Pacific Beach, California	12	La Jolla 7.5' Quad. (1967). 1295m N. and 900m W. of LAT. 32°47'30" N., LONG. 117°15'00" W. In Sea Cliff at S. end Pacific View Drive. Nestor Terrace (Ku and Kern, 1974)	J. P. Kern; J. W. Kennedy, G. L. Kennedy, J. P. Kern, and K. R. Lajoie, 1976	Approx. locality of Bishop and Bishop, 1972
SDSU 2577	Point Loma, California	18	Point Loma 7.5' Quad. (1967). 230m N. and 70m W. of LAT. 32°40'00"N., LONG. 117°15'00"W. In Sea Cliff W. side Point Loma. Nestor Terrace (Ku and Kern, 1974).	J. P. Kern	Locality described and dated by Ku and Kern, 1974
SDSU 2520	Point Loma, California	~20	Point Loma 7.5' Quad. (1967). 1,265m N. and 1,200m E. of LAT. 32°40'00", LONG. 117°15'00" W. In sea Clipp on East Side Point Loma. Nestor Terrace (Kern, 1973).	J. P. Kern	Locality not previously described
M6706 SDSU-2521	Point Loma, California	17	Point Loma 7.5' Quad. (1967). 685m N. and 1,250m W. of LAT. 32°40'00", LONG. 117°15'00" W. In Sea Cliff east side Point Loma. Nestor Terrace (Kern, 1973).	K. R. Lajoie in 1969. J. P. Kern	Locality not previously described
M6703	Point Loma, California	17	Point Loma 7.5' Quad. (1967). 1,390m S. and 260m W. of LAT. 32°42'30" N., LONG. 117°15'00" W. In Sea Cliff west side Point Loma. Nestor Terrace (Ku and Kern, 1974).	K. R. Lajoie, in 1969	Locality not pre- viously described

LOCATION * NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
M6704	Point Loma, California	20	Point Loma 7.5' Quad. (1967). 1360m N. and 290m E. of LAT. 32°40'00"N., LONG. 117°15'00"W. In Sea Cliff West side of Point Loma. Nestor Terrace. (Ku and Kern, 1974).	K. R. Lajoie in 1969	Locality not pre- viously described.
M6702	Point Loma, California	17	Point Loma 7.5' Quad. (1967) 750m S. and 400 m W. of LAT. 32°42'30"N., LONG. 117°15'00"W. In Sea Cliff on West side Point Loma. Nestor Terrace (Ku and Kern, 1974).	K. R. Lajoie in 1969	Locality not pre- viously described.
SDSU 2523	Point Loma, California	6	Point Loma 7.5' Quad. (1967). 145m S. and 855m E. of LAT. 32°40'00" N., LONG. 117°15'00"W. In Sea Cliff of extreme southern tip of Point Loma, about 100m East of Lighthouse. Bird Rock Terrace (Kern, in Press), Formerly names Tia Juana Terrace.	J. P. Kern	Locality discussed by Ku and Kern, 1974
SDSNH 0329	San Diego, California	130-140	La Mesa 7.5' Quad (1967) within 100m RADIUS of Point 450m N. and 275m W. of LAT. 32°50'00" N., LONG. 117° 5'00" W. Ninety-Meter Stretch along west-facing road cut on East side of Santo Road beginning about 35-40m N. of Intersection of Santo Road and El Comal Drive. Linda Vista Terrace (Kennedy, 1973).	G. L. Kennedy in 1975	Locality described by Kennedy, 1973

LOCATION* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
LACH 319	San Diego, California	34	Imperial Beach 7.5' Quad. (1967) within 100m RADIUS of Point 230m N. and 350 m W. of SE corner sec. E., T. 19S., R. 2W. at end of Ridge on North side of the Mouth of Goat Canyon. Pliocene San Diego Formation.	G. P. Kanakoff, and others, in 1959; ? early 1960's	
21653	San Nicolas Island, California	15	San Nicolas Island 7.5' Quad. (1956) 2560 m N. and 1,115 m E. of LAT. 33°14'30" N., LONG. 119°30'30" W. near Army Camp Beach on N. Shore of Island on Terrace 2 (Vedder and Norris, 1964).	J. G. Vedder, S. R. Dabney, and D. J. Milton in 1955	Locality SN-1 of Vedder and Norris, 1963
21664	San Nicolas Island, California	21	San Nicolas Island 7.5' Quad. (1956). 1,525 m N. and 2860 m E. of LAT. 33°14'30" N., LONG. 119°28'00" W. at East end of Island on Terrace 2 (Vedder and Norris, 1963).	J. G. Vedder and N. C. Privratsky in 1956	Locality SN-2 of Vedder and Norris, 1963
21665	San Nicolas Island, California	24	San Nicolas Island 7.5' Quad. (1956). 2645 m S. and 700 m W. of LAT. 33°14'30" N., LONG 119°28'00" W. East of Dutch Harbor on S. Shore of Island. On Terrace 2 (Vedder and Norris, 1963).	J. G. Vedder in 1956	Locality SN-1 of Vedder and Norris, 1963
21662	San Nicolas Island, California	113	San Nicolas Island 7.5' Quad. (1956). 1805 m N. and 1935 m E. of LAT. 33°14'30" N., LONG. 119°30'30" W. on North side of Island on East edge of First deep Canyon East of Celery Creek. On Terrace 5 (Vedder and Norris, 1963).	J. G. Vedder, N. C. Privratsky, and G. P. Frymire in 1956	Locality SN-10 of Vedder and Norris, 1963

LOCATION* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
21663	San Nicolas Island, California	178	San Nicolas Island 7.5' Quad. (1956) 440 m N. and 1750 m E. of LAT. 33°14'30" N., LONG. 119°30'30" W. On Terrace 8 (Vedder and Norris, 1963).	J. G. Vedder and N. C. Privratsky in 1956	Locality SN-11 of Vedder and Norris, 1963
21659	San Nicolas Island, California	200	San Nicolas Island 7.5' Quad. (1956). 870 m S. and 265 m W. of LAT. 33°14'30" N., LONG. 119°28'00" W. East of Hill 818. On Terrace 9 (Vedder and Norris, 1963).	J. G. Vedder in 1955	Locality SN-7 of Vedder and Norris, 1963
21654	San Nicolas Island, California	220	San Nicolas Island 7.5' Quad. (1956) 1245 m S. and 185 m W. of LAT. 33°14'30" N., LONG. 119°28'00" W. East of Hill 818. On Terrace 10 (Vedder and Norris, 1963).	J. G. Vedder in 1955	Locality SN-2 of Vedder and Norris, 1963
21655	San Nicolas Island, California	220	San Nicolas Island 7.5' Quad. (1956) 1005 m S. and 570 m W. of LAT. 33°14'30" N., LONG. 119°28'00" W. East of Hill 818. On Terrace 10 (Vedder and Norris, 1963).	J. G. Vedder in 1955 and 1956	Locality SN-3 of Vedder and Norris, 1963

NOTES FOR APPENDIX I:

*Abbreviations For Locality Numbers:

- M = U.S. Geological Survey (Menlo Park) Cenozoic Locality Number
 21653 - 21665 = U.S. Geological Survey (Washington) Cenozoic Locality Number
 LACM = Los Angeles County Museum of Natural History, Invertebrate Paleontology Locality Number.
 LDCO = Lamont-Doherty Geological, Observatory, Palisades, New York (Wallace S. Broecker locality number).
 SDSU = San Diego State University Locality Number.
 SDSNH = San Diego Society of Natural History Locality Number.

LOCATION# NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
LACH 319	San Diego, California	~34	Imperial Beach 7.5' Quad. (1967) within 100m RADIUS of Point 230m N. and 350 m W. of SE corner sec. E., T. 195., R. 2W. at end of Ridge on North side of the Mouth of Goat Canyon. Pliocene San Diego Formation.	G. P. Kanakoff, and others. In 1959; ? early 1960's	
21653	San Nicolas Island, California	15	San Nicolas Island 7.5' Quad. (1956) 2560 m N. and 1,115 m E. of LAT. 33°14'30" N., LONG. 119°30'30" W. near Army Camp Beach on N. Shore of Island on Terrace 2 (Vedder and Norris, 1964).	J. G. Vedder, S. R. Dabney, and D. J. Milton in 1955	Locality SN-1 of Vedder and Norris, 1963
21664	San Nicolas Island, California	21	San Nicolas Island 7.5' Quad. (1956). 1,525 m N. and 2860 m E. of LAT. 33°14'30" N., LONG. 119°28'00" W. at East end of Island on Terrace 2 (Vedder and Norris, 1963).	J. G. Vedder and N. C. Privratsky in 1956	Locality SN-2 of Vedder and Norris, 1963
21665	San Nicolas Island, California	24	San Nicolas Island 7.5' Quad. (1956). 2645 m S. and 700 m W. of LAT. 33°14'30" N., LONG. 119°28'00" W. East of Dutch Harbor on S. Shore of Island. On Terrace 2 (Vedder and Norris, 1963).	J. G. Vedder in 1956	Locality SN-1 of Vedder and Norris, 1963
21662	San Nicolas Island, California	113	San Nicolas Island 7.5' Quad. (1956). 1805 m N. and 1935 m E. of LAT. 33°14'30" N., LONG. 119°30'30" W. on North side of Island on East edge of First deep Canyon East of Celery Creek. On Terrace 5 (Vedder and Norris, 1963).	J. G. Vedder, N. C. Privratsky, and G. P. Frymyre in 1956	Locality SN-10 of Vedder and Norris, 1963

LOCATION* NUMBER	LOCATION NAME	ELEVATION (METERS)	LOCATION DESCRIPTION	COLLECTION BY	OTHER INFORMATION ON LOCALITY
21663	San Nicolas Island, California	178	San Nicolas Island 7.5' Quad. (1956) 460 m N. and 1750 m E. of LAT. 33°14'30" N., LONG. 119°13'30" W. On Terrace 8 (Vedder and Norris, 1963).	J. G. Vedder and N. C. Privranky in 1956	Locality SH-11 of Vedder and Norris, 1963
21659	San Nicolas Island, California	200	San Nicolas Island 7.5' Quad. (1956). 870 m S. and 265 m W. of LAT. 33°14'30" N., LONG. 119°28'00" W. East of Hill 818. On Terrace 9 (Vedder and Norris, 1963).	J. G. Vedder in 1955	Locality SH-7 of Vedder and Norris, 1963
21654	San Nicolas Island, California	220	San Nicolas Island 7.5' Quad. (1956) 1245 m S. and 185 m W. of LAT. 33°14'30" N., LONG. 119°28'00" W. East of Hill 818. On Terrace 10 (Vedder and Norris, 1963).	J. G. Vedder in 1955	Locality SH-2 of Vedder and Norris, 1963
21655	San Nicolas Island, California	220	San Nicolas Island 7.5' Quad. (1956) 1805 m S. and 570 m W. of LAT. 33°14'30" N., LONG. 119°28'00" W. East of Hill 818. On Terrace 10 (Vedder and Norris, 1963).	J. G. Vedder in 1955 and 1956	Locality SH-3 of Vedder and Norris, 1963

NOTES FOR APPENDIX I:

*Abbreviations For Locality Numbers:

- H - U.S. Geological Survey (Henlo Park) Cenozoic Locality Number
- 21651 - 21665 - U.S. Geological Survey (Washington) Cenozoic Locality Number
- LACH - Los Angeles County Museum of Natural History, Invertebrate Paleontology Locality Number.
- LICH - Lamont-Doherty Geological Observatory, Palisades, New York (Wallace S. Broecker Locality Number).
- SDSU - San Diego State University Locality Number.
- SDSHU - San Diego Society of Natural History Locality Number.