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Title: LATE NEOGENE TECTONICS OF THE MOUTH OF THE GULF OF CALIFORNIA

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Anomaly timescales for the last 90 million years, derived from marine magnetic profiles and published prior to mid-1979, are summarized, illustrated for comparison, and critically reviewed. A revised timescale is constructed using calibration points which fix the ages of anomalies 2.3', 5.5, 24, and 29. An equation is presented for converting K-Ar dates that is consistent with the recent adoption of new decay and abundance constants. The calibration points used in the revised time-scale, named NLC-80, are so converted, as are the boundary ages of geologic epochs within the range of the timescale.

NLC-80 is then used, along with recently acquired and rigorously navigated underway geophysical data from the region of the mouth of the Gulf of California, to prepare detailed bathymetric, gravimetric, and seismo-tectonic maps of the area. The basement ages at DSDP Leg 63 drilling sites 471, 472, and 473 are estimated from magnetic anomalies fit to timescale NLC-80. The estimates agree with biostratigraphically determined basement ages and support the proposal that an aborted ridge of about 14 MY age has left a small fragment of the Farallon Plate beneath the Magdalena Fan. Several large inactive faults are identified on the deep-sea floor west of the tip of the peninsula of Baja California.

Additional magnetic anomaly profiles and bathymetric profiles across the Rivera Ridge are interpreted. These contradict the existence of a

3.5 MY old aborted spreading center on the Maria Magdalena Rise. Instead, it is proposed that an episode of subduction of the Pacific Plate beneath the southeastern tip of Baja California, concomitant with strike-slip faulting west of the peninsula, occurred and that this subduction may be responsible for the uncentered location of the Rivera Ridge within the mouth of the Gulf of California.

A single magnetic anomaly profile obtained northeast of the Tamayo Fracture Zone is used to determine that the rate of Pacific/North American plate motion, for the last 3 MY is 68 km/MY at this location. This result, if correct, indicates that the peninsula of Baja California is separating from mainland Mexico faster than the Rivera Ridge is generating oceanic crust in the wake of opening in the gulf. This, in turn, requires that either slow diffuse extension is occurring presently across the Maria Magdalena Rise, or across the Cabo Corrientes-Colima region, or that the portion of North America south of the trans-Mexican volcanic belt is moving right-slip with respect to the North American Plate at a rate of 10-20 km/MY.

Large horsts and many smaller continental fragments are found within the southern gulf. Several of them have active seismic boundaries, while others have apparently foundered.

The gulf began to open approximately 14-15 MY ago with slow, diffuse block-faulting and the deposition of the Maria Magdalena Fan at the mouth of the gulf. Oceanic crust was exposed in the gulf by about 9-10 MY, at the same time that the Rivera Ridge began reorienting by clockwise rotation. Strike-slip motion along the Tosco-Abreojos Fault took up some of the Pacific/North American motion with the remainder occurring within the gulf itself. During this period the Pacific Plate forming within the gulf was slowly subducting beneath Baja California. By 4-5 MY subduction ceased and all of the Pacific/North American plate motion was shifted to the Gulf of California fault system.

The gulf and peninsula of California are still in the process of adjusting to the change from Pacific/Farallon to Pacific/North American motion.

LATE NEOGENE TECTONICS OF THE MOUTH OF THE GULF OF CALIFORNIA

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TABLE OF CONTENTS

LIST OF TABLES

LATE NEOGENE TECTONICS OF THE MOUTH OF THE GULF OF CALIFORNIA

INTRODUCTION

This dissertation, like all Gaul and so many other things, is divided into three parts. Each section was written as a stand-alone manuscript for submitting separately to professional journals. However, in keeping with the proforma requirements of the University, the sections were retyped into a common format, in this case in the format of the *Journal of Geophysical Research*, and have an integrated bibliography.

Section I developes an up-to-date marine magnetic anomaly timescale intended primarily for use in tectonic studies. Section II and Section III use this timescale and geological and geophysical survey data to examine the history of the opening of the Gulf of California. Section II concentrates on the seafloor immediately outside the gulf proper, and Section III examines the mouth of the gulf itself.

This work, which began ten years ago, is an attempt to apply meso-scale plate tectonics principles to understanding an actively rifting, ocean-continent transition zone. It has been a difficult effort, and many more problems have been raised than solved by it. The work is continuing. The conclusions reached are tentative, in keeping with the new, but still inadequate scale of resolution obtained. Some of the conclusions reached are also unusual. They push the plate tectonics paradigm past its present limits. This is intended. It is important to find the scale at which the assumptions of rigid plates, finite boundaries, and Euler's principle for the surface geometry break down. Capitan de Fragata Pompeyo Leon, the commander of the Mexican Navy Research Vessel

Mariano Matamoros, once pointed out to me that "conclusions are what you reach when you get tired of thinking." I am getting tired, but I am still trying to think.

SECTION I

MARINE MAGNETIC ANOMALY TIMESCALES FOR THE CENOZOIC AND LATE CRETACEOUS: A PRÉCIS, CRITIQUE, AND SYNTHESIS

Fewer than 14 years have passed since the first publication of timescales derived from seafloor spreading magnetic anomalies, and in that time, numerous additions and revisions have been made to them. Biostratigraphic results from the Deep-Sea Drilling Project (DSDP) have confirmed the general accuracy of such timescales and have also been used to calibrate portions of them. Radiometrically determined timescales have better defined the polarity reversal boundary ages for portions of the late Neogene. Core magneto-stratigraphic data have been used to increase the resolution of portions of the anomaly timescales and have also been used to calibrate them. Recently, new decay and abundance constants have been adopted for use in potassium-argon dating methods, increasing the accuracy, and to some extent the confusion, of age assignments made using anomaly timescales. Within the last 4 years at least four new versions of Cenozoic marine magnetic anomaly timescales have been published.

This paper resulted from what began as a brief literature review, the object of which was to select an anomaly timescale for use in intepreting the detailed tectonic history of the Rivera and Juan de Fuca plates. In the process of this review it became apparent, first, that the literature on the topic has become very extensive and, second, that evidence exists in support of making still further revisions to the general history of the geomagnetic field as it is expressed in the seafloor record.

We review those major papers published since 1966 which provide either tables of formulae for determining boundary ages for anomaly source bodies. We also review certain other papers that offer important criticisms or suggestions concerning anomaly timescales. We do not discuss the development of late Neogene radiometrically determined polarity timescales but do include figures illustrating some of those used to calibrate anomaly timescales (Figures 1 and 3). We refer readers wishing such a review to a paper by Watkins (1972).

Our Figure 2 illustrates the marine anomaly timescales discussed and includes the boundary age assignments made by previous workers. We hope it will save others some time and confusion.

We present an equation for converting old K-Ar dates to corrected values consistent with the change in decay and abundance constants, and use this equation to convert certain radiometric and biostratigraphic dates necessary in constructing a revised timescale, here named NLC-80. We offer timescale NLC-80 as an up-to-date but temporary synthesis and carefully specify how it was constructed. Finally, we criticize our own timescale and provide some alternative interpretations.

For economy we discuss particular boundary ages for anomaly source bodies using a convention which distinguishes older from younger. For example, the older boundary of anomaly 29 is designated 29(o), and the younger boundary 29(y). We also refer to published timescales in an abbreviated form. Thus the timescale of Blakely and Cox (1972b) becomes BC-72, and so on. Also for economy, and to avoid ambiguity, we use the abbreviation MY instead of m.y. or Ma to

Figure 1. Radiometrically dated magnetic polarity timescales published prior to 1970. Several of these timescales were used in early determinations of seafloor spreading rates to calibrate marine magnetic anomaly timescales. This is discussed in the text. These scales are not corrected for the new K-Ar decay and abundance constants.

Uncorrected Radiometric Timescales

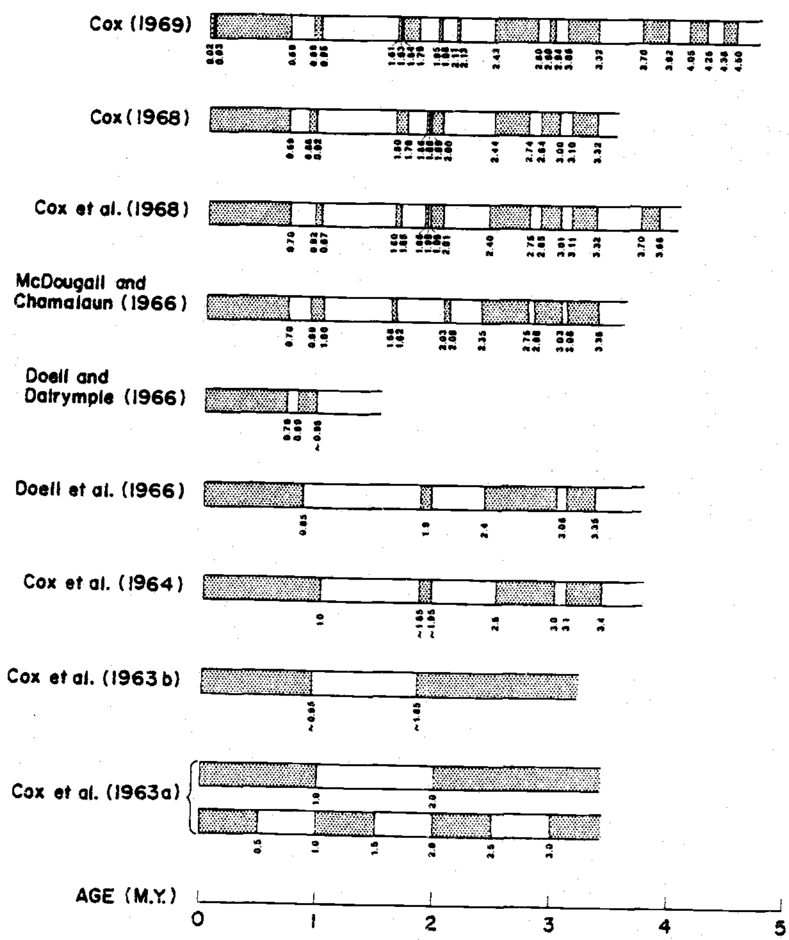


Figure 1.

signify millions of years. We adopt the anomaly numbering scheme employed by Heirtzler et al. (1968) in their timescale HDHPL-68 and include the revised numberings of Blakely (1974), Klitgord et al. (1972, 1975), and LaBrecque et al. (1977). We add certain anomaly numbers in NLC-80 consistent with prior usage.

PREVIOUSLY PUBLISHED MAGNETIC ANOMALY TIMESCALES

PH-66 and V-68

When Vine and Matthews (1963) first suggested that seafloor magnetic anomalies might be related to geomagnetic field reversals, they could only offer the idea as speculation, since the available evidence for reversals was extremely limited. At that time the results of Cox et al. (1963a), which were based upon only nine dated rock samples having determined polarities, were insufficient even to determine which of two proposed and very rudimentary reversal timescales might be most correct (Figure 1, bottom). However, by the following year, Cox et al. (1964) had compiled the results of several studies and proposed a more detailed reversal timescale based upon 64 dated samples. This scale was sufficiently detailed such that Vine and Wilson (1965) used it to generate synthetic seafloor spreading magnetic anomalies using the Vine and Matthews model. Vine and Wilson compared observed profiles from the Juan de Fuca and Pacific-Antartic ridges with one another and with synthetic anomaly profiles, and demonstrated both their similarity and their individual axial symmetry.

It is noteworthy that Vine and Wilson found certain discrepancies between the observed and synthetic anomalies which they attributed to noncontinuous spreading rates. In fact, the discontinuities were caused by inadequacies in the timescale used. The so-called Jaramillo event (anomaly 1') was not distinguished until the following year by Doell and Dalrymple (1966), and Vine and Wilson had mistakenly identified it as the Gilsa event (anomaly 2). Recognition of the Jaramillo event made the error immediately obvious to Vine (1966), who pointed out that if he and Wilson had had more faith in the constant spreading assumption, they could have predicted the Jaramillo event using marine anomaly profiles.

This observation was also apparent to Pitman and Heirtzler (1966). They generated a timescale (PH-66) for the last 10 MY (Figure 2) using profiles from the Pacific-Antarctic Ridge and as assumed half-spreading rate of 4.5 cm/yr, which yielded results consistent with the radiometric timescales published to that time. Pitman and Heirtzler next compared anomalies from the Reykjanes Ridge in the North Atlantic with synthetic anomalies generated using their South Pacific timescale, noted their similarity, and remarked that the spreading rates in the two regions were probably constant over the last 10 MY unless both rates had changed simultaneously and in similar proportion.

Vine (1966) assembled a composite radiometric timescale which was based upon Cox et al. (1964) and Doell and Dalrymple (1966), though not exactly similar to them, at least with respect to the Gilsa event (anomaly 2). He then used this timescale to determine spreading rates for the Reykjanes, Juan de Fuca, Pacific-Antarctic, northwest Indian, and South Atlantic ridges and again demonstrated their similarity and symmetry. In his paper, Vine generated an extrapolated marine magnetic

Figure 2. Marine magnetic anomaly timescales for the Cenozoic and Late Cretaceous. NLC-80, HMW-79 and MD-79 employ newly adopted K-Ar decay and abundance constants. Arrows on NLC-80 indicate calibration points used on that timescale. Arbitrarily selected boundary tie lines are drawn for ease of comparison between timescales. Geological epoch boundaries are from Table 1. Synthetic anomaly profile is generated from NLC-80 and its shape would be typical of anomalies found in middle latitudes over fast, east-west, spreading ridges, measured at the sea surface over an average oceanic water depth of about 3.5 km, generated by two-dimensional source bodies having a thickness of 0.5 km. Each of the six sheets of Figure 2 describe 15 MY. The sheets were designed for assembly into a continuous strip.

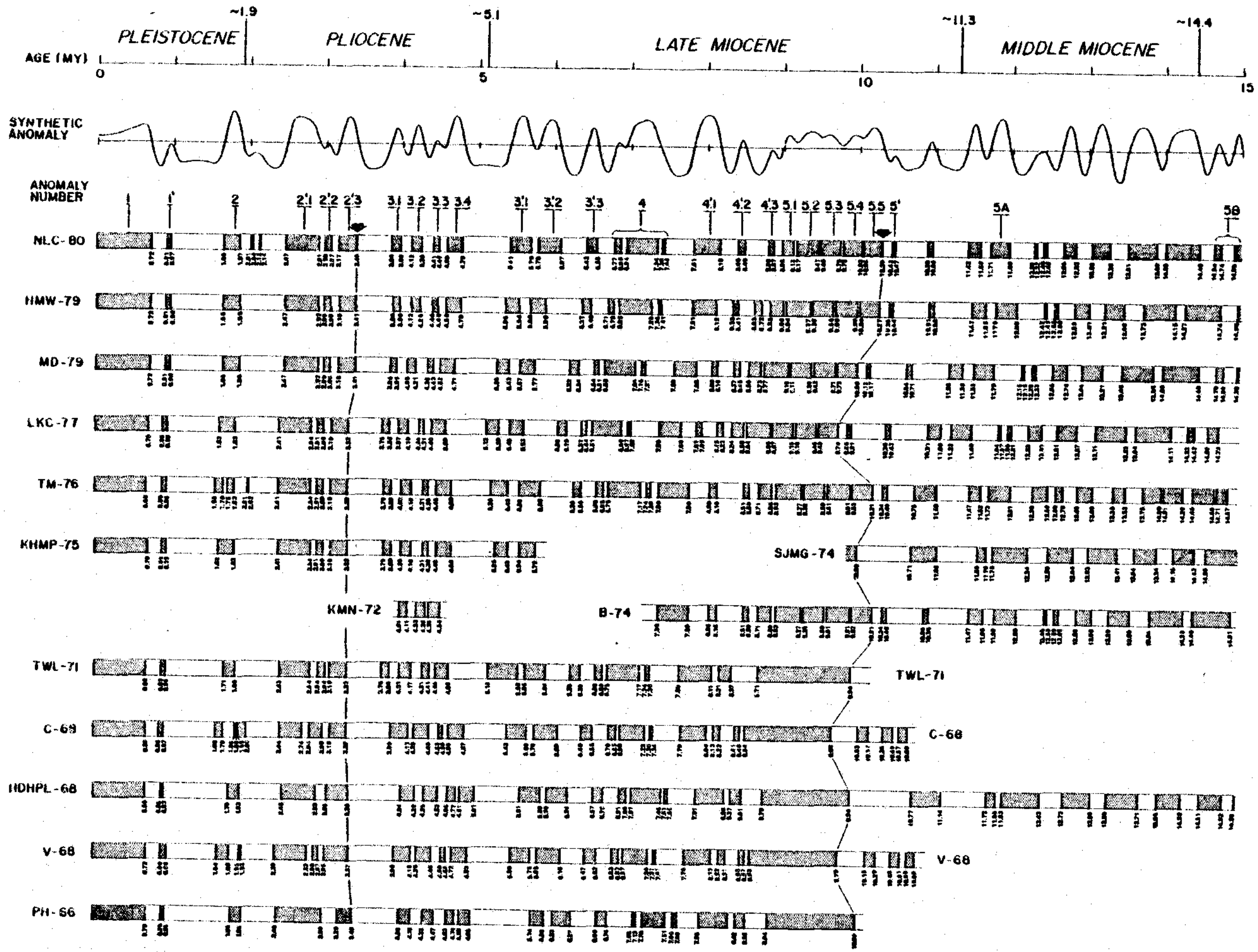
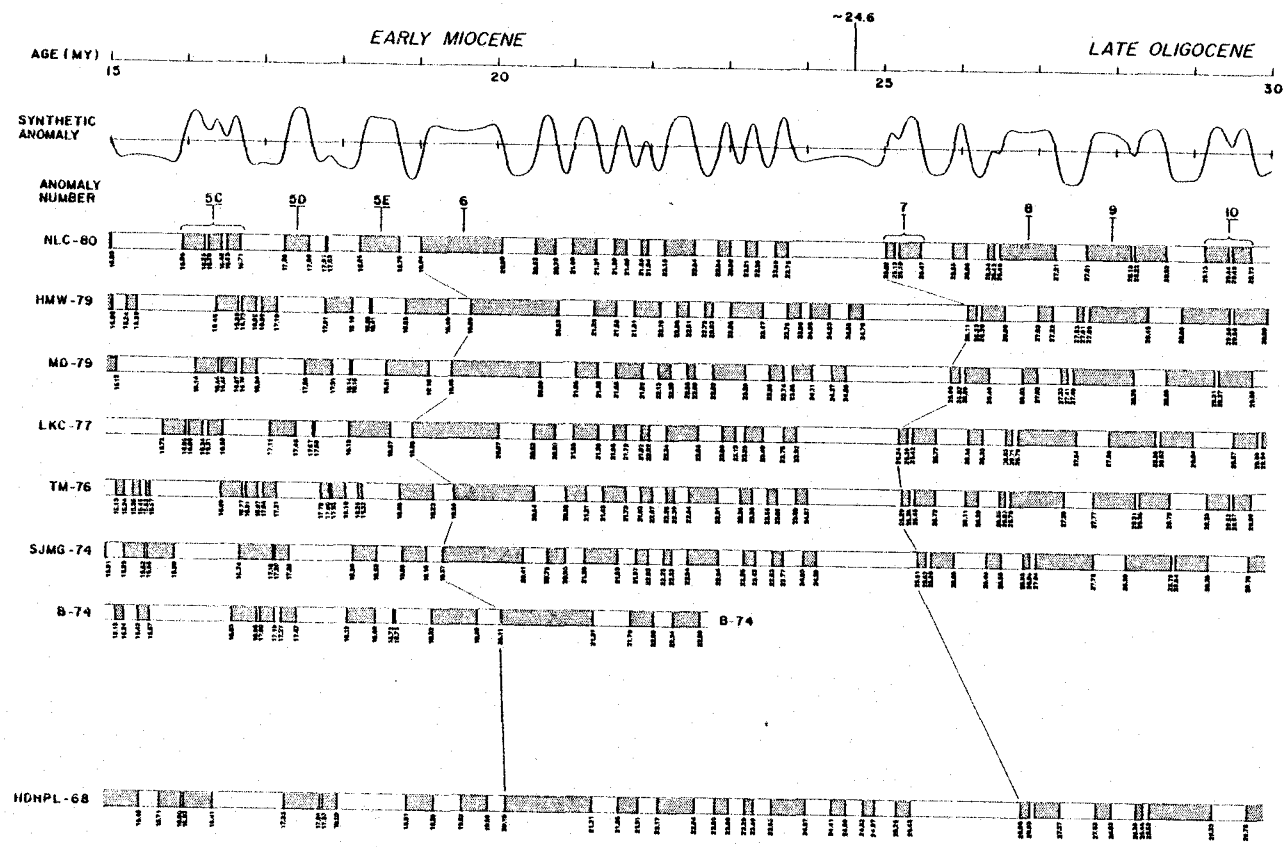

PLEISTOCENE
PLIOCENE
LATE MIOCENE
MIDDLE MIOCENE
~1.9
~5.1
~11.3
~14.4
AGE (MY)
0
5
10
15
SYNTHETIC ANOMALY
ANOMALY NUMBER
1
1'
2
2'1 2'2 2'3
3.1 3.2 3.3 3.4
3'1 3'2 3'3
4
4'1 4'2 4'3 5.1 5.2 5.3 5.4 5.5 5'
5A
5B
NLC-80
HMW-79
MD-79
LKC-77
TM-76
KHMP-75
SJMG-74
KMN-72
B-74
TWL-71
C-69
C-68
HDHPL-68
V-68
PH-66

Figure 2



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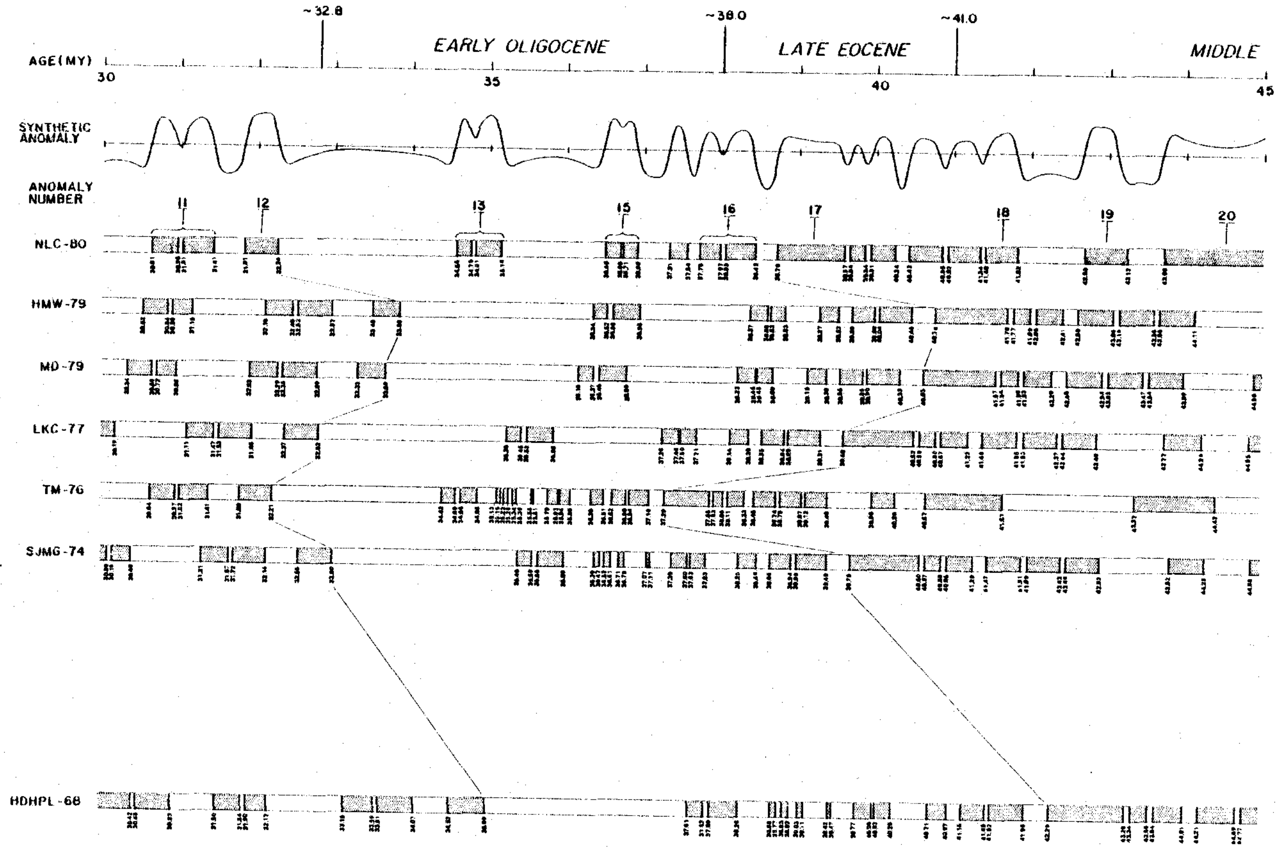

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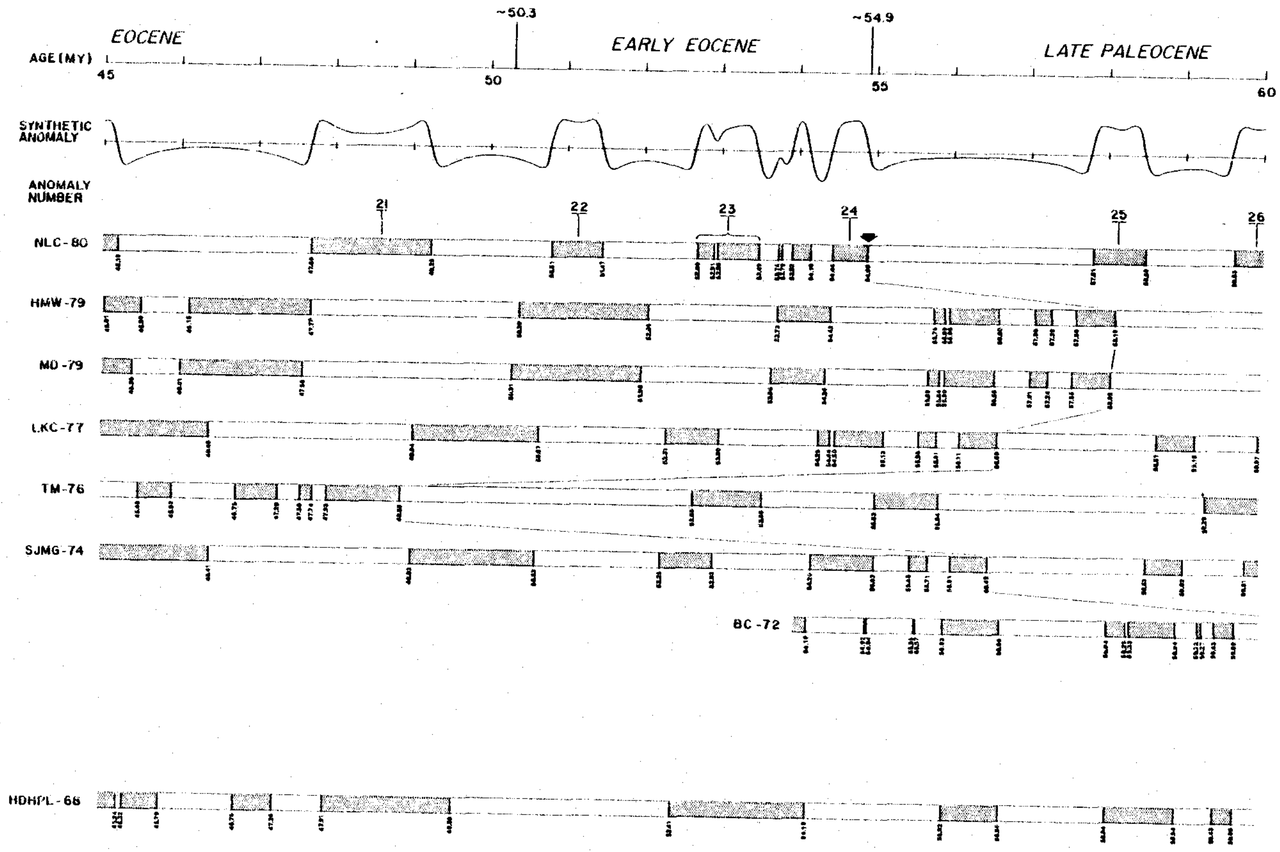

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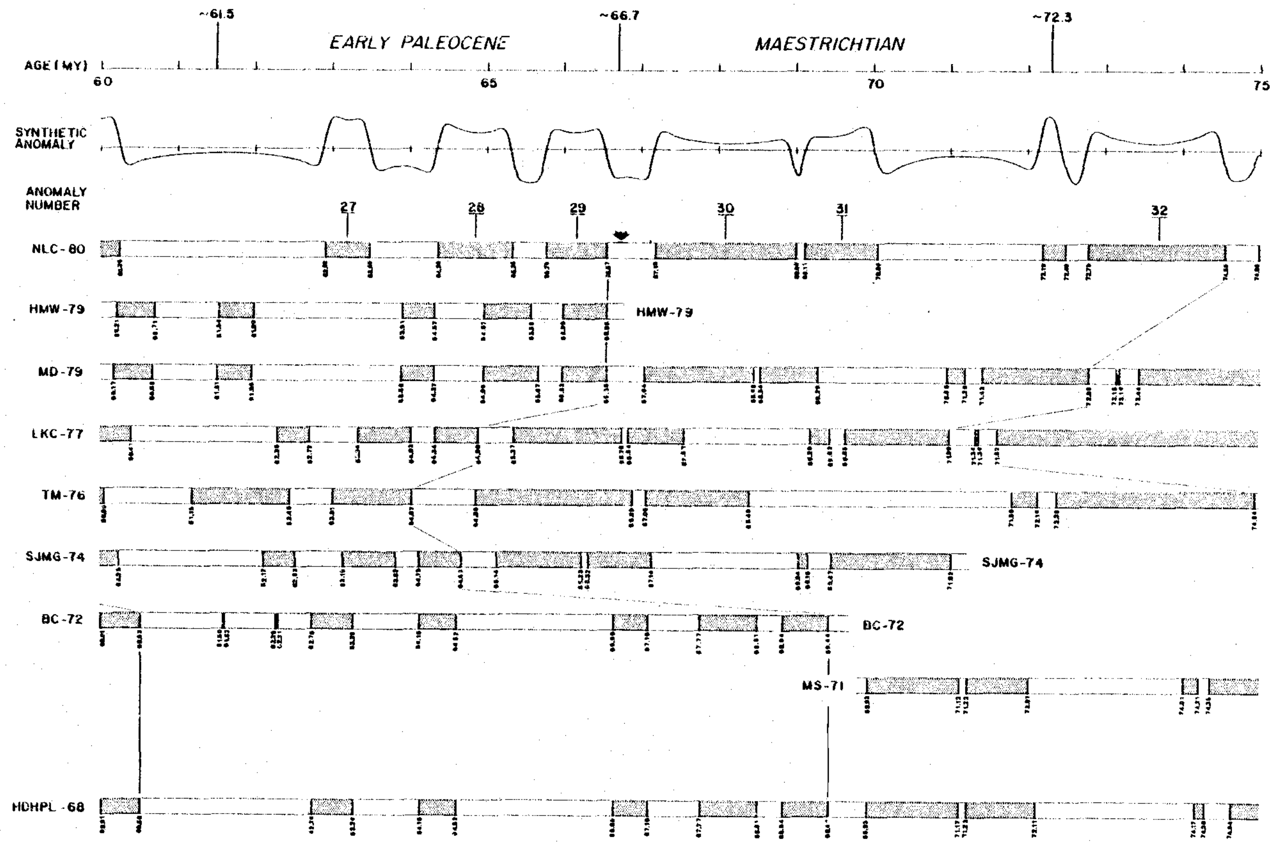

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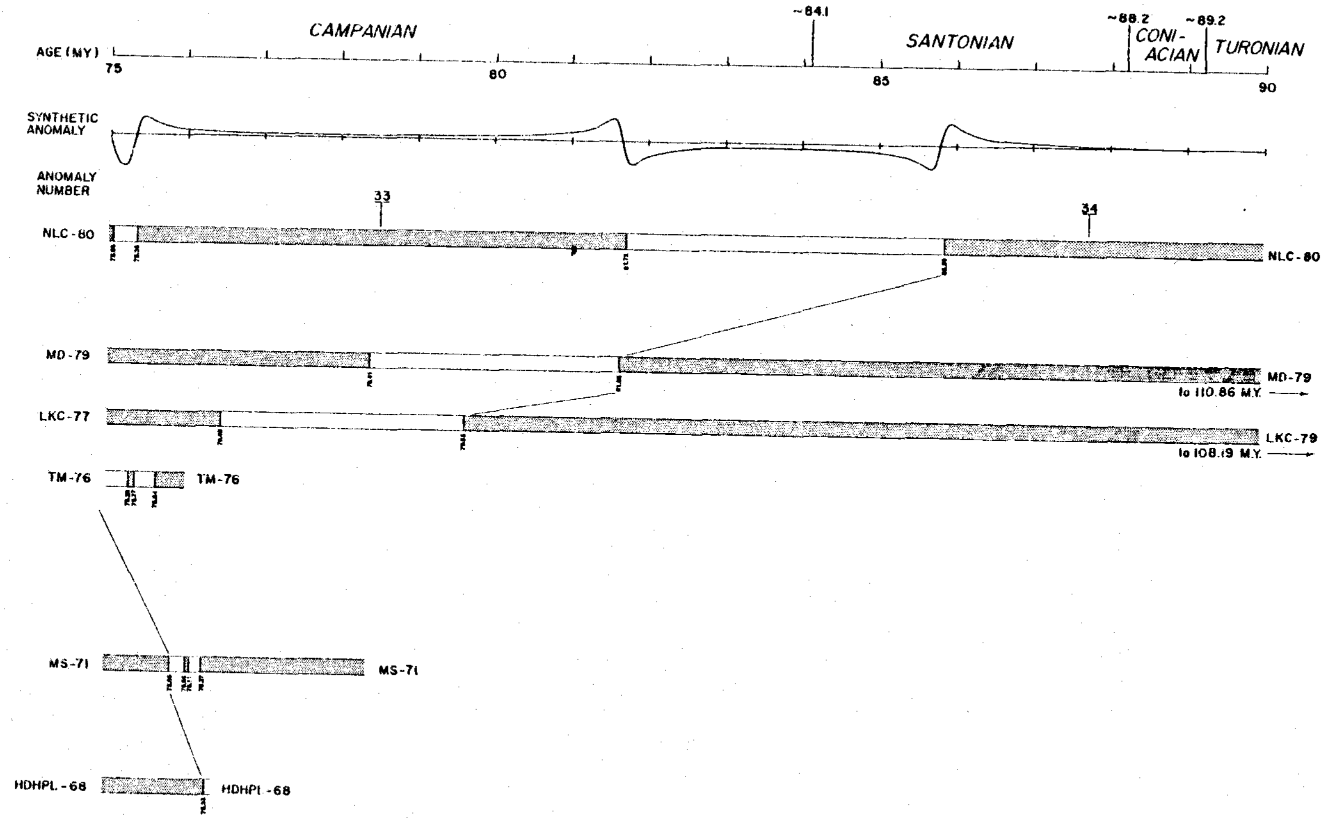


Figure 2 (continued)

anomaly timescale for the last 11.5 MY using *Eltanin*-19 cruise data from the Pacific-Antarctic Ridge and a 4.4 cm/yr half-spreading rate. He did not publish a table of the anomaly boundary ages. However, 2 years later the V-68 timescale (Vine, 1968) was published in the revised proceedings of a symposium on the history of the earth's crust held in 1966. Using anomaly profiles obtained from the East Pacific Rise at 51°S, the Juan de Fuca Ridge at 48°N, and the Reykjanes Ridge at 60°N, Vine first assumed constant rates of seafloor spreading for each of these three areas and then determined those rates and the reversal ages derived from them by comparison with the detailed radiometric timescale of Cox et al. (1968) (Figure 1). Vine next examined an extended magnetic profile (*Eltanin*-19N) obtained from the East Pacific Rise at 51°S (the Pacific-Antarctic Ridge), and by now assuming an overall half-spreading rate of 4.6 cm/yr, he generated an extrapolated marine magnetic anomaly timescale good to approximately 11 MY (just short of anomaly 5A).

Using this South Pacific scale, Vine again went on to demonstrate that the extended pattern of anomalies there was similar in character to that of magnetic profiles obtained from the North and South Atlantic Oceans, the Indian Ocean, and the North Pacific Ocean, these differing only in their rates of seafloor spreading. He next generated a block model for magnetic source bodies, in the approximate range of anomalies 21-33, from a central North Pacific Ocean profile and compared synthetic anomalies generated from the model with profiles obtained from the southwest Pacific and northeast Atlantic Oceans. The comparison indicated that these also only differed in their respective spreading rates.

Following an earlier extrapolation (Vine, 1966), these anomalies were estimated to range in age from approximately 50 to 75 MY.

These early results of Vine, Wilson, Pitman, and Heirtzler clearly and quantitatively supported the validity of the Vine and Matthews hypothesis and made it apparent that, given sufficient data, an extended magnetic reversal timescale could be constructed using seafloor magnetic anomalies.

HDHPL-68

Without doubt, the magnetic anomaly timescale most widely employed to date has been that of Heirtzler et al. (1968). In a consecutive series of four papers published in the March 1968 edition of the *Journal of Geophysical Research* the authors of HDHPL-68 compared the relative distances to particular marine magnetic anomalies from the crests of spreading ridges in the North and South Pacific, the South Atlantic, and the Indian Oceans and used these to select a single long profile to use for generating a continuous, standard magnetic anomaly timescale. The objective, of course, was to choose a profile that was free of any evidence of changes in the rate of seafloor spreading. Heirtzler et al. ruled out an Indian Ocean profile because it only extended to anomaly 16 and a North Pacific profile because the mapped pattern of anomalies was distorted near the Juan de Fuca and Gorda Ridges. They also rejected a South Pacific profile because it indicated major accelerations in spreading rates near anomaly 5 and anomaly 24 when compared with both North Pacific and South Atlantic profiles. The South Pacific spreading rate age for anomaly 7 also violated a paleontologically determined age for the base of a sediment core taken in the North Pacific over that anomaly.

Heirtzler et al. selected the South Atlantic, *Vema*-20, profile as standard and calibrated the age of anomaly 2.3'(o) at 3.35 MY, consistent with radiometric age determinations for that boundary made on subaerial basalts by Doell et al. (1966) and by McDougall and Chamalaun (1966) (Figure 1). They determined a 1.9 cm/yr half-spreading rate for the profile and extrapolated the spreading rate versus distance relationship to approximately 80 MY, beyond anomaly 32. This timescale was consistent with the Cretaceous age determination of a sediment core from the South Atlantic near anomaly 31 and also in close agreement with the earlier estimate made for the age of that anomaly by Vine (1966).

The remarkable 80 MY extrapolation made by Heirtzler et al. (1968) from a calibration date of 3.35 MY was supported at the time it was made by only the most tenuous of evidence, a single Late Cretaceous core. Yet, for the most part, magnetic anomaly timescales published after HDHPL-68 are only modest revisions, additions, or recalibrations of it, and the general plate tectonics reconstructions made using that scale as a time base are still valid. Today, however, greater resolution and accuracy are required for understanding both the finer-scale phenomena of plate motions and the short-period behavior of the earth's field. The disadvantage in HDHPL-68 is that it was generated from a single,sinuous profile obtained from the relatively slow-spreading South Atlantic Ridge. This affected both its resolving power and its accuracy. Note, for example, that it fails to resolve anomaly 2.2' and anomaly 4.3' source blocks, while timescale V-68, which was generated from fast-ridge data, resolved both.

C-68

In a paper devoted primarily to a statistical study of the length of polarity intervals, Cox (1968) constructed a hybrid timescale of radiometric, core magnetostratigraphic and marine anomales. From 0 to 3.2 MY the scale was based on radiometric ages from Cox et al. (1968) and on studies of the paleomagnetism of deep-sea sediment cores. Beyond anomaly 2.3'(o), at 3.32 MY, the V-68 scale of Vine was compressed by a ratio of 3.32/3.37. To our knowledge this scale was never used in any tectonic reconstructions.

TWL-71

From a comprehensive survey of the Reykjanes Ridge south of Iceland, which employed satellite navigation techniques, Talwani et al. (1971) generated timescale TWL-71. Average distances between the ridge crest and prominent anomalies were determined along 12 closely space profiles made perpendicular to the ridge. Then, assuming that the HDHPL-68 age for anomaly 5(o) of 9.94 MY was correct and that spreading on the Reykjanes Ridge had been constant since that time, a residual distance-versus-time curve was constructed comparing measured distances with distances predicted using HDHPL-68. The residuals were considered to represent errors in the timescale of Heirtzler et al. (1968). A new hybrid scale was constructed using radiometric age data from Cox (1969) (modified by core magnetostratigraphic information) to anomaly 2.3'(o) at 3.32 MY. Anomaly 3.1'(y) was fixed at 5.18 MY as a compromise between residual distance data which indicated a corrected age of 5.31 MY and a date of 5.06 MY assigned by Foster and Opdyke (1970) using core magneto-stratigraphy. Beyond anomaly 3.1'(y) the residual distance data alone were used to correct HDHPL-68. The advantage of TWL-71 over HDHPL-68 is that many closely spaced and parallel profiles were used in its construction. This technique reduces noise and eliminates questions about the ideal two-dimensionality of the seafloor spreading anomalies. The disadvantages in TWL-71 are first that it was generated from profiles obtained over a slow-spreading ridge, which limits its resolution, and second that it is a hybrid, compromise scale and therefore difficult to put to certain kinds of use without risking circularity.

MS-71

From an analysis of shipboard and aeromagnetic profiles obtained in the Indian Ocean, McKenzie and Sclater (1971) proposed modifications and additions to HDHPL-68 beyond anomaly 30. A determination was made of the average distances between particular anomalies in the range of anomalies 22 to 33. This information was then compared with similar data from the North Pacific Ocean at 40°N from a study by Raff (1966) and from the South Atlantic Ocean using the *Vema*-20 data from Dickson et al. (1968). In this anomaly range, the South Atlantic distance data were found to be linearly proportional to the North Pacific distance data, at least as far back as anomaly 30. McKenzie and Sclater (1971) therefore assumed that variations in the Indian Ocean distance data were due to changes in Indian Ocean spreading rates occurring near the times of anomalies 23 and 31. North Pacific distance data were then used to generate MS-71; however, no details of these data were presented in the paper.

BC-72

Blakely and Cox (1972b), using the same signal-enhancing techniques applied in an earlier paper (Blakely and Cox, 1972a), analyzed six magnetic profiles from the northeast Pacific Ocean in order to resolve short-term magnetic polarity events within the range of anomalies 21 to 29. Profiles were first reduced to the pole to eliminate asymmetry, then stretched to a common spreading rate by fitting major anomalies to HDHPL-68. The profiles were then algebraically averaged to attenuate noise. Six short-polarity intervals were recognized and included in BC-72 as modifications to HDHPL-68. Subsequently, three-component magnetometer data were obtained from a low-altitude aeromagnetic profile over the original survey area (Blakely et al., 1973). These data supported the two-dimensionality of the source bodies associated with the two longest of the six previously determined polarity intervals and indicated the possible presence of an additional new polarity interval. The data were too noisy, however, to confirm the presence of the other four short intervals in question.

Cande and LaBrecque (1974) pointed out that very short polarity intervals are virtually indistinguishable from large, single-polarity, geomagnetic intensity fluctions, when observed from the ocean surface. The issue of distinguishing intensity fluctuations from true polarity reversals is significant for those studies concerning the origin and behavior of the field. However, our original purpose in conducting this review was to adopt or to construct a marine magnetic anomaly time-scale for use in making detailed plate tectonic reconstructions. Therefore to the extent that a particular anomaly is a common feature of appropriate magnetic profiles, it is a useful time marker and should be included in the timescale. Features of short duration are particularly useful in distinguishing between anomalies when dealing with relatively short magnetic profiles. Strictly, the determination of whether or not a particular short-duration anomaly truly represents a field reversal requires independent paleomagnetic confirmation. Practically, in plate tectonics applications it is not required. Logically, the burden of proof appears to be on those who would argue that any particular two-dimensional, marine magnetic anomaly is not due to a geomagnetic field reversal. Anomaly polarity timescales are essentially identical to radiometric polarity timescales, at least for the last 3.5 MY. To accept this and then argue without proof that any older two-dimensional anomaly is not due to a field reversal is inconsistent. Moreover, short-polarity events are documented, but intensity fluctuations of the type needed to produce single-polarity wiggles are not.

In constructing the NLC-80 timescale we include only the two longer events of BC-72, whose presence was supported by the subsequent three-axis magnetometer study of Blakely et al. (1973). It is worth noting that the four events of BC-72 which are omitted from NLC-80 are of normal polarity and their duration is only of the order of 0.02 MY.

KMN-72

Using a deep-tow magnetometer and a bottom transponder navigation system, Klitgord et al. (1972) conducted two separate surveys, six months apart, of the seafloor off the southern tip of Baja California.

Magnetic observations from both surveys were used to determine the average spatial distribution of anomalies 3.2, 3.3, and 3.4. This information was then used to generate a revised timescale, for the interval studied, by fixing anomaly 3.2(y) at 4.01 MY, the TWL-71 age for that boundary, and by applying an overall 3.15 cm/yr half-spreading-rate value to the distance information. The spreading rate was determined by the regression of anomaly distances, from the nearby ridge crest, onto the TWL-71 timescale.

The accuracy of KMN-72 is questionable. Since no common transponders were used between the two survey sections, one survey was adjusted to the other by using bathymetric features yielding "a final relative position accuracy of less than 200 m". However, absolute positioning was with radar and therefore "only accurate to within a few kilometers". Both estimates seem optimistic, particularly since the mapped orientation of anomalies 3.2, 3.3, and 3.4 is about 35°, while the strike of the ridge crest is about 21° and the strike of anomaly 5 is more nearly north-south. The authors themselves noted the discrepancy and suggested that it could have been due either to survey orientation errors, which raises the question of navigational accuracy, or to the existence of unmapped fracture zones which casts doubt upon the matching of bathymetric features. The survey area has undergone large-scale tectonic reorientations since at least anomaly 5 time.

B-74

Blakely (1974), using the same signal-enhancing techniques employed in generating BC-72, analyzed 14 parallel and closely spaced magnetic profiles from the northeast Pacific Ocean, west of the Juan de Fuca and Gorda ridges, in the range of anomalies 4.1' to 6A. The 14 profiles were selected from an area where mapped anomalies were extraordinarily regular and apparently free from distortions due to tectonic complications. The survey, conducted by the National Oceanic and Atmospheric Administration in 1971, used satellite navigation techniques.

These profiles were again reduced to the pole, adjusted to a constant spreading rate with respect to 17 points in HDHPL-68 and stacked. Several new short-wavelength anomalies were recognized. The stacked North Pacific profile was then compared to stacked South Pacific profiles (*Eltanin*-20E and 20W) and stacked Indian Ocean profiles (*Eltanin*-41N and 41S). The newly recognized anomalies were again found. Anomaly 5 of Heirtzler et al. (1968) was interpreted to consist of five shorter-polarity events. Anomalies 4.5' and 5', which were apparent in V-68 but not in HDHPL-68 or TWL-71, were confirmed, again demonstrating the advantage of constructing anomaly timescales from profiles obtained over fast-spreading ridges.

As a by-product of adjusting the spreading rates of the original profiles to 17 points in HDHPL-68, information was obtained on local spreading rates for 16 time intervals. Radical, short-term changes in spreading rates were implied. For example, a deceleration of 3.19 cm/yr/MY apparently occurred at approximately 19 MY, and nearly identical, synchronous accelerations were recognized in South Pacific and Indian ocean data. Blakely concluded that it would be most reasonable to assume that continuous spreading occurred in the North and South Pacific and Indian oceans during the time interval studied. The local accelerations could then be explained either as artifacts of discontinuous spreading in the South Atlantic implicit in HDHPL-68 or as inaccuracies in HDHPL-68 caused by the fact that it was generated from a single-sinuous profile, the only kind of data available to Heirtzler et al. in 1968. A constant spreading rate, northeast Pacific timescale was then constructed by fixing anomaly 5.1(y) at the 8.71 MY age from TWL-71 and anomaly 6(o) at the 21.31 MY age from HDHPL-68. Fine-scale biostratigraphic calibration points were considered but rejected owing to the large potential errors involved.

Blakely's (1974) choice of 8.71 MY as a calibration point merits discussion. Talwani et al. (1971) used a 9.94 MY date from HDHPL-68 to fit the older end of their timescale TWL-71. In a similar fashion, Blakely (1974) chose to fix anomaly 6(y) to an HDHPL-68 date, but then went on to register his scale to TWL-71 at anomaly 5.1(y) instead of using a corresponding HDHPL-68 date. There were two reasons for doing so. First, the character of anomaly 5 in B-74 is very different from that in HDHPL-68. Second, if he had selected anomaly 5.5(o) as a calibration point, the younger end of his timescale, by extrapolation, would have seriously disagreed with all previously published timescales. His choice of 8.71 MY as a calibration point was a compromise between fixing B-74 to readily identifiable anomalies and minimizing radical spreading rate discontinuities, introduced as artifacts, in the time range of anomalies 2.3'(o) to 5.1(y). This last problem has been approached by later workers, and one of the conclusions of this review is that the time range in question is still very poorly constrained.

SJMG-74

At the same time that Blakely was working on modifications to the younger end of HDHPL-69, Sclater et al. (1974) proposed a recalibration near the older end. For four DSDP drilling sites having good sediment to basement contacts on identifiable magnetic anomalies older than anomaly 13, they noted that the biostratigraphic age determinations of the basal sediments were consistently 5-8 MY younger than the ages of magnetic anomalies 21, 24, 26, and 30 given by HDHPL-68. This prompted a further examination using similar evidence from a total of 13 DSDP sites that were thought to be located on or close to identifiable magnetic anomalies and had good sediment to basement contacts. Five of these sites were rejected for various reasons. A comparison was then made of magnetic ages with paleontologic ages by using the absolute age assignments for geological epochs of Bergren (1972). Paleontologic ages were found to be consistently equal to or younger than magnetic ages.

An adjustment to HDHPL-68 was then proposed to bring the older portion of it into agreement with biostratigraphic ages. Anomaly 30(o) was assigned a biostratigraphic age of about 66 MY, and the HDHPL-68 scale was assumed to be correct at 10 MY. This compressed HDHPL-68 such that the 65 MY Cretaceous-Paleogene boundary was located between anomalies 29 and 30 instead of between 26 and 27.

In their paper, Sclater et al. (1974) stated that they were not proposing a formal revision of the magnetic timescale but instead were developing their "own relationship" between magnetic anomalies and geological ages. They stated that such a revision should await the results from later DSDP legs, more detailed analyses of older anomalies, and a careful consideration of the ages given to reversals dated on land and in DSDP cores.

It should also be noted that Sclater et al. did not attempt any fine-scale adjustments to the magnetic timescale in an effort to remove all discrepancies with biostratigraphic age determinations. An examination of their Figure 2 shows that some biostratigraphic age determinations, based on different fossil groups (e.g., calcareous nannoplankton versus foraminifera), are ambiguous by as much as 6 or 7 MY. In particular, the biostratigraphic age determinations for DSDP sites 16 and 36 could be used to argue that anomaly 5 is younger than anomaly 4. The two age estimates also differ by a maximum range of approximately 10 MY, and this is with respect to anomalies whose absolute ages are thought to be less than 10 MY.

We concur with Sclater et al. in their decision to make only a single, conservative biostratigraphic adjustment to the anomaly timescale. In timescale NLC-80 we will propose that a similar adjustment be made to HDHPL-68 at anomaly 24. The biostratigraphic evidence available today could perhaps be used to support three such adjustments (Berggren et al., 1978). We choose to make only one adjustment that will approximately satisfy all of the available evidence without risking the possible introduction of artificial spreading accelerations as timescale artifacts.

<u>KHMP-75</u>

Deep-tow magnetic profiles obtained from six different areas of the Pacific basin (or five separate plate boundaries including the

Pacific-Juan de Fuca, the Pacific-Gorda, the Pacific-Rivera, the Cocos-Nazca, and the Pacific-Antarctic) were used by Klitgord et al. (1975) to determine the ratios of spreading velocities for various combinations of ridge pairs. Spreading half rates were first determined using calibration points at 0.70, 2.41, and 3.32 MY, and the assumption of continuous spreading on both the west flank of the Pacific-Antarctic Ridge from 0 to 6 MY and on the Pacific-Rivera from 3 to 6 MY. The magnetic anomaly boundary ages along each profile were then determined by inversion and averaged between the six profiles, providing timescale KHMP-75. Because of the frequent use of calibration points, the resulting boundary ages are quite similar to those of TWL-71, particularly with respect to anomalies 3.1, 3.2, 3.3, and 3.4. However, they are quite different with respect to anomalies 3.1' and 3.2', which may reflect on the validity of the constant spreading assumption for the age range of 5-6 MY.

Since widely separated ridges may possess unique spreading histories, real distinctions in magnetic anomaly profiles might be lost in averaging anomaly boundary ages. In addition, three of the ridges involved, the Juan de Fuca, the Gorda, and the Rivera, have rotated in a clockwise sense since anomaly 5 time; therefore single-profile determinations of their spreading velocities are unconvincing. In spite of our objections, however, KHMP-75 closely corresponds to the radiometric timescale of Cox (1969) to anomaly 2.3'(o), and with the anomaly scale TWL-71 to anomaly 3.4(o). Also since KHMP-75 was constructed without using fine-scale biostratigraphic or core-magnetostratigraphic adjustments, we employ part of it in timescale NLC-80.

TM-76

Tarling and Mitchell (1976) proposed a revised Cenozoic polarity timescale generally based on 'compromise solutions' between core magnetostratigraphy and marine magnetic anomaly records. For Neogene time the number of reversals in their proposed sequence was based preferentially upon the sedimentary record, while the durations of events were based upon those compromise solutions. The entire Cenozoic geological timescale was recalibrated by using the European, glauconite-dated, continental stratigraphy of Odin (1975). Particularly large adjustments were made in the Paleogene, based upon those isotopic dates. The authors also made a major adjustment to the age of anomaly 24 based upon an isotopic age determination (48-49 MY) of reversely magnetized east Greenland basalts interpreted by Tarling and Mitchell (1976) to be somewhat older than anomaly 24.

The Tarling and Mitchell timescale was critically reviewed, even "rejected" in a strongly worded paper by Berggren et al. (1978). Central to their objections was a criticism of the reliability of dating glauconite by the potassium-argon method. The Paleogene ages determined by Odin (1975) were thought to be much too young and "scarcely warrant immediate, uncritical acceptance nor [do] the modifications to the Paleogene part of the Cenozoic timescale that Tarling and Mitchell (1976) have made, based on them". A second objection was to associating the eastern Greenland Blossville Group basalts with the initial opening of the North Atlantic and therefore in thinking them to be correlated with anomaly 24. This same objection was raised by LaBrecque et al. (1977), who noted that there is no close age correspondence between marginal extrusive events and the initiation of rifting. They cited as examples the Deccan Traps in India and basalts in western Greenland and Baffin Island as having been extruded well after rifting.

After discussing the difficulties inherent in dating glauconites, Berggren et al. (1978) pointed out that the Paleogene portion of an earlier Berggren (1972) timescale depended in large part upon K-Ar determinations on glauconites (many of them by Odin). They then went on to make a detailed reexamination of glauconite, biotite, and sanidine K-Ar ages determined for continental stratigraphic sequences and of continental biostratigraphic correlations with their marine equivalents. They reached the following conclusions:

1. The early-middle Eocene boundary occurred at about 49.5 MY rather than 44 MY as accepted by Tarling and Mitchell (1976), a significant difference of more than 5 MY.

2. The age of anomaly 21 is approximately 48 MY instead of 44 MY.

3. The age of anomaly 24 is approximately 53 MY instead of 48 MY.

4. The age of anomaly 26 is approximately 57-58 MY instead of 55.5 MY.

It should be emphasized that these revised ages for anomalies 21, 24, and 26 are about 2.0-3.5 MY younger than those given in SJMG-74, and so the disagreement between Berggren et al. (1978) and Tarling and Mitchell (1976) is to some extent one of degree, at least in effect. We favor the revised Paleogene geologic timescale of Hardebol and Berggren (1978) and agree that sufficient biostratigraphic evidence exists from DSDP results to justify revising the age of anomaly 24. We do so in timescale NLC-80 but only adjust it to the Paleocene-Eocene boundary of Hardenbol and Berggren, which is here corrected for new K-Ar constants to be 54.9 MY (Table 1). This adjustment is similar in kind

TABLE 1. Boundary Ages for Late Cretaceous, Paleogene, and Neogene Epochs and Ages Corrected for New Potassium-Argon Decay Constants

	Uncorrected Age, MY	Source*	Corrected Age, MY	Value Used in NLC-80
Pleistocene				
Pliocene	1.8	1	1.85	1.9
Late Miocene	5.0	1	5.13	5.1
Middle Miocene	11.0	1	11.29	11.3
Early Miocene	14.0	1	14.37	14.4
Late Oligocene	24.0	2	24.63	24.6
Early Oligocene	32.0	2	32.84	32.8
Late Eocene	37.0	2	37.96	38.0
Middle Eocene	40.0	2	41.04	41.0
Early Eocene	49.0	2	50.26	50.3
Late Paleocene	53.5	2	54.88	54.9
Early Paleocene	60.0	2	61.53	61.5
Maestrichtian	65.0	2	66.66	66.7
Campanian	70.5	3	72.29	72.3
Santonian	82.0	3	84.06	84.1
Coniacian	86.0	3	88.16	88.2
Turonian	87.0	3	89.18	89.2
Cenomanian	89.5	3	91.74	91.7
Albian	94.0	3	96.34	96.3

*Sources are 1, Berggren and van Couvering (1972); 2, Hardenbol and Berggren (1978); and 3, Obradovich and Cobban (1975).

to that made for anomaly 30 by Sclater et al. (1974), and it approximately satisfies the three adjustments to anomaly ages proposed by Berggren et al. (1978). To some extent it is also consistent with the sense of the anomaly 24 revision proposed by Tarling and Mitchell (1976) on different grounds.

Beyond agreeing with the criticisms by Berggren et al., we feel in addition that Tarling and Mitchell placed excessive emphasis on fine-scale biostratigraphic and magnetostratigraphic age determinations in constructing TM-76. The sedimentary record is subject to numerous complications including variations in sedimentation rate, compaction, erosion, reworking, chemical changes, magnetic instability, etc., and biostratigraphic age determinations are frequently questionable, as the previously discussed results from DSDP sites 16 and 36 indicate. Yet, although it is not made clear by Tarling and Mitchell, as many as eight, and possibly more, calibration points or adjustments may have been used in constructing that portion of TM-76 younger than anomaly 6. Moreover, it is difficult to determine the specific reason for many of the compromise ages which they selected. Some examples follow.

Although a 0.68 MY age for anomaly 1(o) is certainly an acceptable choice within the existing uncertainties, Tarling and Mitchell (1976) provide no reason for preferring that particular age to the then published values of 0.69, or 0.70 MY, obtained either from K-Ar dating (Figure 1) or seafloor spreading scales (Figure 2). The source for the boundary ages of anomaly 2 is not stated. Boundary ages for anomalies 1', 2', 3, 3.1'(o), and 3.2'(y) were apparently taken from KHMP-75 (Figure 2). The boundary age of anomaly 3.1'(y) is a compromise between one unstated source and a biostratigraphic age. TWL-71 boundary ages seem to have been used for anomalies 3.3'(o) and 4, but it is not clear how the boundary ages for 3.2'(o) and 3.3'(y) were obtained. B-74 was evidently used for anomalies 4' through 5'. For the segments older than anomaly 5 there is an unrecognizable mix of B-74 and stratigraphic ages, including two isotopically dated ash horizons in sedimentary cores at 11.2 and 12.3 MY. DSDP results are used as a stratigraphic tie for anomaly 6(y).

These apparent calibration points come from a variety of sources including biostratigraphy, magnetostratigraphy, radiometric age determinations, and various seafloor spreading timescales, each of which is subject to its own uncertainties and sources of error. Thus TM-76, particularly in the range younger than anomaly 6, is neither fish nor fowl, and we wonder at the number of artificial spreading rate changes that would be introduced by this kind of fine-scale stretching and compressing of the anomaly timescale. At the very least we lack confidence in the use of TM-76 for tectonic reconstructions.

Instead we feel that the relative constancy of seafloor spreading rates has been conclusively demonstrated in the linear relationships found in anomaly distance-versus-distance plots which compare numerous ridge pairs, bounding numerous lithospheric plates, from numerous oceans, for numerous intervals of the past. This has been illustrated many times, and we urge skeptical co-workers to review such figures as are found in the work of Pitman et al. (1968), Dickson et al. (1968), LePichon and Heirtzler (1968), Heirtzler et al. (1968), and Blakely (1974). If TM-76 were applied to the distance information presented in such figures, the resulting inference would necessarily be that all of the lithospheric plates were subject to simultaneous, short-term, high-magnitude accelerations. We do not deny this possibility, but we do consider it to be very unlikely.

LKC-77

LaBrecque et al. (1977) incorporated into their anomaly timescale parts of previously published scales including HDHPL-68, TWL-71, MS-71, BC-74, and KHMP-75. They limited their selection to those studies which provided increased resolution to parts of the Heirtzler et al scale and which were based exclusively on marine magnetic anomalies. To some extent, TWL-71 used core-magnetostratigraphic data, but the section interpolated into LKC-77 was derived exclusively from anomalies. Their scale was fixed at 3.32 MY for anomaly 2.3'(o) from KHMP-75, 7.39 MY for anomaly 4.1'(y) from B-74, and 64.90 MY for anomaly 29(1) on the basis of the relative position of that anomaly with respect to the 65 MY Cretaceous-Paleogene boundary expressed in a sedimentary section in Gubbio, Italy (Alvarez et al., 1977). This last calibration point is essentially identical to the anomaly 29-30 and Cretaceous-Paleogene boundary relationship proposed earlier by Sclater et al. (1974), using DSDP results.

LaBrecque et al. (1977) eliminated anomaly 14, since it is not found in most marine magnetic profiles. The positions of anomalies 4.2' and 4.3' were arbitrarily adjusted for better correspondence with anomaly patterns in the southeast Indian and South Pacific Oceans. The relative spacings of anomalies 29 to 34, based on then unpublished data from the North Pacific were extrapolated by assuming that spreading in the North Pacific was continuous from anomalies 23 to 34. Although the authors referred to the radiometric age dating of part of anomaly 5 done by McDougall et al. (1976a) on Icelandic basalts, they chose not to calibrate LKC-77 near the end of anomaly 5. They also mentioned the systematically young DSDP biostratigraphic dates found in the Paleogene and suggested that they were probably due to small errors in HDHPL-68, but made no adjustment. The big shift in anomaly 24 age made by Tarling and Mitchell (1976) was not accepted. Moreover, LaBrecque et al. (1977) reversed the emphasis and adjusted several biostratigraphic age boundaries to their revised seafloor spreading timescale using the core magnetostratigraphic and biostratigraphic results of Ryan et al. (1974) and Alvarez et al. (1977). They developed a Late Cretaceous to Recent geological timescale based on those correlations and upon the scale of van Eysinga (1975). We support their effort and applaud their courage.

Renewing an older argument, LaBrecque et al. (1977) discussed "tiny wiggles" in marine magnetic anomaly records and expressed concern that these short-wavelength anomalies were becoming accepted as records of full scale reversals. In a pictorial presentation of their paleomagnetic polarity scale they omitted seven events from the B-74 scale including the four reversed polarity events within anomaly 5 proposed by Blakely (1974). However, these events were included in their numerical table of boundary ages. As stated previously, the authors also omitted most of the short-polarity events from BC-72. In our scale, NLC-80, we include the B-74 events, believing that these have been essentially confirmed by the work of McDougall et al. (1976a). We also include the so-called Reunion events by interpolation from the radiometric scale of Mankinen and Dalrymple (1979). We agree with the emphasis placed on seafloor magnetics by LaBrecque et al. (1977) in their construction of LKC-77. Our timescale NLC-80 is structurally very similar to theirs, except that we include a few more events, fix two additional calibration points, and convert the absolute ages of all calibration points to corrected ages using new K-Ar decay constants.

MD-79

In 1977 the Subcommission on Geochronology of the International Union of Geological Sciences recommended the adoption of new atomic abundance and decay constants used in potassium-argon dating. Mankinen and Dalrymple (1979), using the new constants and 354 K-Ar dated igneous rock samples with determined magnetic polarities, compiled a new radiometric polarity timescale for the interval 0-5 MY (Figure 3). It is noteworthy that from anomaly 1 to anomaly 2.3' the revised timescale is very similar to the earlier radiometric scale of Cox (1969) when it is corrected for new K-Ar constants. The boundary ages assigned to anomalies 3.1 through 3.4 were considered less certain by Mankinen and Dalrymple.

Mankinen and Dalrymple also converted the marine magnetic anomaly timescale LKC-77, which is here call MD-79. We emphasize that MD-79 is essentially the scale of LaBrecque et al. (1977), expanded nonlinearly to correct it for the change in K-Ar constants. Dalrymple (1979) published a table for converting western (non-Russian) K-Ar ages, and we present an equation for the same purpose that provides a precision of 10^{-2} MY, using the constants provided in the Mankinen and Dalrymple paper.

$$t_{new} = 1804.1 \ln (1.0728e^{t_{old}/1885} - 0.0728) \quad (1)$$

We use this equation to convert the two biostratigraphic calibration points used in NLC-80, the boundary ages (Table 1) of Cenozoic epochs from Berggren (1972) and Hardenbol and Berggren (1978), the boundaries of Late Cretaceous ages from Obradovich and Cobban (1975), the Icelandic radiometric polarity scales of McDougall et al. (1976a, 1976b, 1977), and the timescale of Cox (1969).

HMW-79

The radiometrically determined polarity timescales illustrated in Figure 1 are composite scales generated by integrating K-Ar dated polarity data obtained from widely separate locations throughout the world. Beyond about 3.5 MY the precision of the K-Ar method begins to approach the average duration of individual polarity events, and the determination of boundary ages becomes increasingly ambiguous. The problem becomes apparent in comparing the various published estimates for the boundary ages of anomalies 3.1 through 3.4. The radiometric scales differ among themselves and are also quite different from marine magnetic anomaly scales (Figure 2) which assume constant local rates of seafloor spreading. K-Ar age determinations made on oceanic basalts are subject to large errors because of hydrothermal alteration and weathering. It is because of this problem, of course, that the older portions of polarity timescales were determined by extrapolating marine magnetic anomaly data.

In Iceland, thick stratigraphic sequences of subaerial lava flows, thought to have extruded at a fairly regular rate, allow the relative age and polarity of lava members to be unambiguously determined. Regression analysis of K-Ar ages onto stratigraphic height data have resulted in the generation of radiometric polarity timescale sections discontinuously ranging from 3.5 to 12 MY. Three of these scales by McDougall et al. (1976a, 1976b, 1977), corrected here for new K-Ar decay constants, are illustrated in Figure 3. The problem of correlating polarity events between the scales of various workers persists, however, as an examination of the various estimates for anomaly 3 and anomaly 3' boundary ages will reveal.

Harrison et al. (1979) integrated the data from several such stratigraphic sections in both eastern and western Iceland. The K-Ar ages ranged over an interval of from about 3 to almost 13 MY. They calculated the difference between the average K-Ar age determinations of particular polarity events and their ages as given by the seafloor spreading timescale MD-79. They found that the K-Ar ages were predominantly greater by about 0.2-0.3 MY. As a results of this analysis, Harrison et al. recalibrated MD-79 at 8.5 and 13 MY.

We agree that the combined paleomagnetic stratigraphy and K-Ar dating on Iceland indicate that the MD-79 boundary ages for magnetic anomalies 3 through 5A should be increased. However, because of scatter in the K-Ar determinations and the noncontinuous nature of the extrusion process, and because there are no lavas exposed on Iceland older than about 13 MY, we feel that the data more readily justify a single recalibration of the marine magnetic anomaly timescale. Accordingly, in NLC-80 we fix anomaly 5.5(o) at 10.30 MY (Figures 2 and 3), consistent with the recalculated radiometric timescale of McDougall et al. (1976a).

Figure 3. NLC-80 boundary ages compared with recently published radiometric timescales. It is noteworthy that that part of the Cox scale younger than about 3.5 MY, when corrected for new K-Ar constants, is very similar to the Mankinen and Dalrymple scale which was published a decade later, and which was based upon about twice as many samples. The similarity between anomaly timescales (e.g. KHMP-75, TWL-71, V-68) and the radiometric timescales (e.g. Cox, 1969; Mankinen and Dalrymple, 1979) is also significant.

Corrected Radiometric Timescales and NLC-80 Calibration Points

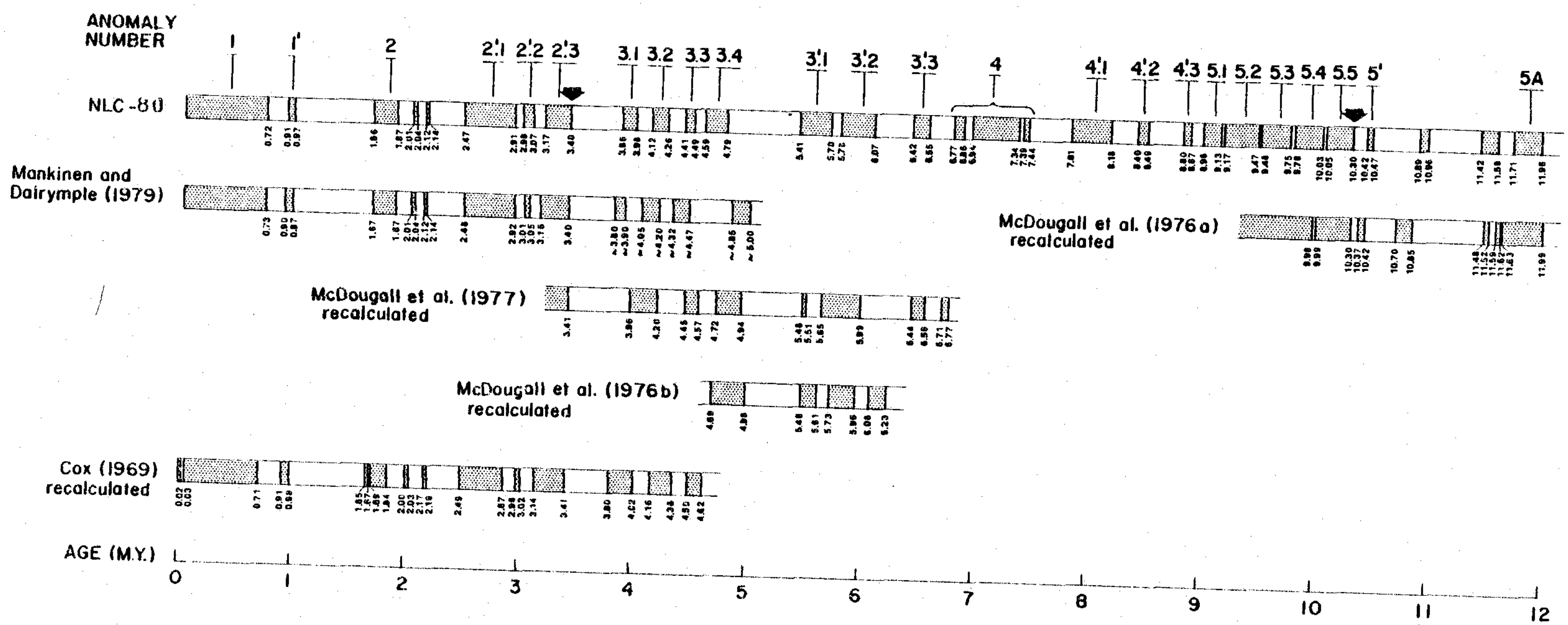


Figure 3.

This accomplishes the purpose of Harrison et al. (1979), within the resolution indicated in their Figure 6, and does not risk introducing an artifical spreading rate change at 13 MY as a timescale artifact.

THE ANOMALY 24 PROBLEM

A graphical summary of oceanic crustal ages determined using biostratigraphic evidence from DSDP sites is presented by LaBrecque et al. (1977, Figure 4). Sites 19, 38M, 39, and 213 yield basal sediments with biostratigraphic ages covering about a 12 MY period in the late Paleocene through late and middle Eocene. Although the precision of these estimates ranges from about 2 to about 6 MY, the ages are all younger by about 2-5 MY than ages predicted by using timescale LKC-77. LaBrecque et al. noted these discrepancies and suggested that the continuous South Atlantic spreading assumption of Heirtzler et al. (1968) may require revision in the Paleogene. However, since there may be systematic errors in Paleogene biostratigraphy, they made no such adjustments.

Tarling and Mitchell (1976) proposed large adjustments to the geologic timescale as previously discussed. Their revised Paleocene-Eocene boundary is about 5 MY younger than that of Berggren (1972), and anomaly 24 was tied to that adjusted boundary by using biostratigraphic evidence from DSDP site 39 published by Sclater et al. (1974) and by the stratigraphic position and isotopic ages of basalts in east Greenland. Berggren et al. (1978) chose not to adjust the age of the Paleocene-Eocene boundary but did adjust anomaly 24 to comply with the site 39 evidence, making its age about 3.5 MY younger than did Berggren (1972).

Figure 4. Interocean spreading rate comparisons of North Pacific, South Pacific, and South Atlantic anomaly age-distance data pertinent to the discussion of adjusting the age of anomaly 24. (a) Original data estimated from Heirtzler et al. (1968). (b) Ages are corrected and anomalies 5 and 29 are fixed using NLC-80 values. (c) Anomaly 24 is fixed at 54.5 MY consistent with Berggren et al. (1978) and with NLC-80. (d) Anomaly 24 is fixed at 49.0 MY consistent with Tarling and Mitchell (1976). Anomaly 6 is interpolated.

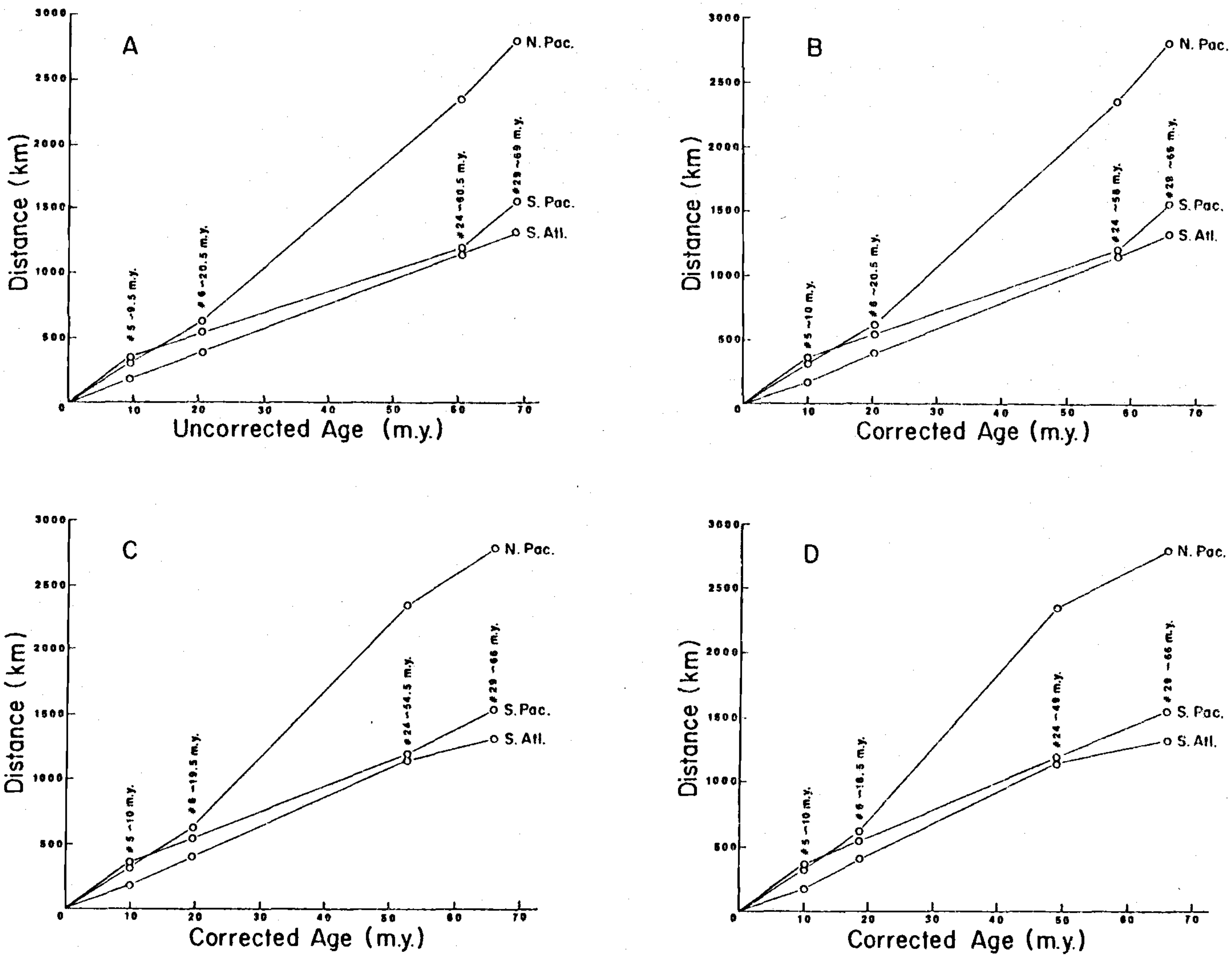

A
B
C
D
Distance (km)
Uncorrected Age (m.y.)
Corrected Age (m.y.)
N. Pac.
S. Pac.
S. Atl.
#5 ~9.5 m.y.
#6 ~20.5 m.y.
#24 ~60.5 m.y.
#29 ~69 m.y.
#5 ~10 m.y.
#24 ~58 m.y.
#28 ~66 m.y.
#6 ~19.5 m.y.
#24 ~54.5 m.y.
#29 ~66 m.y.
#6 ~18.5 m.y.
#24 ~49 m.y.

Figure 4

There is evidence, independent of biostratigraphy, in support of a younger age for anomaly 24. A comparison of the distance from ridge crests to particular anomalies in the North and South Pacific and South Atlantic Oceans (Figure 4a) indicates that, in relation to the assumption of constant spreading in the South Atlantic Ocean, large spreading accelerations occurred in the North Pacific about the time of anomaly 6 and in the South Pacific about the times of anomalies 5 and 24.

It was this comparison that originally led Heirtzler et al. (1968) to reject the South Pacific distance data as a possibly base for developing a standard anomaly timescale. It is important to recognize that at the time that HDHPL-68 was developed, it was necessary to assume that at least one such profile represented the record of a constantly spreading ridge. No convincing, additional calibration points were available apart from the late Neogene radiometric scales published to that time. Since then an important revision to HDHPL-68 has been made by adjusting anomaly 29 to be younger than the Cretaceous-Paleogene boundary. The obvious point is that the assumption of 90 MY of continuous spreading in the South Atlantic Ocean no longer holds. If anomalies 2.3' and 5 are fixed to radiometric scales, and if anomaly 29 is adjusted, then corresponding accelerations are implied in the spreading history of the South Atlantic Ocean.

If anomaly 24 is adjusted, in order to conform with DSDP biostratigraphic results, to the Paleocene-Eocene boundary of Hardenbol and Berggren (1978), an additional acceleration is introduced into the South Atlantic (Figure 4c).

We find it interesting that if anomaly 24 is further adjusted to the age given the Paleocene-Eocene boundary by Tarling and Mitchell (1976), then the spreading record in the South Pacific becomes constant from anomalies 5 to 29 and beyond (Figure 4d). Our problem then becomes one of making the choice of possible adjustments to anomaly 24. While we admit to being intrigued by the possibility of continuous South Pacific spreading prior to 10 MY, but recognize that it is not required. It seems quite possible that if major, long-term spreading rate changes occur at the boundary of a large plate pair, these changes in motion could (or perhaps even should) be reflected eventually in the motions of other large plates, either by coupling across adjacent plate boundaries or perhaps by some sort of worldwide responses to changes in mantle convection rates. However, the entire topic of plate-driving mechanisms is speculative and we do not presume that this effect be required.

We select the more conservative adjustment and fix anomaly 24 at about 55 MY, consistent with the findings of Hardenbol and Berggren (1978). This provides relatively good agreement between timescale NLC-80, radiometric dates and other anomaly timescales over the interval of 3.4-12 MY. Adjustments to anomaly 24 affect this portion of the timescale by extrapolation and interpolation.

At present, Butler and Lindsay (1979) are compiling the magnetic stratigraphy of Paleocene and lower Eocene continental deposits in the Big Horn Basin of Wyoming. They have clearly identified anomalies 25 and 26 in the Paleocene and a long reversed interval younger than anomaly 25 that extends at least into the lowermost Eocene. Thus the biostratigraphic age of anomaly 24 would appear to be at least as young as the Paleocene-Eocene boundary--the value to which we adjusted it. It may even result that the absolute age for anomaly 24 proposed by Tarling and Mitchell is right but for what we consider to be wrong reasons. Continuing work on the problem, both in Wyoming and in the Italian sections, will be watched with interest.

CONSTRUCTION OF MAGNETIC ANOMALY TIMESCALE NLC-80

1. From anomaly 1 to anomaly 3.4(o) we use timescale KHMP-75 and fix anomaly 2.3'(o) at 3.40 MY, consistent with the new radiometric age determination for that polarity reversal boundary made by Mankinen and Dalrymple (1979). The conversion equation is

$$t = \left[\frac{3.40}{3.32} K \right] \tag{2}$$

where K is the age given in KHMP-75. Thus anomalies 3.1 through 3.4 are extrapolated beyond 3.40 MY on the assumption of constant seafloor spreading. The Réunion events of Mankinen and Dalrymple (1979) are added by interpolation between anomalies 2 and 2.1'.

2. From anomaly 24(o) to anomaly 29(o) we fix anomaly 24(o) at the Eocene-Paleocene boundary of Hardenbol and Berggren (1978), recalculated for new K-Ar constant at 54.9 MY. We next recalculate the Cretaceous-Paleogene boundary of Hardenbol and Berggren (1978) to be 66.7 MY and assume the same relative position for that boundary with

respect to ancmalies 29(o) and 30(y) in timescale HDHLP-68 as that used by LaBrecque et al. (1977) in timescale LKC-77. HDHPL-68 is then interpolated between 24(o) and the Creaceous-Peleogene boundary using the conversion equation

$$t = \left[\frac{H - 60.53}{69\text{-}54 - 60.53} \right] (66.7 - 54.9) + 54.9 \qquad (3)$$

where H is the age given in HDHPL-68. Those polarity reversals from the study of Blakely and Cox (1972a) supported by the three-axis magnetometer study of Blakely et al. (1973) are interpolated into this portion of the recalibrated scale.

3. From anomaly 4.1'(y) to anomaly 24(o) we tie anomaly 5.1(y) from timescale B-74 to the corresponding date used in HDHPL-68 so that no artificial acceleration is introduced near anomaly 6A. B-74 is fit into HDHPL-68 using the equation

$$B' = \left[\frac{B - 8.71}{(21.31 - 8.71)} \right] (21.31 - 8.79) + 8.79 \qquad (4)$$

where B is the age given in B-74. This yields an interim age for anomaly 5.5(o) of 10.28 MY (uncorrected for new K-Ar constants). We then fix anomaly 5.5(o) at 10.30 MY using the radiometric age for that polarity reversal boundary determined by McDougall et al. (1976a) here corrected for new K-Ar constants (see Figure 3). The B' values from anomaly 4.1'(y) to anomaly 6A(o), and the HDHPL-68 timescale from anomaly 6A(o) to anomaly 24(o) are then calculated using the equation

$$t = \left[\frac{B' (\text{or } H) - 10.28}{(60.53 - 10.28)} \right] (54.9 - 10.30) + 10.30 \qquad (5)$$

Anomaly 14 is omitted, consistent with LaBrecque et al. (1977).

4. Between anomalies 3.4(o) and 4.1'(y) we interpolate HDHPL-68 using the conversion equation

$$t = \left[\frac{H - 5.01}{(7.91 - 5.01)} \right] (7.81 - 4.79) + 4.79 \qquad (6)$$

5. From anomalies 29(o) to 34(y) we extrapolate the timescale LKC-77 from relocated anomaly 23(y), at 52.69 MY, to beyond the Cretaceous-Paleogene boundary at 66.7 MY, consistent with the procedure used by LaBrecque et al. (1977). The conversion equation is

$$t = \left[\frac{L - 65.0}{(65.0 - 54.29)} \right] (66.7 - 52.69) + 66.7 \qquad (7)$$

where L is the age given in LKC-77.

CONCLUSIONS

Timescale NLC-80 is at best of temporary utility. We anticipate that further, more precise adjustments to the age of anomaly 24 are justified and will soon be suggested by several groups of workers. This is turn may require that the age of anomaly 34(y) be fixed, so that its newly extrapolated spreading age will not radically violate its biostratigraphic age. Ironically, this may result in the introduction of an artifical spreading rate change at anomaly 29 time. There is, in addition, some evidence that suggests that the age of anomaly 6 may require adjustment. This in turn will affect by extrapolation those portions of the timescale between anomalies 2.3' and 5.1. While we have carefully tried to avoid both circular reasoning and the introduction of artifical spreading rate changes in the construction of NLC-80, we still lack confidence in its accuracy, particularly between anomalies 2.3' and 5.5 where most of the cutting and splicing have been done.

Timescale NLC-80 is also at best a critical reshuffling of some very old cards from some very different decks. Its accuracy, or the accuracy of any anomaly timescale, is ultimately limited by the quality of the anomaly-versus-distance data used to make it up. Most of these data were acquired prior to the advent of plate tectonics, from ship tracks which were set out for other purposes and which were sailed using low-accuracy navigation systems. Thus detailed, fine-scale calibrations of anomaly timescales may be meaningless unless the quality of the data base itself is improved first.

Within the last decade, very accurate navigation systems have become available to the marine science community. Knowledge of the various structural features of the seafloor has greatly increased. Geometrical methods for determining and describing plate motions have become more powerful. New signal-enhancing techniques have been applied to the analyses of marine magnetic data. New radiometric techniques have been developed that may be of great utility in determining the absolute ages of submarine basalts, and deep sea drilling hole reentry and continuous sampling capabilities have been developed, all of which now make it possible to completely re-examine the general problem of marine magnetic anomalies by initiating a field program specifically and exclusively designed to develop a new, high-precision magnetic anomaly timescale.

The results of such a program would have valuable, fundamental application to many diverse fields of research including plate tectonic reconstructions, core magnetostratigraphy, biostratigraphy, geomagnetic field reversal frequency studies, oceanic age-depth relationships, crustal evolution studies, ridge processes, and multiplate geometrical studies.

We feel that such a program is not only desirable but necessary. First-generation anomaly timescales have successfully served their purpose but are nearing the ultimate limit of their accuracy. Second-generation tectonics analyses will require a second-generation timescale. Unfortunately, such a program, if properly organized, would be an expensive, multi-ocean, multi-ship, multi-institution cooperative effort. Such a project can only be initiated with the broad support of the geological community.

SECTION II

BATHYMETRY AND OCEANIC CRUSTAL AGES IN THE VICINITY OF THE MOUTH OF THE GULF OF CALIFORNIA ILLUSTRATED USING DEEP SEA DRILLING PROJECT LEG 63 UNDERWAY GEOPHYSICAL PROFILES

THE DATA BASE

Since 1975 researchers of the School of Oceanography at Oregon State University and of the Dirección General de Oceanografia, an agency of the Mexican Secretaría de Marina, have participated in a cooperative marine geophysical research program intended to construct a reconnaissance scale geophysical atlas of the Pacific economic zone of Mexico. Toward this end, four survey cruises have been conducted using vessels of the Mexican Navy to obtain underway bathymetric, gravimetric, and magnetic data. Because of the rigorous navigational requirements inherent in measuring gravity at sea, and because useful LORAN-C coverage does not exist off the Pacific coast of Mexico, the cruises were designed as "steaming cruises." Few station data were collected; tracklines were laid out to be long and straight in order to minimize the number of Eötvös discontinuities introduced into observed gravity with course and speed changes.

We merged all the Mexican project data with the considerable volume of geophysical data previously acquired off Mexico by research vessels of Oregon State University. The whole was iteratively renavigated to minimize trackline crossing errors, while we paid particular attention to calculated versus observed Eötvös discontinuities.

By repeated calculation and comparison, a tedious process that in effect treats the shipboard gravimeter as an inertial navigation instrument, a large internally consistent set of well-navigated geophysical survey tracklines of the Pacific margin of Mexico has been generated. Those tracks within the subject area of this report are illustrated in the inset to Figure 5.

These data and additional data of comparable accuracy (obtained from the National Geophysical and Solar-Terrestrial Data Center and the Defense Mapping Agency) were used to construct a set of marine geophysical maps of the region west of Baja California (Calderon R. and Couch, 1980). Values for the root-mean-square of the crossing errors for the free-air gravity anomaly maps of this region ranged from 2.0 to 4.6 mgal (2-0 to 4.6 X 10^{-5} m/s^2), with an estimated overall positional accuracy of 2 km. In this study we use part of the same high-quality data set along with DSDP Leg 63 bathymetric, magnetic, and single-channel seismic reflection profiles between Sites 471, 472, and 473 to construct two maps of the region near the mouth of the Gulf of California.

A bathymetric map (Figure 5) contoured at a 200 meter interval was constructed using, in addition to the data discussed above, other recently published maps of parts of the region as underlays. These include maps of the Rivera Fracture Zone and vicinity by Mammerickx et al. (1978), the Gulf of California proper by Bischoff and Niemitz (1980), and the Tamayo Fracture Zone as mapped by Lewis et al. (1979). We also used certain renavigated bathymetric profiles for the region west of Baja California provided by William Normark of the U. S. Geological Survey. Line drawings of Leg 63 single-channel seismic reflection profiles are included as part of Figure 5.

We constructed an oceanic crustal isochron map (Figure 6) indicating the age of the deep seafloor in millions of years (MY). The isochrons were interpreted from marine magnetic anomaly profiles as fitted to time scale NLC-80 (Ness et al., 1980). The map was compiled from Mexican project data and DSDP Leg 63 profiles. Additional magnetic anomaly profiles from other sources were examined, in particular the profiles west of Baja California illustrated by Chase et al. (1970), when our own Mexican project data were inadequate. We made no attempt to renavigate magnetic profile data from other sources or to integrate them with our files because the bulk of the available information was obtained on cruises conducted prior to the advent of non-military satellite navigation systems and because gravity data were not obtained during those cruises.

In summary, the two maps compiled for this report are based primarily on our own data set; we are reasonably confident of the navigational accuracy of these data. The maps cover a swath extending approximately 100 km to either side of the DSDP Leg 63 tracklines connecting Sites 471, 472, and 473; they were designed specifically to provide physiographic and tectonic background information pertinent only to Leg 63 objectives. An interpretation of the tectonic history of the mouth of the Gulf of California region, based upon Leg 63 results, is presented by Yeats in the Leg 63 green volume. Ness, Sanchez Z. and Couch are presently preparing a more extensive discussion of the tectonic history of the central portion of the Pacific margin of Mexico on the basis of the OSU/DGO Mexican project data.

BATHYMETRY AT THE MOUTH OF THE GULF

For clarity and economy we refer to that section of the East Pacific Rise located between the Rivera and Tamayo fracture zones as the Rivera Ridge, and that portion of the Middle America Trench north of the Rivera Fracture Zone at the Rivera Trench. We name the thick fan of sediments found at the base of the continental slope, southwest of Magdalena Bay, the Magdalena Fan. DSDP Site 471 is located on this feature (Figure 5 and Figure 5 section). The fan extends westward from the slope base at 3000 meters depth to a swale marked by the 3600 meter contour just south and east of a prominent seamount located near 23.4°N, 113.3°W. A single-channel seismic reflection profile, here labeled DSDP-63N, indicates that the western edge of the fan, or the eastern side of the swale, is marked by a small basement high. The fan extends to the north as far as 24.2°N, 112.7°W, and to the south as far as 23.3°N, 111.8°W. Bathymetrically it appears to be fault-bounded at both sides. The seismic reflection profile DSDP-63N indicates that the fan is more than 1.75 s thick near the slope base where oceanic basement dips toward the northeast beneath Baja California. A pronounced free-air gravity anomaly minimum extends along the base of the continental slope west of the peninsula (Huehn, 1977; Coperude, 1978; Calderon R., 1979; Calderon R. and Couch, 1980). It is contiguous with the Cedros Trough far to the northwest. In the region south of Cabo San Lázaro it apparently marks the sediment-covered extension of that feature in the subsurface, which is generally interpreted to be a fossil subduction zone. Near 23°N, 111°W, the axis of this minimum (labeled as the approximate base of the continental slope in Figure 6)

Figure 5. Bathymetry and DSDP Leg 63 seismic reflection profiles at the mouth of the Gulf of California. The inset shows the survey tracklines used to prepare the bathymetric map. Line drawings of DSDP Leg 63 1000 in^3 airgun records are shown at the bottom. Note the clear bathymetric expression of the Magdalena Fan and the Ulloa Fracture Zone. Also note the generally complicated bathymetry west of the peninsula.

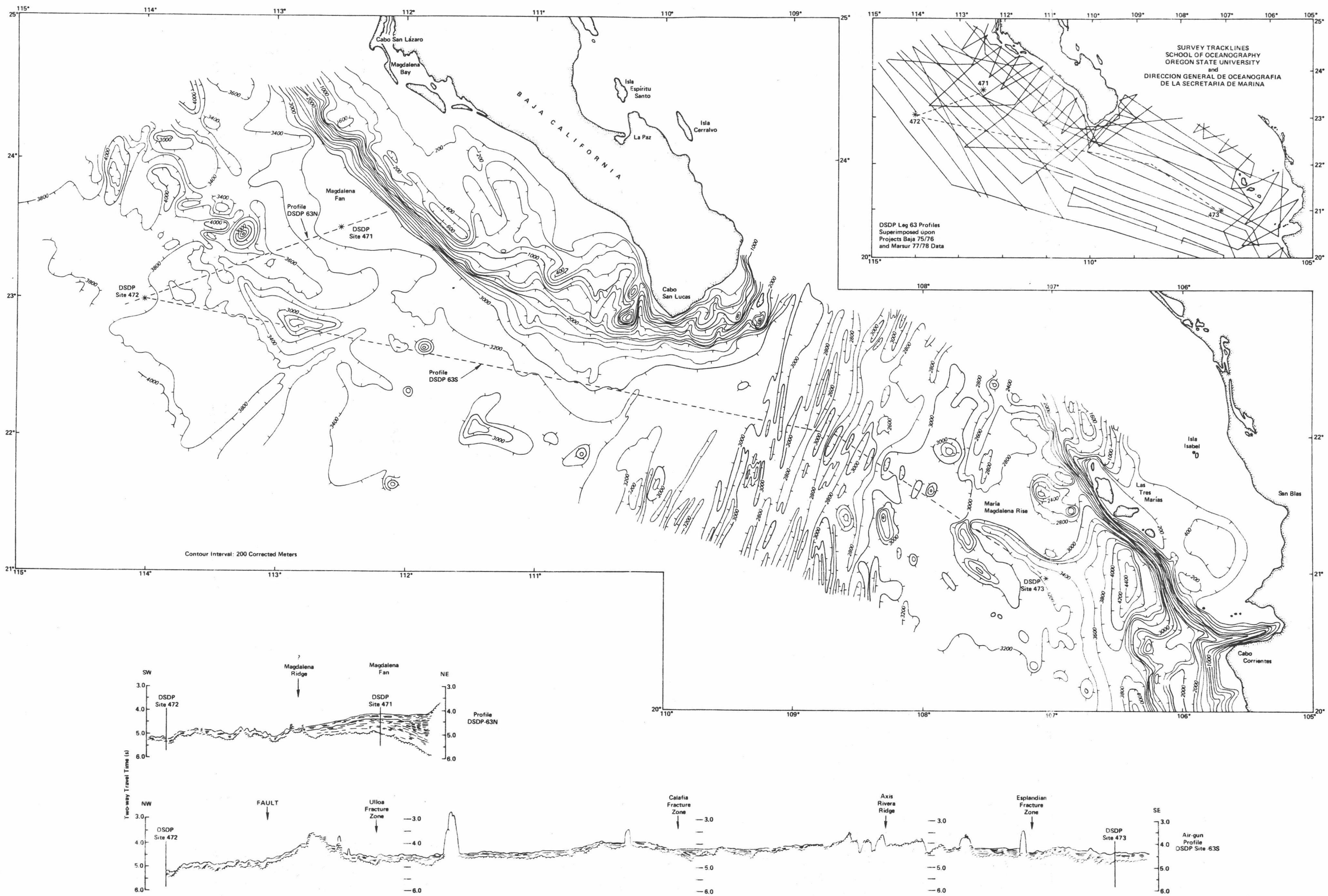

Cabo San Lázaro
Magdalena Bay
BAJA CALIFORNIA
Isla Espíritu Santo
La Paz
Isla Cerralvo
Magdalena Fan
Profile DSDP 63N
DSDP Site 471
DSDP Site 472
Cabo San Lucas
Profile DSDP 63S
Contour Interval: 200 Corrected Meters
SURVEY TRACKLINES
SCHOOL OF OCEANOGRAPHY
OREGON STATE UNIVERSITY
and
DIRECCION GENERAL DE OCEANOGRAFIA
DE LA SECRETARIA DE MARINA
DSDP Leg 63 Profiles
Superimposed upon
Projects Baja 75/76
and Marsur 77/78 Data
Isla Isabel
Las Tres Marías
San Blas
María Magdalena Rise
DSDP Site 473
Cabo Corrientes
SW
NE
Magdalena Ridge
Magdalena Fan
Profile DSDP-63N
Two-way Travel Time (s)
NW
SE
FAULT
Ulloa Fracture Zone
Calafia Fracture Zone
Axis Rivera Ridge
Esplandian Fracture Zone
Air-gun Profile DSDP Site 63S

Figure 5

forms a small cusp where several pronounced gravimetric lineations meet. This trouch, and presumably the thick wedge of sediments masking it, extends to the south and east of Cabo San Lucas at the tip of the peninsula.

The physiography of the deep seafloor west of the continental slope of the peninsula is quite complicated. At least four small depressions deeper than 4000 meters exist in the region. One, near 24°N, 114.3°W, appears in map view to be fault-bounded and is more than 4400 meters deep. We can recognize no dominant bathymetric trend in the region north of 23°N and west of 113°W. However, bathymetry and discontinuities in the crustal isochrons allow us to identify at least one probable fault, here called the San Lázaro Fracture Zone. In general, the major structural characteristics of this particular area are of a scale finer than our trackline separation. However, two other significant features may be recognized in the bathymetry of the region west of Cabo San Lucas.

First, a well-defined trough extends toward the northeast from 22°N, 113.5°W and meets the slope base at 23.3°N, 111.7°W. It is noteworthy that this feature, here called the Ulloa Fracture Zone, meets the peninsula at a point where the character of the continental shelf and slope abruptly changes. Several linear bathymetric features are truncated along a line extending onto the continent from the Ulloa Fracture Zone, but this may be coincidental.

Second, an unusual bathymetric high is located near 22.8°N, 112.8°W. In map view it is triangular in outline, bounded to the southeast by the Ulloa Fracture Zone, and to the southwest by a bathymetric gradient that also appears to offset the magnetic anomaly pattern near 22.8°N, 113.5°W, and to the northeast by a long trough about 3600 meters deep marking the distal part of the Magdalena Fan. Thus it appears to be fault-bounded on at least two, and perhaps all three, sides. In profile view (Figure 5 section) the feature is unusual in appearance. It is distinct from typical seamount profiles, such as the one located farther east along the same section. The feature is approximately 50 km wide along this DSDP track and exhibits about 1000 meters of relief. It looks more like a ridge crest in profile than does the actual Rivera Ridge, which is located farther east.

East of 110°W, the linear ridge and trough province of the actively spreading Rivera Ridge trends toward the north-northeast and generally lies above 3000 meters depth. It is not possible to locate the precise spreading axis from bathymetry data alone or, for that matter, from magnetic anomalies with or without bathymetry. Two fairly deep troughs, both relatively free of sediment fill, occur near the ridge axis. Both, however, are discontinuous along the trend of the ridge, and the approximate middle of the central magnetic anomaly is located east of the two troughs. The situation is additionally confused because the DSDP profile (Figure 5) crosses the ridge very near where we propose a small left offset in the spreading axis. From the ridge area to Site 473 the DSDP Leg 63 track runs parallel and very near to a fracture zone trending northwest from 21°N, 107°W. This feature, named Fracture Zone W by Mammerickx (1980) and here called the Esplandian Fracture Zone, is very well defined bathymetrically as far west as about 107.7°W, where the Leg 63 profile may actually cross it. We believe that the fracture zone may extend to the ridge crest at 22°N on the basis of seismic activity and offsets in magnetic anomalies (to be discussed later). This fault also appears to extend across the Rivera Trench into continental crust at the slope base just west of Cabo Corrientes.

The DSDP-63S profile (Figure 5 section) illustrates a broad, gentle rise in acoustic basement immediately southwest of Cabo San Lucas that seems to be related to proximity with the peninsula. This rise lies seaward of the gravitational trough previously discussed and may represent an outer trench high caused by flexure of the lithosphere. If so, the profile would be tangent to the high that bends around the tip of the peninsula. In any case the feature is not a sediment fan, as it might appear in map view.

Just east of the high there is a small depression in the bathymetry that is parallel to the trend of the ridge and trough province. The seismic reflection profile shows it to be adjacent to a pronounced sediment-filled basement low. On the basis of offsets in the magnetic anomalies (to be discussed in the next section) we consider this basin to be part of a long, east-trending fault, here called the Calafia Fracture Zone.

Finally, seismic activity and offsets in both bathymetry and magnetics aid us in recognizing a second left offset in the Rivera Ridge, here called the Montalvo Fracture Zone, located at 21.2°N, 108.9°W.

In summary, the bathymetry of the region west of southern Baja California is complicated. By limiting our data set only to that information we consider to be reliably located, we have sacrificed some resolution, but we are confident that our interpretation is at least not overly affected by faulty navigation. To some extent, analysis of the magnetic anomalies will enable us to better define the location and orientation of certain faults immediately west of the peninsula. Two major faults in the study area are quite visible from the bathymetry alone. These are the Ulloa and Esplandian fracture zones, both of which may extend into the continental crust.

OCEANIC CRUSTAL ISOCHRONS AT THE MOUTH OF THE GULF

Total magnetic field anomalies were determined by application of 1975 International Geomagnetic Reference Field values to values measured along the track lines indicated in Figure 5. These were then compared with synthetic magnetic anomaly profiles generated using the method of Talwani and Heirtzler (1964). Marine magnetic anomaly time scale NLC-80 (Ness et al., 1980) was used as a time base. The synthetic anomaly profile illustrated at the bottom of Figure 6 is similar to that which would be measured at the sea surface, over 3000 meters of water, with magnetic source bodies of 500 meters thickness, an assumed half-spreading rate of 30 km/MY at the Rivera Ridge, and a ridge trend of 25°. The asymmetry of the calculated anomalies, caused by the 25° departure of the spreading ridge from a north-south orientation, requires an adjustment in assigned ages depending upon whether peaks are located east or west of the ridge crest. These ages were proportioned from the NLC-80 time base, and the observed anomalies (along the tracks illustrated in the inset to Figure 5) were assigned ages to tenths of millions of years. DSDP Leg 63 magnetic anomaly profiles DSDP-63N and

-63S are illustrated in Figure 6 and show the age assignments we made to them. The crustal isochron map is the result of all such correlations made between observed magnetic anomaly profiles in the study area.

The axis of the Rivera Ridge as indicated in Figure 6 was located by interpolation to zero age between the youngest isochrons on either side of the ridge. Because of the possibility of spreading asymmetries younger than 0.7 MY, the actual axis of divergence may be located slightly differently than we specify here.

The profiles from earlier studies of the magnetics of the Rivera Ridge area (e.g., Larson, 1972) and later studies that used the same data base (e.g., Mammerickx, 1980) were not integrated into this work, because we lack confidence in their navigational accuracy. West of southern Baja California, and in particular west of 114°W, however, our Mexico project data were insufficient, and so we examined older profiles illustrated in Chase et al. (1970) to try to determine crustal ages seaward of DSDP Site 472.

The crustal isochrons on the Pacific flank of the Rivera Ridge appear to have been parallel to the ridge back to at least 2.0 MY. Progressively older isochrons on the Pacific plate appear to have fanned anticlockwise very slightly between 2 MY, and 6.5 MY, and more strongly between 6.5 MY and 9 MY. On the Rivera plate south of the Esplandian Fracture Zone, the same anticlockwise fanning of older isochrons appears to begin at 2.5 MY and by 7.3 MY the oldest identifiable positive anomaly are oriented almost north-south. On the Pacific side, this due north-south orientation occurred at about 9 MY. North of the Esplandian Fracture Zone the isochrons were approximately parallel to the ridge back to 5.3 MY except very near the fracture zone

Figure 6. Oceanic crustal isochrons at the mouth of the Gulf of California. The synethetic anomaly profile was generated using timescale NLC-80. The inset shows the apparent flank spreading rates on the Rivera Ridge. Note the anomaly symmetry about the Magdalena Ridge, and the large number of anomaly offsets west of the peninsula.

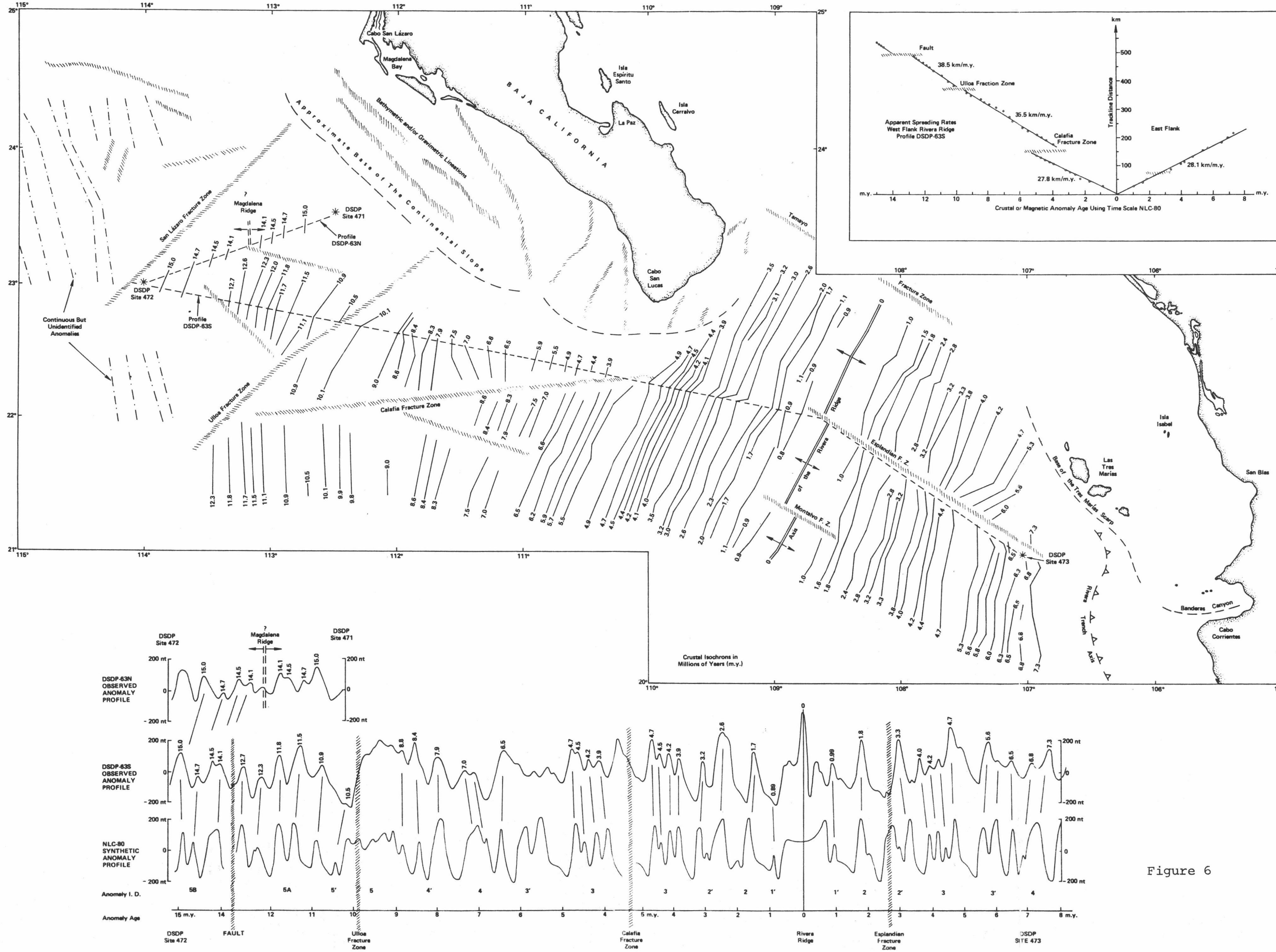

Cabo San Lázaro
Magdalena Bay
Isla Espíritu Santo
Isla Cerralvo
La Paz
BAJA CALIFORNIA
Cabo San Lucas
Bathymetric and/or Gravimetric Lineations
Approximate Base of The Continental Slope
San Lázaro Fracture Zone
Magdalena Ridge
DSDP Site 471
DSDP Site 472
Profile DSDP-63N
Profile DSDP-63S
Continuous But Unidentified Anomalies
Ulloa Fracture Zone
Calafia Fracture Zone
Tamayo Fracture Zone
Axis of the Rivera Ridge
Esplandian F. Z.
Montalvo F. Z.
DSDP Site 473
Base of the Tres Marias Scarp
Rivera Trench Axis
Las Tres Marias
Isla Isabel
San Blas
Banderas Canyon
Cabo Corrientes
Crustal Isochrons in Millions of Years (m.y.)
Apparent Spreading Rates West Flank Rivera Ridge Profile DSDP-63S
Fault
38.5 km/m.y.
Ulloa Fraction Zone
35.5 km/m.y.
Calafia Fracture Zone
27.8 km/m.y.
East Flank
28.1 km/m.y.
Trackline Distance km
Crustal or Magnetic Anomaly Age Using Time Scale NLC-80
DSDP-63N OBSERVED ANOMALY PROFILE
DSDP-63S OBSERVED ANOMALY PROFILE
NLC-80 SYNTHETIC ANOMALY PROFILE
Anomaly I. D.
Anomaly Age
DSDP Sites 472
FAULT
Ulloa Fracture Zone
Calafia Fracture Zone
Rivera Ridge
Esplandian Fracture Zone
DSDP SITE 473

Figure 6

itself. We estimate the basement age of DSDP Site 473 to be about 6.5 MY from the isochron map and the DSDP-63S profile correlation (Figure 5).

We interpret progressively older anomalies back to at least 5.3 MY in the section of the Rivera plate north of the Esplandian Fracture Zone. This disagrees with the findings of Mammerickx (1980), who proposed the existence of an aborted 3.5 MY spreading center on the topographic high due west of the Tres Marias Islands at 21.5°N, 107°W. This feature, named the Maria Magdalena Rise by Mammerickx, is bounded approximately by the 3000 meter depth contour. Our bathymetry, which differs slightly from that of Mammerickx, shows a narrow high (at 2600 meters depth) located at 22°N, 107.5°W (Figure 5). This feature could constitute physiographic evidence in support of her proposed ridge, however, our interpretation of the magnetic anomalies is that this feature is on crust 3.8 to 4.0 MY old, with progressively older anomalies to the east. Furthermore, the 2600 meter bathymetric high is located on the western edge of the Maria Magdalena Rise, which contradicts the age-depth relationship required by the aborted ridge model of Mammerickx.

Our interpretation of the magnetic anomalies of the study area does not support the existence of Fracture Zone X of Mammerickx. Her Fracture Zone Y similarly has no definite magnetic expression, but does appear bathymetrically to be in line with the left-offset montalvo Fracture Zone, which we show at the Rivera Ridge on the basis of magnetic and bathymetric offsets and, in particular, on the basis of recurrent seismic activity.

If our interpretation of the magnetic anomalies near the Esplandian Fracture Zone is correct, then an unusual tectonic history is indicated in the crustal isochron pattern. Note that the fracture zone shows no offset from 1.0 to 2.4 MY, that it appears to be right-offset from 2.4 to perhaps 4.7 MY and that it may be left-offset beyond 4.7 MY, depending upon the reality of the kinks in the isochrons at 4.7, 5.3, 5.6, and 6.0 MY. The fracture zone may have multiple traces near 107°W. At the western end of the fracture zone we propose a small left offset of the Rivera Ridge younger than 1 MY. Note also that the fracture zone does not have bathymetric expression west of the ridge. All of this implies a complicated spreading history, possibly involving several periods of minor asymmetrical spreading, and also perhaps requiring the past existence of an independent northern segment of the Rivera plate.

If we are correct in denying the presence of an aborted ridge west of the Tres Marias Islands, then the asymmetrical location of the Rivera Ridge, and the contrast in oldest anomaly ages on either side of the gulf seem to require that crust older than 3.5 MY was subducted northwestward beneath the southeastern tip of Baja California, as proposed by Huehn and Couch (1976). This is, of course, kinematically possible, provided that at least the southernmost portion of Baja California be decoupled from the Pacific plate during the time of subduction. This in turn would imply right lateral strike-slip motion along the west side of the peninsula similar, for example, to that proposed by Spencer and Normark (1980).

Finally, the anticlockwise fanning of anomalies with distance from the ridge found on both the Pacific and Rivera plates indicates that the Rivera Ridge began rotating clockwise, acting independently of the East Pacific Rise, at approximately the young boundary age of anomaly 5 (~9 MY) as proposed earlier by Ness and Lynn (1975).

South and west of southern Baja California, the pattern of isochrons is very complicated. The observed magnetic anomalies along profile DSDP-63S show a repetition of anomaly 3 immediately south of Cabo San Lucas. Anomaly 3' is difficult to identify farther west, but the correlations of anomalies 4, 4', and 5 are convincing. Apparent spreading half-rates measured along this profile (Figure 6 inset) increase at about 5 MY from 28 to 36 km/MY. We identify this offset as the eastern end of what is here called the Calafia Fracture Zone. A series of isochron offsets older than 5 MY extend this feature to the west as far as 112.5°W, and differences in isochron orientation extend it farther west to about 113.3°W. It has very little bathymetric expression but may bound the northern flank of a topographic high near 22°N, 111.5°W. This feature is in turn bounded to the south by an unnamed fracture zone older than 6.5 MY trending east-southeast as defined by isochron offsets.

Farther west along the DSDP-63S profile, a slight change in apparent spreading half-rate occurs at the Ulloa Fracture Zone. We can only convincingly identify the 10.9 MY isochron across the length of the fracture zone. Other profiles provide no help. But, if our 10.9 MY correlation is correct, it is noteworthy that there is very little offset in isochrons across the Ulloa Fracture Zone, despite the fact that it has pronounced bathymetric definition.

Another isochron offset is observed at about 13 MY along the DSDP-63S profile. We have no additional magnetic evidence to help define its orientation. A bathymetric gradient trends in the direction indicated and intersects the Ulloa Fracture Zone at 113°W where that feature has a slight change in trend.

The western end of profile DSDP-63S is characterized by anomalies that are similar to the synthetic anomalies from 14 to 15 MY. This similarity is certainly not ideal, but the interpretation made is consistent with the rest of the profile. We attempted to use the profiles illustrated in Chase et al. (1970) to help confirm our correlation, but found that the anomalies shown were very difficult to identify by comparison with synthetic anomalies. The dot-dash lines on Figure 6 mark the positive peaks of anomalies that we could recognize as continuous between profiles. We could not project them north of 22.5°N or south of 23°N with confidence. Therefore our estimate of 15.2 MY for the crustal age at DSDP Site 472 is made exclusively on the basis of our own data. It is, however, in agreement with the anomaly identifications made by Chase et al. (1970).

One possible explanation for our inability to identify the anomalies shown by Chase et al. is that the timescale (NLC-80) used in this study incorporates the North Pacific, anomaly 4 to anomaly 6 timescale of Blakely (1974). This postdates the timescale used in Chase et al. Assuming that the Blakely timescale is accurate, and we do, then the anomalies west of ~114°W in this study are either or a radically different age than that given by Chase et al. or are a product of nonconstant spreading. Lacking more detailed survey tracklines, we can only pose the problem.

Profile DSDP-63N connects Sites 471 and 472. We emphasize the very good correlation between the 63N and 63S profiles from 14 to 15 MY. However, the eastern half of DSDP-63N is difficult to correlate with synthetic anomalies. Paleontological evidence presented in the Leg 63 green volume indicates that the basement ages of Sites 471 and 472 are similar, implying either a large fault offset somewhere between the sites or an aborted ridge located midway between them. Both possibilities seemed unlikely to the first three authors of this report when they read the Leg 63 onboard results article (Haq et al., 1979). It seemed more likely that the problem posed by the similar dates was due to difficulties in the biostratigraphy. We tried to fit profile DSDP-63N to DSDP-63S, and to constant spreading synthetic anomaly profiles, but kept coming back to the mirror symmetry of DSDP-63N about its midpoint. The eastern half of that profile certainly does not fit corresponding points in Profile DSDP-63S. The most reasonable conclusion that we could reach is that Site 471 basement is indeed as old or slightly older than Site 472 basement, and we here estimate its age at 15.5 MY.

This is not a completely satisfying conclusion, because it requires the rather ad hoc presence of a fault trending approximately east from 23.3°N, 113.1°W. It is possible that the swale marking the distal part of the Magdalena Fan is fault-controlled, as previously discussed. In this case the topographic high near 23°N, 113°W would be fault-bounded on all three sides. In our isochron map we indicate that this fault terminates at the aborted spreading center, here named the Magdalena Ridge. We estimate the age of the ridge to be about 13.7 MY, if it exists. The fault probably continues west of the ridge, but we are unable to determine its orientation.

SECTION III

A RECONNAISSANCE SCALE GEOPHYSICAL SURVEY OF THE SOUTHERN GULF AND THE MOUTH OF THE GULF OF CALIFORNIA

MARINE GEOPHYSICAL DATA USED IN THIS STUDY

Since 1975, geophysicists from the School of Oceanography at Oregon State University have participated in a cooperative marine research program with scientists from the Dirección General de Oceanografía intended to map the reconnaissance scale geophysical feature of the Pacific economic zone of Mexico. Underway geophysical data, including bathymetric gravimetric and magnetic data, were obtained on cruises conducted in 1975, 1976, 1977, and 1978 aboard DGO directed research vessels of the Armada de Mexico. These data have been merged with the large volume of geophysical observations made in the region by OSU research vessels working on other programs, and the whole data set has been rigorously renavigated. In this study we have used part of it to examine the mouth of the Gulf of California.

The importance or validity of any conclusions reached here is ultimately dependent upon the quality of the position information in the data set. Navigational accuracy is the limiting factor in measuring gravity while underway at sea. A one degree error in determining the course made good can cause an error in reduced gravity of as much as 1.6 mgal (1.6×10^{-5} m/sec^2), and a tenth of a knot error in east-west components of velocity can cause a gravity error of as much as 0.75 mgal. Since milligal-order accuracy is desired, we pay considerable attention to the navigation problem. No useful loran coverage exists in the study area. Non-differential Omega is subject to large propagation errors.

Navigational satellite units provide absolute, but non-continuous position information. Therefore, individual survey transects were planned to be long, single-directional, and to have one end or even both ends located by land fixes, if possible. Figure 7 shows the zig-zag pattern of transects we typically employed in the region to help deal with the navigation problem.

All shipboard navigation files were iteratively adjusted by minimizing crossing errors between all OSU/DGO transects, and particularly by comparing calculated with observed Eötvös discontinuities occurring at course and speed change points along individual transects. By adjusting the navigation until the differences between these are minimum we, in effect, treat the gravimeter as an inertial navigation unit. Although the process is tedious, it yields gravity values (and therefore, navigational positions) that we are confident of.

Other studies using part of this data set, made on the west side of the peninsula of Baja California by Huehn (1977), Coperude (1978), and Calderon R. (1978), have RMS trackline crossing errors in gravity of 3.6, 3.5, and 4.6 mgals respectively. A study of the larger region extending from Guaymas to Lazaro Cardenas, made by Sanchez Z. (1981), yielded an RMS crossing error in gravity of 5.0 mgals. This is half of the contour interval we use for mapping gravity anomalies. We estimate the overall positional accuracy of this complete OSU/DGO data set to be better than two nautical miles (∿4 km). Our tracklines are nominally ten nautical miles (∿20 km) apart or less.

Figure 7. Geophysical tracklines made by research vessels of Oregon State University and the Direccion General de Oceanografia of Mexico. All tracks have been renavigated to gravity quality as discussed in the text. The wide lines across the mouth of the gulf show the locations of illustrated bathymetric and magnetic profiles.

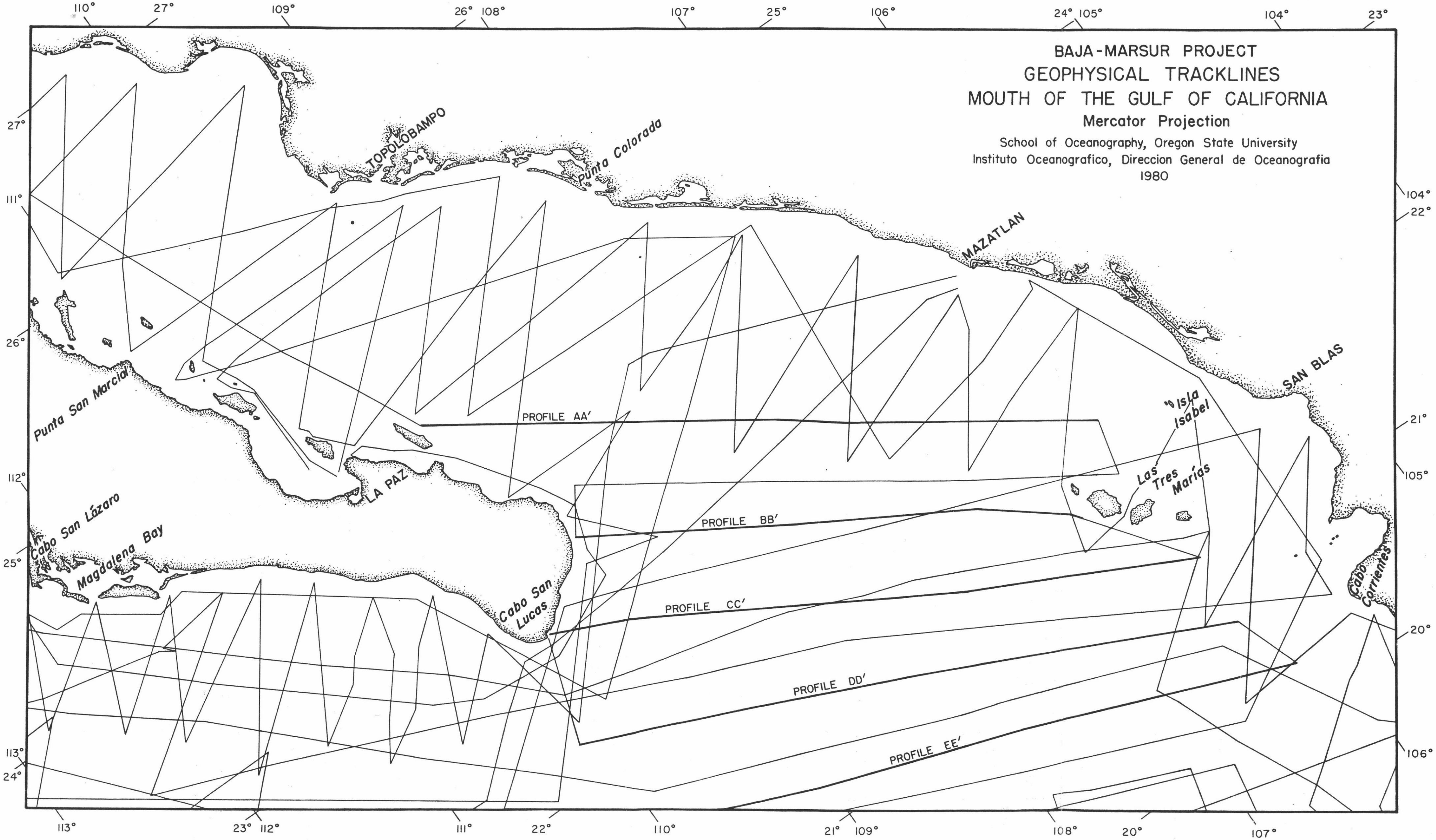

BAJA-MARSUR PROJECT
GEOPHYSICAL TRACKLINES
MOUTH OF THE GULF OF CALIFORNIA
Mercator Projection
School of Oceanography, Oregon State University
Instituto Oceanografico, Direccion General de Oceanografia
1980
TOPOLOBAMPO
Punta Colorada
MAZATLAN
SAN BLAS
Isla Isabel
Las Tres Marías
Cabo Corrientes
Punta San Marcial
LA PAZ
Cabo San Lázaro
Magdalena Bay
Cabo San Lucas
PROFILE AA'
PROFILE BB'
PROFILE CC'
PROFILE DD'
PROFILE EE'
110°
27°
109°
26°
108°
107°
25°
106°
24°
105°
104°
23°
111°
112°
113°
22°
21°
20°
23°
111°
110°
109°
108°
107°
106°

Figure 7

Gravity measurements were made using S-42, a LaCoste and Romberg stable-table gravimeter. Free-air gravity anomalies were calculated using the International Gravity Formula of 1967 (International Association of Geodesy, 1971) to determine theoretical gravity values at the latitude of observation.

The total magnetic field was measured along tracklines using a proton precession magnetometer towed 150-180 meters behind the ship. Total magnetic field anomalies were calculated using the International Geomagnetic Reference Field of 1975 (International Association of Geomagnetism and Aeronomy, 1976) to determine regional field values as a function of latitude, longitude, and time.

Bathymetric measurements were corrected for variations in the velocity of sound in seawater using Matthews tables (1939).

Certain additional marine geophysical data were integrated with this study. A few submarine pendulum gravity values (Worzel, 1965) exist for the study area west of Baja California. Trends in project ROSE gravity data were used to fill gaps in the OSU/DGO survey trackline distribution, but no effort was made to rigorously renavigate and integrate the entire ROSE data set. Those tracklines were laid out for different purposes, and much of the gravity data will be difficult to recover. Some DSDP Leg 63 underway geophysical data were used as discussed in an earlier paper (Ness et al., 1981). We were provided with some files of older, but critically examined and renavigated, bathymetry for the west side of Baja California which was first used by Spencer and Normark (1979) in their work on the Tosco-Abreojos Fault. Bathymetric maps, recently published by Mammerickx et al. (1978), Lewis, Robinson et al. (1979), and Bischoff and Niemitz (1980) were used as underlays during contouring. Otherwise, this study depends almost exclusively upon new data based on gravity-quality navigation.

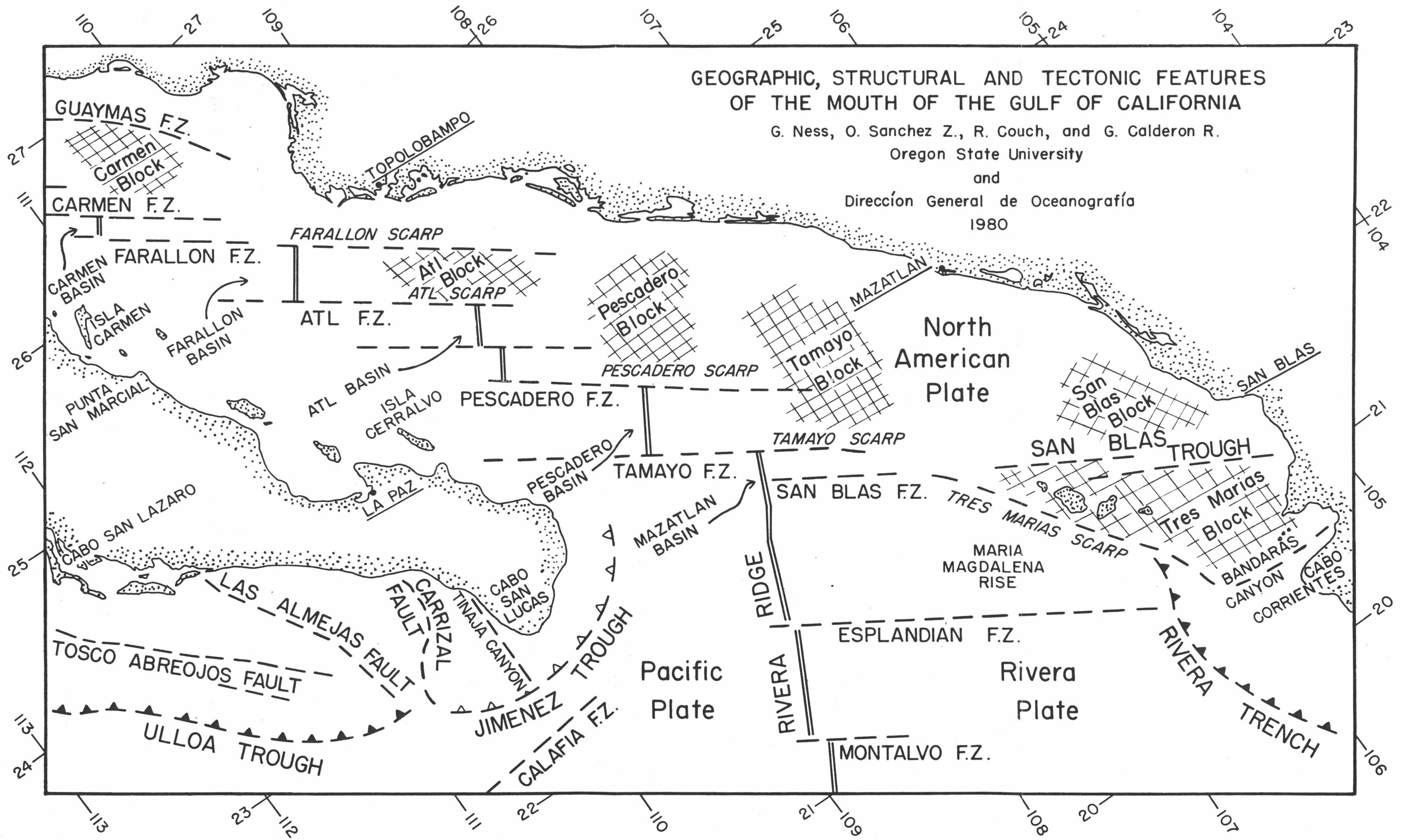
Within the Gulf proper, our bathymetry differs only slightly from the recent map of Bischoff and Niemitz, and Bischoff feels (personal communication) that even the earlier map of Rusnak, Fisher, and Shepard (1964), which was contoured in fathoms, already reliably located the major features of the Gulf. Thus, our successive efforts in that area have only constituted a little fine-tuning, and we conclude that the seafloor feature northwest of the Tamayo Fracture Zone are, by now, known and reasonably well located, at least at a reconnaissance scale. However, on the west side of the peninsula and near the mouth of the Gulf, in the vicinity of the Tamayo Fracture Zone and the Tres Marias Islands, and on the northern Rivera Plate, our bathymetry defines several important features which, previously, were either poorly mapped or unrecognized.

Still, problems persist. For example, we know from our own navigation that the Tres Marias Islands are badly located on standard nautical charts. These charts, in fact, provide printed warnings to that effect, and one of our "very carefully renavigated" tracklines actually crossed Maria Magdalena Island, even though most of us who were on the ship at the time couldn't remember having done so. Being cosmographers at heart, and feeling confident that our tracklines were accurately located relative to the mainland, we first considered relocating the group of islands to where we thought they should be. However, after recognizing the ambiguity and the possible hazard in making piecemeal adjustments, we demurred. We moved the track.

Finally a new problem has developed. During a spring 1981 cruise in the study area we often went more than 12 hours without obtaining a satellite fix. Apparently, the satellite orbits have precessed until some are now coplaner. At low latitudes this can result in a long time between satellite passes. If it is any consolation, with continued precession, the problem itself should pass. In the meantime considerable attention should be paid to the navigation problem in cruise planning, even on non-gravity cruises.

The features we describe in this study are probably real, and they are probably located near where we show them to be. We have tried to avoid mapping them to fit our preconceived notions. Figure 8 shows the locations of the various features discussed in this study.

Figure 8. Location map of significant features of the mouth of the gulf discussed in the text. This illustration serves as both an introduction and a summary since many of the features shown were only identified as a result of this study.



GEOGRAPHIC, STRUCTURAL AND TECTONIC FEATURES
OF THE MOUTH OF THE GULF OF CALIFORNIA
G. Ness, O. Sanchez Z., R. Couch, and G. Calderon R.
Oregon State University
and
Direccíon General de Oceanografía
1980
GUAYMAS F.Z.
Carmen Block
CARMEN F.Z.
TOPOLOBAMPO
FARALLON SCARP
FARALLON F.Z.
CARMEN BASIN
Atl Block
ATL SCARP
ATL F.Z.
ISLA CARMEN
FARALLON BASIN
Pescadero Block
MAZATLAN
Tamayo Block
North American Plate
PESCADERO SCARP
ATL BASIN
ISLA CERRALVO
PESCADERO F.Z.
PUNTA SAN MARCIAL
SAN BLAS
San Blas Block
TAMAYO SCARP
SAN BLAS TROUGH
TAMAYO F.Z.
PESCADERO BASIN
LA PAZ
SAN BLAS F.Z.
TRES MARIAS SCARP
Tres Marias Block
CABO SAN LAZARO
MAZATLAN BASIN
MARIA MAGDALENA RISE
BANDARAS CANYON
CABO CORRIENTES
LAS ALMEJAS FAULT
CARRIZAL FAULT
TINAJA CANYON
CABO SAN LUCAS
RIDGE
ESPLANDIAN F.Z.
TOSCO ABREOJOS FAULT
TROUGH
Pacific Plate
RIVERA
Rivera Plate
RIVERA TRENCH
JIMENEZ
CALAFIA F.Z.
ULLOA TROUGH
MONTALVO F.Z.
110
27
109
108
26
107
25
106
105
24
104
23
111
22
104
21
112
105
20
113
106
24
113
23
112
111
22
110
21
109
108
20
107

Figure 8

BATHYMETRY

The physiography is the region encompassing the southern Gulf of California and the mouth of the Gulf of California is very complicated (Figure 9). The morphology of the seafloor in the Gulf is dominated by a series of axial basins connected by steep, subparallel scarps and linear troughs. These features are quite striking in map view. Individual scarps are linear over quite large distances. Together, certain scarps and troughs are colinear for as much as 200-250 km. Rusnak, Fisher, and Shepard (1964), described these en eschalon features, which are oriented approximately 10° counterclockwise from the general trend of the gulf, as faults along which as much as 250 km of crustal separation has apparently occurred. Vine (1966) described them in contemporary terms as transform faults, offset by short spreading centers in the basins. The basins become progressively deeper toward the south. At the mouth of the Gulf, on either side of the Tamayo Fracture Zone, the spreading centers are finally far enough removed from continental blocks and high sedimentation rates that they begin to resemble oceanic ridges. Even here, however, the precise axis of rifting is impossible to identify from bathymetric profiles alone. The Rivera Ridge, which is that part of the East Pacific Rise between the Rivera and Tamayo Fracture Zones, actually consists of a band of parallel ridges and troughs more than 100 km wide.

The active Rivera Trench, that part of the Middle American Trench north of the Rivera Fracture Zone, is more than 4.6 km deep and has a relief with respect to the adjacent oceanic seafloor of about 1.5 km.

Figure 9. Bathymetric map of the mouth of the gulf. Note the common presence of apparently block-faulted terrain both inside the gulf proper and on the Pacific side of the peninsula. Also note the swale east of the Tres Marias Islands.

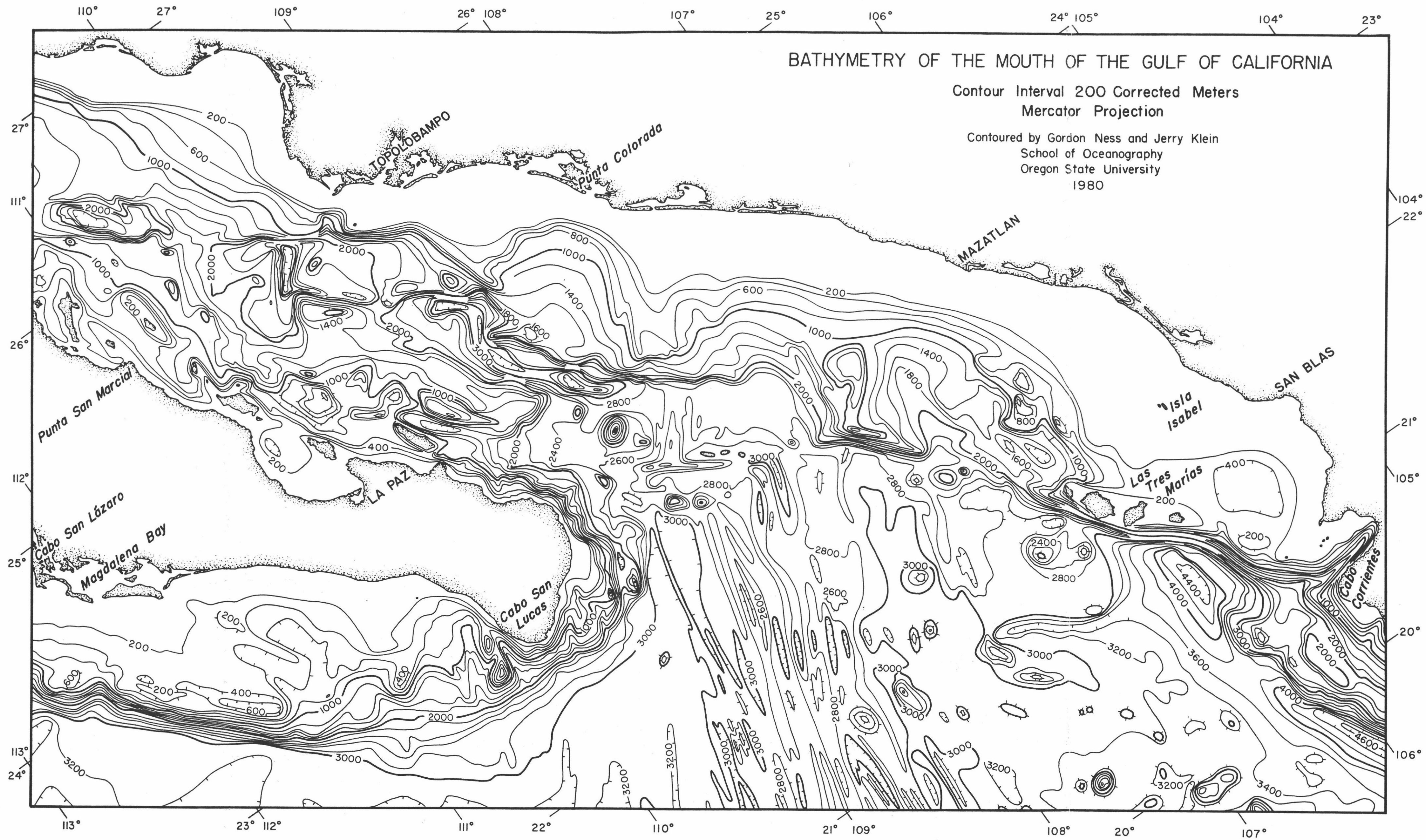

BATHYMETRY OF THE MOUTH OF THE GULF OF CALIFORNIA
Contour Interval 200 Corrected Meters
Mercator Projection
Contoured by Gordon Ness and Jerry Klein
School of Oceanography
Oregon State University
1980
TOPOLOBAMPO
Punta Colorada
MAZATLAN
SAN BLAS
Isla Isabel
Las Tres Marías
Cabo Corrientes
Punta San Marcial
LA PAZ
Cabo San Lázaro
Magdalena Bay
Cabo San Lucas

Figure 9

On the west side of Baja California a fossil trench, the Ulloa Trough, (Ness et al., 1981) is covered with sediments including those of the thick Magdalena Fan (Yeats, Haq, et al., 1981).

The Pacific continental shelf and slope of southernmost Baja California appear to be very complexly faulted. The Tosco-Abreojos Fault trends parallel to the margin of the peninsula. It extends from about 23.5°N, 111.5°W, south of Punta Tosco, to the vicinity of Punta Abreojos, which is well to the northwest of Cabo San Lazaro and outside of this study area. It is a discontinuous, poorly defined (tosco, Span. = "rough") bathymetric feature, although it has some good expression south of Bahia Magdalena. It was identified by Spencer and Normark (1979) in a very perceptive (abreojos, Span. = "open your eyes") compilation and study of older bathymetric and seismic reflection profiles. They suggested that this fault zone may have been a strike-slip boundary, separating the Pacific and North American plates, between 4 and 14 MY, and that it possibly accumulated ∿270 km of right offset over that period.

To the east of this fault, which is apparently inactive, we recognize two presently active faults in the continental crust of southernmost peninsular California. The Las Almejas Fault has fair bathymetric expression, extending from about 23°N, 111°W into Bahia Magdalena just west of the very small Bahia de Las Almejas (Figure 8). It is more apparent in gravity as will be discussed later. Yeats and Haq show that it continues as recent surface faulting onto Isla Santa Margarita, the large island bounding Bahia Magdalena on the south. Spencer and Normark (1979) find recent offsets in acoustic reflectors east of the Tosco-Abreojos Fault. We find teleseismic activity along the trace of the fault as will be discussed later. Yeats and Haq, and Spencer and Normark find evidence that the fault displacement is vertical, west side up, or at least that it has a large vertical component. We have not attempted a fault plane solution on any of the teleseismic events associated with the fault.

Farther east, the Carrizal Fault is also active at the teleseismic level. It extends from the mouth of the Rio Carrizal to about 22.8°N, 110.8°W (Figure 8). The Rio Carrizal is only very occasionally a rio. Its bed is located in a linear, northeast trending arroyo. On land the 200 meter topographic contour swings seaward, parallel to the arroyo. It is higher on the southeast side. Offshore, a colinear bathymetric contour is offset in the opposite sense. Thus the Carrizal Fault appears to be a scissor fault, with the hinge located near the coast. Molnar (1973) shows two left-lateral fault plane solutions for earthquakes along the Carrizal Fault. Its relationship with the apparently inactive Tinaja Canyon - La Paz Fault, which trends to the north, is unknown.

The Calafia, Esplandian and Montalvo fracture zones have been discussed in another work (Ness et al., 1981). The Calafia F.Z. has little bathymetric expression. It is largely covered with sediments and is apparently inactive. The Montalvo F. Z. is a small offset in the Rivera Ridge. The Esplandian F. Z. was first identified by Mammerickx (1980). It has strong bathymetric expression extending from 21.3°N, 107.6°W to the Rivera Trench at 21.0°N, 106.7°W. It may have been related to the Calafia F. Z. prior to about 4 MY. It is interesting that it is nearly in line with the western limit of Banderas Canyon on the other side of the Rivera Trench, and Banderas Canyon is almost certainly fault controlled. The Esplandian F. Z. may cross the southern edge of the Maria Magdalena Rise, which Mammerickx (1980) considers to be an aborted spreading center. The rise is the lobate feature, approximately 100 km across, outlined by the 3000 m contour southwest of the Tres Marias Scarp. It is markedly higher than the adjacent, younger seafloor to the west. Our bathymetry shows a thin ridge (the 2600 m contour at 22°N, 107.5°W) which trends to the north, bounding the western edge of the Maria Magdalena Rise.

The Tres Marias Scarp bounds the Maria Magdalena Rise to the north. It is an extremely steep feature, consisting of two smoothly curved segments in map view, with a cusp near 21°N. The lower continental slope west of Cabo Corrientes is structurally complicated by two probable fault blocks, one located at 20.1°N, 106.3°W. The northern flank of the second block is probably controlled by the Banderas Canyon Fault. This block protrudes into the Rivera Trench. The Rivera Trench axis has a saddle at 20.3°N, 106.5°W near the block.

A swale, which trends to the northwest, is located on the shelf just to the east of the Tres Marias Islands. It reaches a depth of more than 400 m. There are some small, borderland-style blocks located on the slope near 22.3°N, 106.6°W. A broad canyon bounds the eastern flank of the Tamayo Block, a promontory or ness (the first author is partial to the second term) that juts into the gulf from the mainland. The Tamayo Scarp is very steep, and appears to be oriented toward the Tres Marias Scarp. The Tamayo F. Z. offsets the Rivera Ridge from the Pescadero Divergence along an active transform near 23.2°N, 108.4°W. Its southeastern transform extension along the Tamayo Scarp (and along the San Blas Trough which will be discussed later) is actually an active transform that separates part of the northern Rivera Plate from the North American Plate. The northwestern extension of the Tamayo F. Z. bathymetrically continues to about 23.8°N, 109.5°W.

The eastern submarine slope of the peninsula of Baja California consists of numerous borderland-style banks and basins, similar to those south of Mazatlan. All are apparently fault bounded. Some of these small blocks are located far out in the gulf. These are so close to the present spreading axes that they must have only recently foundered or ceased acting as independent blocks.

The larger Pescadero Block near 24°N, 108.2°W is another structural promontory or ness which, like the Atl and Tamayo Blocks, projects into the gulf. The Atl F. Z. connects the Farallon Basin with the Atl Basin. Previously, the Atl Basin has been considered to be morphologically and sedimentologically a part of the Pescadero Basin. Tectonically, these are separate features, so we have named the Atl Basin and Atl F. Z. to distinguish them from the Pescadero Basin and Pescadero F. Z.

The Farallon Basin marks the divergence zone connecting the Atl F. Z. and the Farallon F. Z. The basin itself extends to the southwest beyond the trace of the Atl F. Z. The Farallon F. Z. is identified by steep scarps both on the mainland slopes southwest of Topolobampo and again on the peninsular slope northeast of Carmen Island.

The Carmen Basin, though small, is probably bounded by two fracture zones, the Farallon and Carmen, with a short divergence zone between.

Finally, and very much in general, the coastal province of the mainland near the southern gulf is depositional and the topography is gentle. The shelf is relatively broad. On the opposite side of the Gulf of California, the peninsula is topographically bounded on the east by extremely steep slopes. The peninsular shelf, on the gulf side, is narrow to non-existent. The topography of the peninsula is very mountainous on the eastern side, with either elevated and exposed plutons or volcanics making up the eastern spine. It is low and covered with thick sediments on most of the interior and on the Pacific side. Regionally, the peninsula resembles several large prisms of continental crust, generally tipped toward the west, eroded on the east, and having thick, sediment filled basins in the western interior that are again fault bounded on the extreme west by uplifted metamorphic rocks. The peninsula is remarkably similar in scale, in structural style, and in geology to the Sierra Nevada in Alta California. And, like the Sierra Nevada, the peninsula constitutes the western boundary of an extensional, block faulted province, in this case, the Gulf of California.

FREE-AIR GRAVITY ANOMALIES

The trouble with doing marine gravity surveys is that even if you have been very rigorous in your navigation, very considerate of the idiosyncracies of your gravimeter, very careful to make frequent base-ties, and very patient and diligent in the data reduction and contouring, you still end up with a map that looks a lot like smoothed bathymetry. This is particularly true if there is a lot of bathymetric relief in the area being mapped. This complaint has been frequently uttered by others, and we have even muttered it ourselves in darker moments. But, despite the difficulties, gravity measurements are also of great value in exploration, most simply and obviously when mapped gravity trends are contrary to bathymetric trends. Then, gravity data provide deep structural information at little expense relative to seismic refraction methods, and continuous structural information at little expense relative to seismic reflection methods. Gravity surveys are a most economical way of discovering unknown buried structure and of continuing known buried structure. Gravity mapping has been very useful in this study, particularly in locating buried trenches, faults, and transform fault extensions in or near continental crust.

Figure 10 shows the marine free-air gravity anomaly contours for this study area. Anomalies over the deep seafloor at the mouth of the Gulf of California (on either side of the Rivera Ridge) range by only 10 to 20 mgals around zero, indicating an isostatically compensated crust. The Rivera Ridge, the Esplandian F. Z., and the Montalvo F. Z. show only the slightest gravity expression, if any. A thin east-west

Figure 10. Free-air gravity anomaly map of the mouth of the gulf. Note the gravitational expression of the sediment-filled Ulloa Trough at the base of the continental slope west of the peninsula. This feature continues around the tip of the peninsula. Also note the steep gradients marking fault traces on the shelf west of the peninsula, and the linear gravity minima in the gulf that mark the buried extensions of the main gulf transform faults. The bathymetric swale east of the Tres Marias Islands is further characterized by a gravity trough extending to the coast.

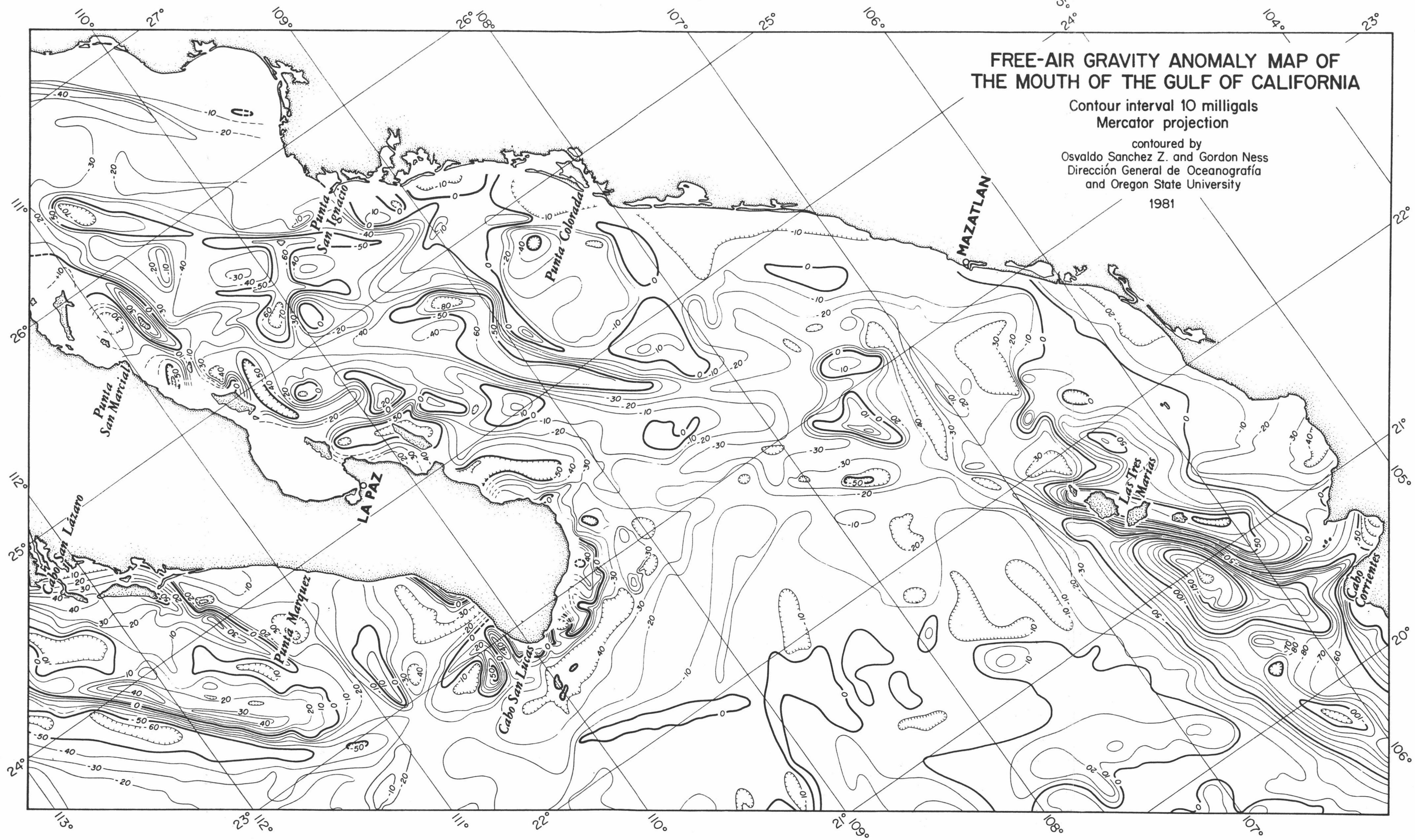

FREE-AIR GRAVITY ANOMALY MAP OF
THE MOUTH OF THE GULF OF CALIFORNIA
Contour interval 10 milligals
Mercator projection
contoured by
Osvaldo Sanchez Z. and Gordon Ness
Dirección General de Oceanografía
and Oregon State University
1981
MAZATLAN
LA PAZ
Punta San Ignacio
Punta Colorada
Punta San Marcial
Cabo San Lázaro
Punta Marquez
Cabo San Lucas
Las Tres Marías
Cabo Corrientes

Figure 10

trending single-contour, positive anomaly extends from the eastern end of the Calafia F. Z. toward the ridge, suggesting a possible association with the Esplandian F. Z. Such a relationship should be expected between younger and older fracture zone segments near a reoriented ridge. The orientation of the Calafia F. Z. is consistent with an earlier, east-west direction of Pacific/Farallon plate motion away from a north-trending East Pacific Rise, prior to the rotation of the Rivera Ridge. The low-amplitude linear anomaly in question could be the expression of a reoriented segment of the Calafia F. Z. intermediate to the present direction of Pacific/Rivera plate motion. However, the amplitude of the anomaly is small, and it appears on only one profile. It may signify nothing.

In contrast, the Tamayo F. Z. shows up very well in gravity. The intersection of the Rivera Ridge and the Tamayo F. Z., at 23°N, 108°W in the Mazatlan Basin, is marked by a -40 mgal anomaly. Gravity lows of -30 mgal extend to both the northwest and the southeast. A very pronounced gravity trough of -50 to -60 mgals near 23.8°, 109.5°W marks the aseismic, extension of the Tamayo F.Z.

Another gravity lineation, parallel to the Tamayo F. Z., is evident near 22.5°N, 107.8°W. We refer to this as the San Blas Fracture Zone. It appears to extend across the bathymetric gap between the Tamayo and Tres Marias scarps, colinear with the gravity minimum we call the San Blas Trough. A large, positive gravity ridge, southwest of the San Blas Trough is obviously associated with the Tres Marias Islands. We refer to this region as the Tres Marias Block, and consider it to be a fault-bounded unit of continental material structurally similar to the

Tamayo, Pescadero, and Atl blocks as previously discussed. Each of these blocks is well marked by positive free-air anomalies.

The Pescadero F. Z. transform extension appears, in gravity, to continue all the way to a saddle in the Tamayo Block near 23°N, 107.5°W. Gravity minima extend northward into the continental slope on both flanks of the Tamayo Block. The -40 mgal anomaly east of the Tamayo Block extends as far north as 23.3°N. This feature, which we refer to as the Mazatlan Trough, and a similar gravity trough between the Tamayo Block and the Pescadero Block are doubtless old rifts which separate these now foundered pieces of continental crust from the mainland.

The Atl Fracture Zone extends from a -80 mgal anomaly in the Atl Basin, through the center of the Farallon Basin, and continues to about 25.6°N, 110.5°W. The central axis of the Farallon Basin extends, both in bathymetry and in gravity, to the southwest of the Atl F. Z. It terminates near 25.2°N, 110.2°W, probably against a transform extension which also bounds the southern flank of a small block at 25.2°N, 109.9°W. This later fracture zone passes through a small left offset in the Atl divergence zone located at 24.5°N, 109.1°W. We refer to it as the Murillo Fracture Zone, and to the small gravity and bathymetric high near 24.4°N, 108.9°W as the Murillo Block.

The northeast end of the Farallon Basin is terminated by the Farallon Fracture Zone which continues toward the northwest, ultimately bounding the southwest flank of the Carmen Basin near 26.3°N, 110.9°W. The southeastern extension of the Farallon F. Z. is well marked bathymetrically by the Farallon Scarp. It continues perhaps as far as 24.5°N, 108.2°W, off Punta Colorada, in a gravity low bounding the east side of the Atl and Murillo Blocks.

The Carmen Basin is bounded to the northeast by the Carmen Fracture Zone which, in turn, extends toward the southeast as far as 26°N, 110.5°W.

The southeastern extension of the Guaymas Fracture Zone is very well marked by the -40 mgal gravity trough passing through 27°N, 110.5°W.

The many, small, boundered blocks that make up the eastern submarine slope of Baja California are bounded by pronounced, linear gravity minima which often extend beneath the sediment fill. The orientations of most of these bathymetric and gravimetric banks and troughs are either north-south or east-west. Neither of these orientations is parallel to the presently active fracture zones and basins in the axial gulf. Similarly, the banks and troughs off Mazatlan also are not aligned with present-day rifting trends. Banderas Canyon at the southeastern side of the mouth of the Gulf, and Tinaja Canyon off of Cabo San Lucas are also oriented north-south and east-west, as are parts of the active Carrizal and Las Almejas Faults. These trends probably reflect the initial direction of divergent stress at the mouth of the Gulf of California -- a Farallon/Pacific direction.

A large amplitude gravity minimum, the Ulloa Trough (Ness et al., 1981) extends along the base of the slope on the west side of the southern peninsula. It has no bathymetric expression. It is a sediment filled continuation of the Cedros Deep, which is located to the north off of Vizcaino Bay. The gravity trough curves to the east into a cusp located at 22.9°N, 110.8°W. The Cedros Deep and the Ulloa Trough are thought to be fossil trenches -- zones where the Farallon Plate, and later even the Pacific Plate, converged on the North American Plate prior to the separation of Baja California from the mainland. South of the tip of the peninsula at -30 to -50 mgal minimum, the Jimenez Trough, is also covered with sediments and it also disappears into a saddle near the cusp. After presenting additional evidence, we will conclude that this feature is also a fossil subduction zone, similar to the Ulloa Trough and the Cedros Deep.

The faults on the shelf and slope of the west side of the peninsula are strongly marked by gravity anomalies. A south trending gravity trough extends from Bahia de Las Almejas near 24.4°N, 111.5°W toward the cusp at 22.9°N, 110.8°W. A gravity trough associated with the Carrizal Fault extends from the coast near 23.7°N, 110.4°W toward the same cusp. A south trending maximum in gravity along 110.9°W and a west trending maximum along 23.1°N also point to the same cusp at 22.9°N, 110.8°W.

MAGNETIC ANOMALY PROFILES AND SPREADING RATE DETERMINATIONS

The OSU/DGO survey tracklines over the deep seafloor in the mouth of the Gulf of California were laid out to be approximately perpendicular to the Rivera Ridge (Figure 7). Representative bathymetric and magnetic anomaly profiles AA' through EE', obtained along these transects, are illustrated in Figure 11 through 15. We have used marine magnetic anomaly timescale NLC-80 (Ness et al., 1980) and the method of Talwani and Heirtzler (1964) to generate synthetic magnetic anomaly profiles for comparison with observed profiles in order to determine seafloor spreading rates. The synthetic anomalies illustrated at the bottoms of Figure 11 through 15 are generated using a simple 2-D boxcar model for source bodies 500 m thick, in 3000 m of water, with a ridge orientation 25° clockwise from north and a nominal flank spreading rate of 30 km/MY. Because of the 25° orientation of the Rivera Ridge away from due north, the magnetic anomalies are asymmetrical, and the peaks of any particular anomaly on either side of the ridge have slightly different ages.

Pacific/Rivera Motion

Profile EE' (Figure 11) crosses the Rivera Ridge immediately south of the Montalvo F. Z. and shows excellent agreement between the synthetic and observed anomalies except within about one million years of the ridge axis. Typically, the central anomaly along the Rivera Ridge is complicated. It has several peaks and is frequently skewed in a sense opposite that expected. Note, for example, the change in the direction of skewness of the central anomaly between profile EE' and the other profiles illustrated here. Also, typically, there is no unambiguous relation one way or another between the bathymetry and anomaly amplitudes. Note, for example, that the seamount shown on the Pacific flank of profile EE' has no observable effect on anomaly 3, but that an unusually large amplitude for anomaly 1' occurs near a deep trough at about 25 km distance from the ridge axis.

The bathymetry of the Rivera flank of profile EE' shows an expected deepening with age and distance from the ridge axis out to about 85 km and 3.3 MY. It then begins to shallow, to become generally smoother, and to exhibit the typical shape of a trench outer swell with further distance. We point out here, for later discussion, that the bathymetry appears to change character at 85 km on the Rivera flank of profile EE', but the magnetic anomalies indicate a nearly continuous

Figure 11. Bathymetric and magnetic profile EE'. The synthetic anomalies are slightly skewed because the Rivera Ridge is oriented approximately 25° clockwise from a northerly orientation. With the exception of the central anomaly, the observed anomaly profile is in excellent agreement with the synthetic anomalies.

(a) Age-distance plot of anomaly identifications shown in Figure 11.

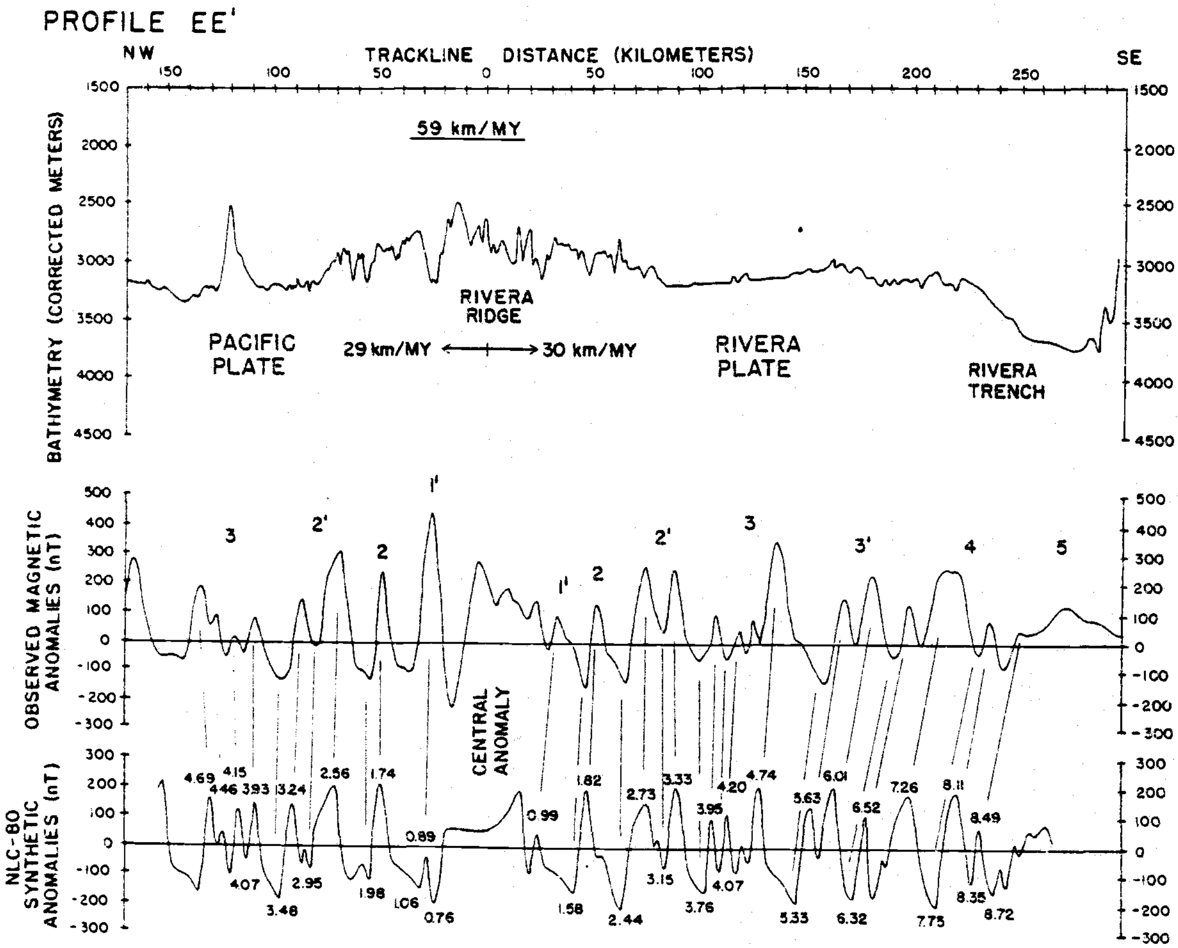

PROFILE EE'
NW
TRACKLINE DISTANCE (KILOMETERS)
SE
59 km/MY
BATHYMETRY (CORRECTED METERS)
RIVERA RIDGE
PACIFIC PLATE
29 km/MY
30 km/MY
RIVERA PLATE
RIVERA TRENCH
OBSERVED MAGNETIC ANOMALIES (nT)
CENTRAL ANOMALY
NLC-80 SYNTHETIC ANOMALIES (nT)

Figure 11.

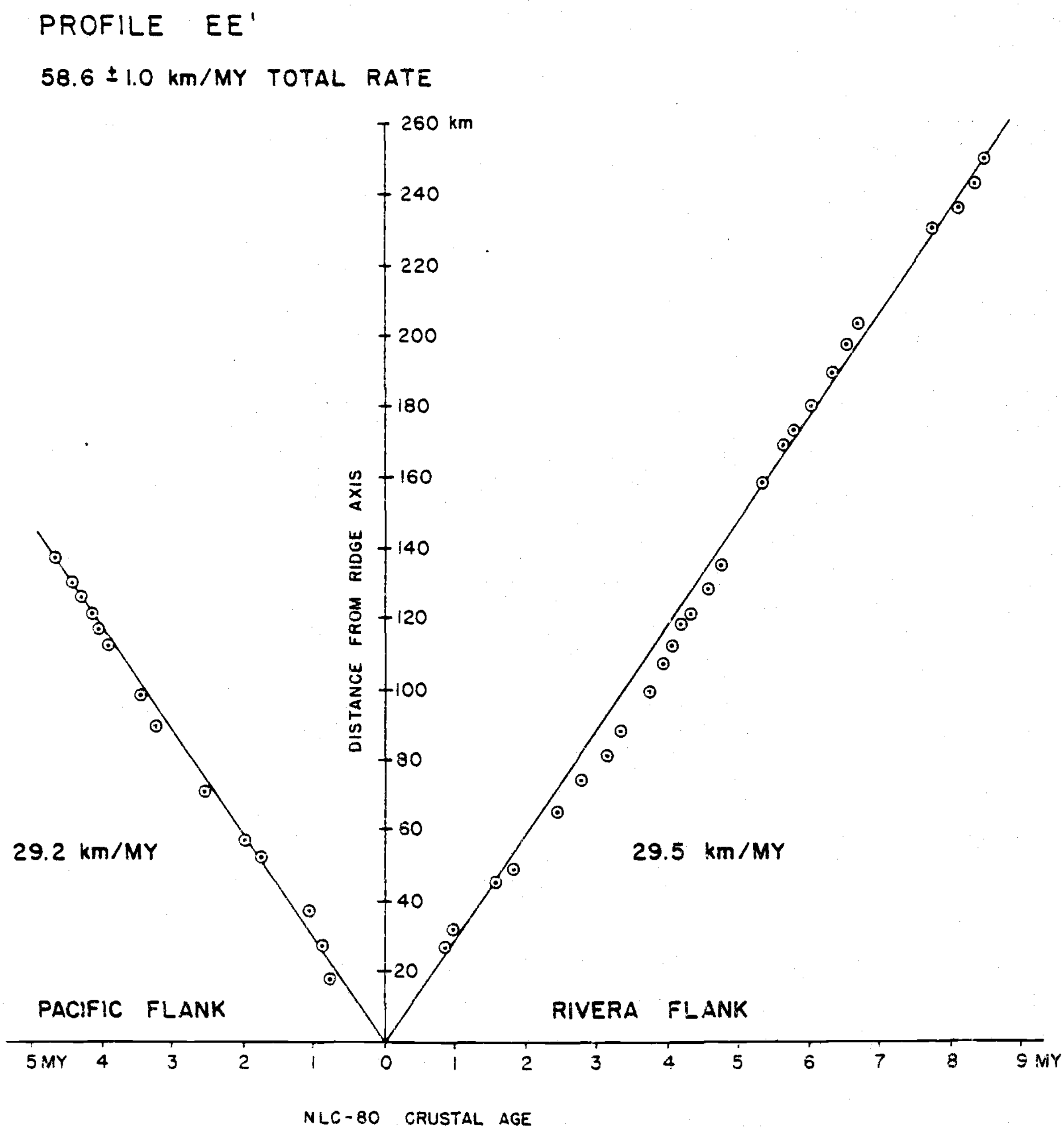

PROFILE EE'
58.6 ± 1.0 km/MY TOTAL RATE
260 km
240
220
200
180
160
140
120
100
80
60
40
20
DISTANCE FROM RIDGE AXIS
29.2 km/MY
29.5 km/MY
PACIFIC FLANK
RIVERA FLANK
5 MY
4
3
2
1
0
1
2
3
4
5
6
7
8
9 MY
NLC-80 CRUSTAL AGE

Figure 11a.

spreading history across that point. Also note that on the Pacific flank of profile EE' the corresponding deepest point in the bathymetric profile occurs near 150 km and 4.8 MY, significantly different from the Rivera Flank.

The anomaly correlations shown in Figure 11 are used in Figure 11a to estimate symmetrical, apparent flank spreading rates of 29-30 km/MY, with an apparent total rate of Pacific/Rivera plate separation of about 59 km/MY. The straight lines drawn through the age-distance points in Figure 11a are not statistically determined. They simply connect the origin at the ridge (zero age, zero distance) with the oldest, most distant, age-distance point. The points fit the line very well, with a maximum departure near 3.5 MY on the Rivera flank. If this deviation is meaningful (it may not be since it is not reflected in the Pacific flank age-distance plot), it occurs near the bathymetric change at 85 km. Profile DD' (Figure 12) crosses the Rivera Ridge between the Montalvo F.Z. and the Esplandian F.Z. It is very similar in character to profile EE', and shows an even greater correspondence between the observed and synthetic magnetic anomaly profiles. In this case the central anomaly is correctly skewed. The correlations near anomaly 4 are tenuous but direct and require no special pleading. The unnamed seamount at 120 km on the Rivera flank does not superimpose with the positive peak in anomaly 3 at 4.74 MY.

The apparent flank spreading rates (Figure 12a) are nearly symmetrical and yield a Pacific/Rivera apparent plate separation rate of about 54 km/MY. Slight accelerations may exist near 3.5 and 6.5 MY. The change in bathymetry shown at 3.5 MY on profile EE', here may occur at about 2.7 MY although the inflection is not as obvious.

Figure 12. Profile DD' is similar to profile EE'. Both are located south of the Esplandian Fracture Zone on the Rivera Ridge. Again the anomalies are very easy to identify. It is important to note that profile DD' is located within the mouth of the gulf, and yet it is still possible to trace anomalies as old as 9 MY on the Rivera Plate flank of the ridge.

(a). Spreading rate plot for profile DD'.

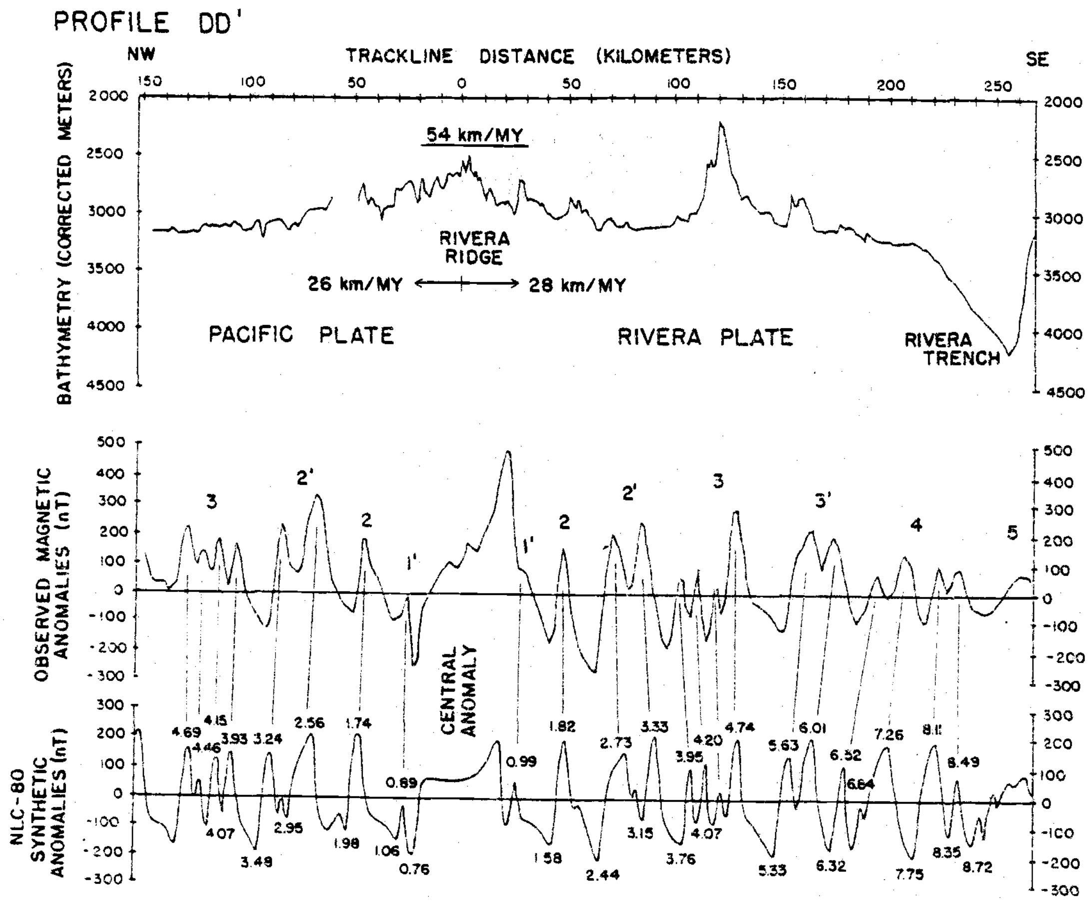

PROFILE DD'
NW
TRACKLINE DISTANCE (KILOMETERS)
SE
BATHYMETRY (CORRECTED METERS)
54 km/MY
RIVERA RIDGE
26 km/MY
28 km/MY
PACIFIC PLATE
RIVERA PLATE
RIVERA TRENCH
OBSERVED MAGNETIC ANOMALIES (nT)
CENTRAL ANOMALY
NLC-80 SYNTHETIC ANOMALIES (nT)

Figure 12.

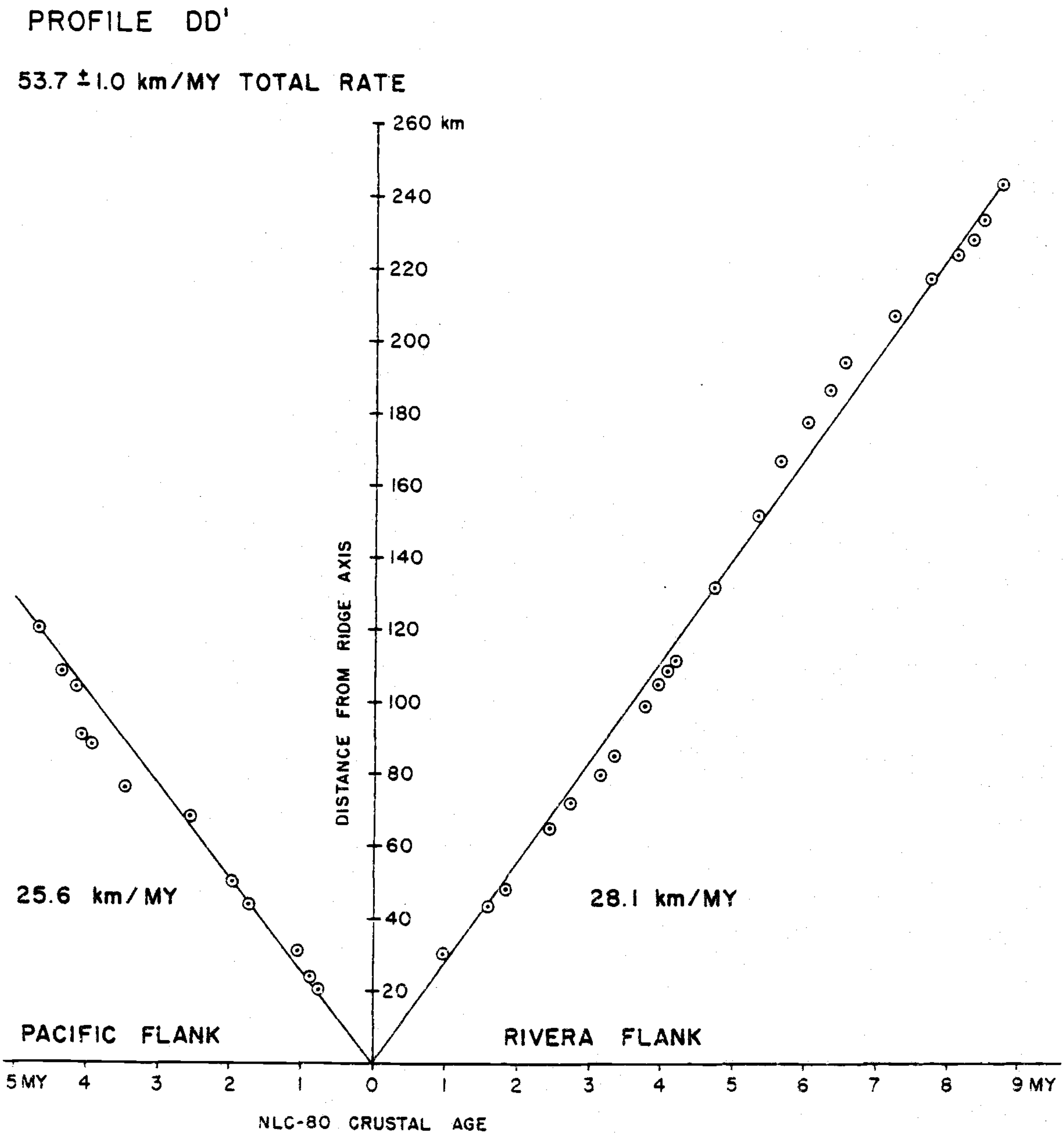

PROFILE DD'
53.7 ± 1.0 km/MY TOTAL RATE
260 km
240
220
200
180
160
140
120
100
80
60
40
20
DISTANCE FROM RIDGE AXIS
25.6 km/MY
28.1 km/MY
PACIFIC FLANK
RIVERA FLANK
5 MY
4
3
2
1
0
1
2
3
4
5
6
7
8
9 MY
NLC-80 CRUSTAL AGE

Figure 12a.

The Maria Magdalena Rise

Profile CC' (Figure 13) extends from the harbor at Cabo San Lucas, on the tip of Baja California, across the mouth of the Gulf of California to a point in the Rivera Trench immediately south of the Tres Marias Islands. Note that the trench axis is almost a kilometer deeper here than on profile EE'. On either flank of the Rivera Ridge the seafloor progressively deepens, reaching a local depth maximum at a distance of about 70 km and at an age of about 2.5 MY, a million years younger than the corresponding point on profile EE'.

On profile CC', the oldest oceanic crust exposed near the base of the slope of the peninsula is about 3.9 MY, the age of the peak of anomaly 3.1. The magnetic anomalies on the Rivera flank of profile CC' are symmetrical and identifiable through anomaly 2' to perhaps 3.8 MY, or about the age of the oldest seafloor shown on the Pacific flank of this profile. We stress that the Maria Magdalena Rise extends from a point about 65 km from the ridge axis, then to the Rivera Trench, but progressively older magnetic anomalies recognizably extend from the ridge axis to at least 110 km, and perhaps to as much as 150 km, although the anomaly 3 correlation is tenuous. Thus, continuous magnetic anomalies repeatedly cross the inflection in bathymetry. By simply associating observed anomaly peaks with synthetic anomaly peaks as far back as 5.63 MY, we obtain the age-distance relationships shown in Figure 13a. These correlations provide a good fit to a straight line describing an apparent 30 km/MY Rivera flank spreading rate, with nearly symmetrical spreading on the Pacific flank, and these correlations yield a Pacific/Rivera apparent separation rate of about 57 km/MY.

Figure 13. Profile CC' is located north of the Esplandian Fracture Zone. Note the symmetry of anomalies through 2', at 3.76 MY on the Rivera Plate flank. Coherent, progressively older, anomalies extend about 35 km on to the flank of the Maria Magdalena Rise, past the bathymetric minimum at approximately 65 km distance from the ridge.

(a) spreading rate plot for profile CC'.

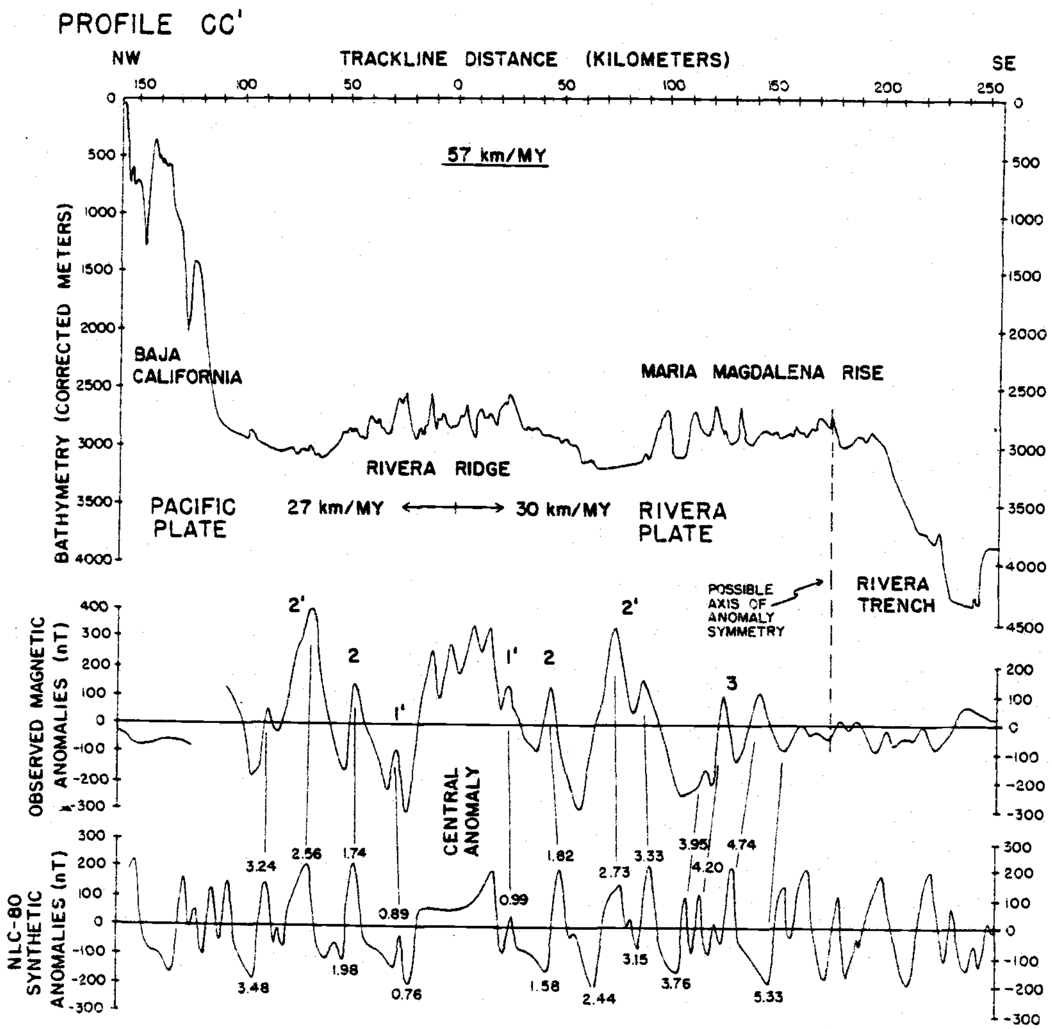

PROFILE CC'
NW
TRACKLINE DISTANCE (KILOMETERS)
SE
57 km/MY
BATHYMETRY (CORRECTED METERS)
BAJA CALIFORNIA
MARIA MAGDALENA RISE
RIVERA RIDGE
PACIFIC PLATE
27 km/MY
30 km/MY
RIVERA PLATE
POSSIBLE AXIS OF ANOMALY SYMMETRY
RIVERA TRENCH
OBSERVED MAGNETIC ANOMALIES (nT)
CENTRAL ANOMALY
NLC-80 SYNTHETIC ANOMALIES (nT)

Figure 13.

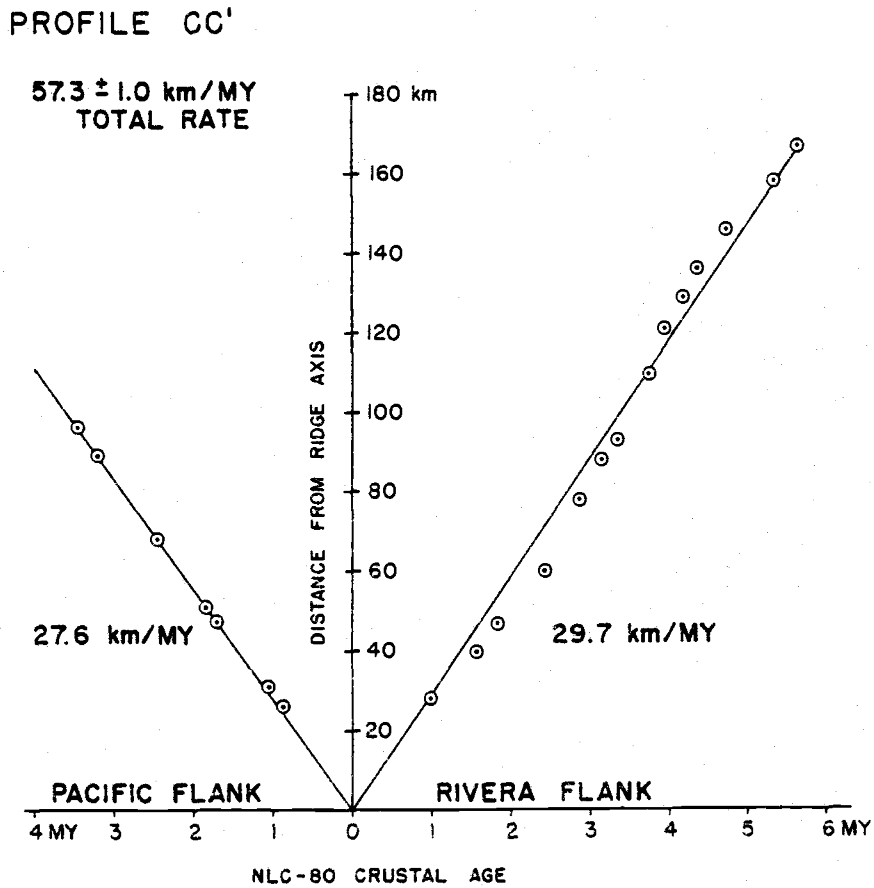

PROFILE CC'
57.3 ± 1.0 km/MY
TOTAL RATE
180 km
160
140
120
100
80
60
40
20
DISTANCE FROM RIDGE AXIS
27.6 km/MY
29.7 km/MY
PACIFIC FLANK
RIVERA FLANK
4 MY
3
2
1
0
1
2
3
4
5
6 MY
NLC-80 CRUSTAL AGE

Figure 13a.

Mammerickx (1980) has argued that the Maria Magdalena Rise is an aborted ridge, where spreading occurred prior to a ridge jump at 3.5 MY which is thought to be responsible for the present uncentered location of the active Rivera Ridge. Figures 8 and 9 illustrate how the ridge is displaced toward the peninsular side of the gulf. Her proposal is an attractive, direct solution to that problem. However, it faces several severe difficulties and we will propose other reasonable explanations.

First, there may simply be a difference in the rate of spreading on either side of the Ridge. The distance from the ridge to the Jimenez trough parallel to the Esplandian F.Z. is about 100 km. The distance from the ridge to the Rivera Trench along the same trajectory is about 250 km. Thus spreading would have to be more than twice as fast on the Rivera flank as one the Pacific flank, and it would need to be even more asymmetrical if the Rivera Plate converges on the North American Plate at the Rivera Trench, as is commonly thought to be the case. An examination of spreading rates along profile CC' rules this simple explanation out completely. As shown in Figures 13 and 13a, the flank rate of spreading are essentially identical at least back as far as 3.5 MY where the anomaly identifications are unambiguous.

Second, there may have been two episodes of spreading, as proposed by Mammerickx, an early phase on the Maria Magdalena Rise dating from the initial opening of the mouth of the gulf, and a later phase following a ridge jump at 3.5 MY. Difficulties with this solution appear through a comparison of profiles CC' and BB' (Figure 14). The Maria Magdalena

Figure 14. Profile BB'. Note the radical change in character in the bathymetry of the Maria Magdalena Rise compared with profile CC'. Note also that the possible axis of anomaly symmetry has shifted to the western flank of the Rise. The crest of the rise is also higher than the crest of the Rivera Ridge.

(a) Spreading rate asymmetry is more pronounced on this profile than on profile CC'.

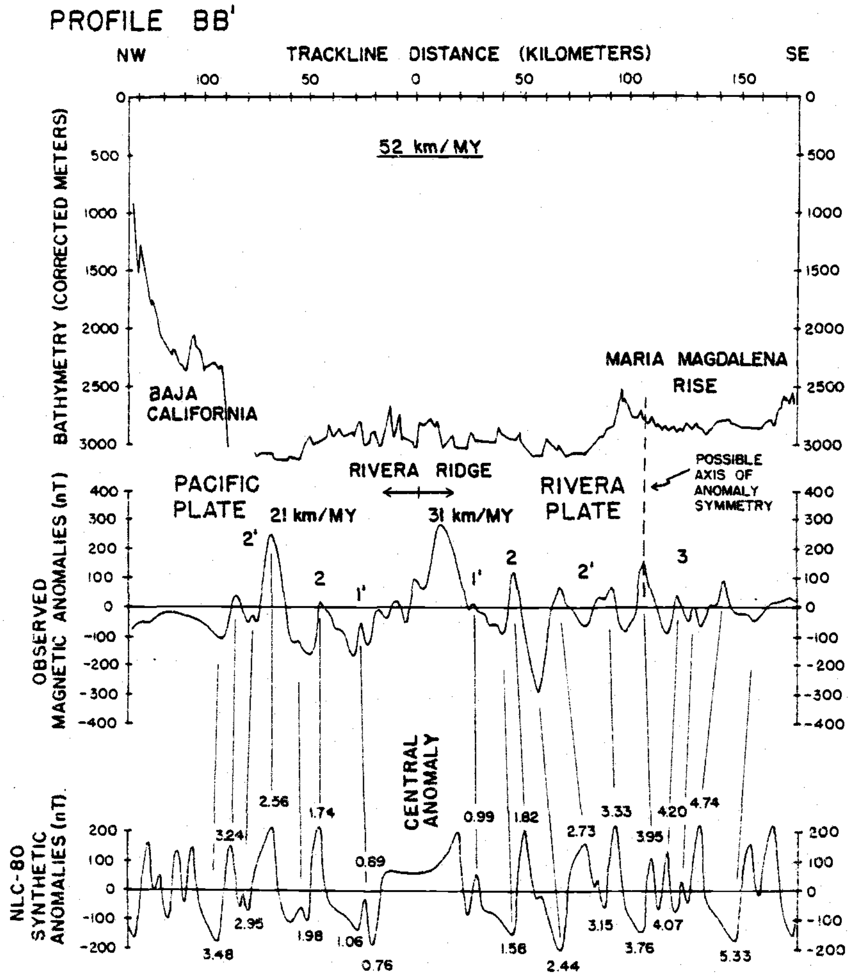
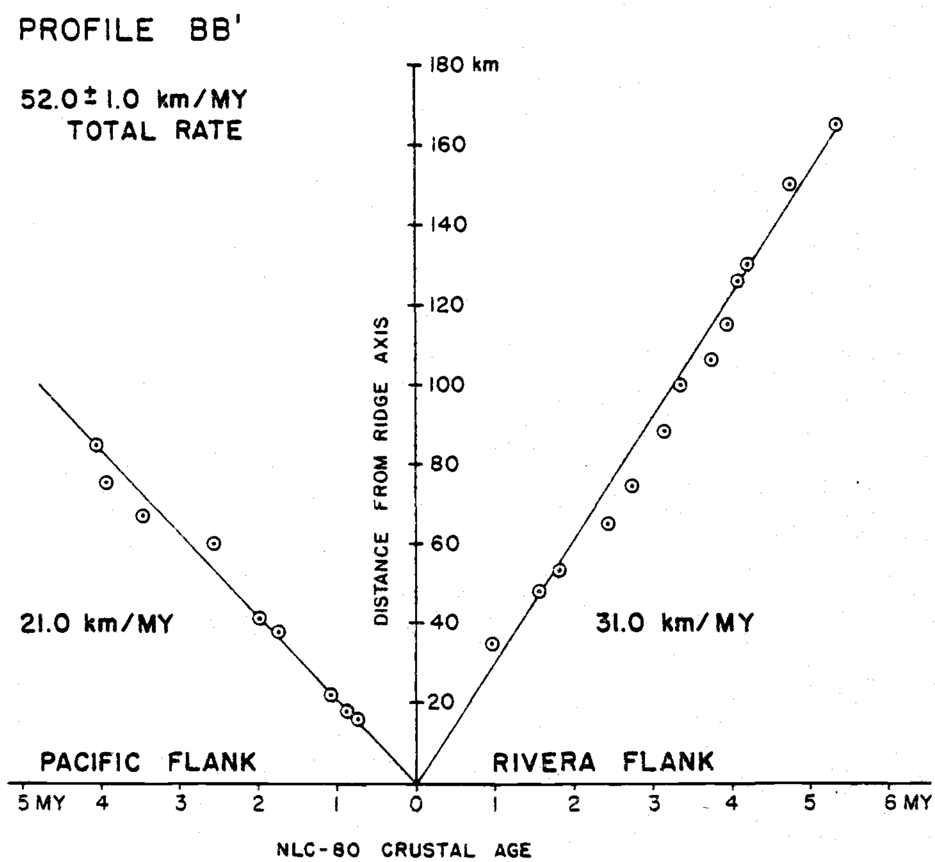

PROFILE BB'
NW
TRACKLINE DISTANCE (KILOMETERS)
SE
BATHYMETRY (CORRECTED METERS)
52 km/MY
BAJA CALIFORNIA
MARIA MAGDALENA RISE
RIVERA RIDGE
PACIFIC PLATE
RIVERA PLATE
POSSIBLE AXIS OF ANOMALY SYMMETRY
21 km/MY
31 km/MY
OBSERVED MAGNETIC ANOMALIES (nT)
CENTRAL ANOMALY
NLC-80 SYNTHETIC ANOMALIES (nT)

Figure 14.



PROFILE BB'
52.0 ± 1.0 km/MY
TOTAL RATE
180 km
160
140
120
100
80
60
40
20
DISTANCE FROM RIDGE AXIS
21.0 km/MY
31.0 km/MY
PACIFIC FLANK
RIVERA FLANK
5 MY
4
3
2
1
0
1
2
3
4
5
6 MY
NLC-80 CRUSTAL AGE

Figure 14a.

Rise has no central bathymetric peak, no axis of morphological symmetry, as should be expected from the Mammerickx proposal and normal age-depth relationships. On profile CC' the rise is highest near its southeast flank, where it begins to plunge into the trench. On profile BB' it appears to be deepest near its center, and to be bounded on either side by peaks including the long ridge at 22°N, 107.5°W shown on the bathymetric map (Figure 9). If anything, the morphology of the rise on profile BB' is inverted from the expected age-depth relationship. Also note that the depth of the rise is approximately the same as that of the Rivera Ridge on profile CC', and that it is even higher than the ridge on profile BB', in both cases contradicting the proposed age-depth relationships.

We are not able to convincingly identify magnetic anomalies over the Maria Magdalena Rise older than about 3.8 MY on profile CC' and about 3.3 MY on profile BB'. However, if we examine these profiles for possible axes of anomaly symmetry, in an attempt to find support for the Mammerickx aborted ridge hypothesis, we find on profile CC' a possible axis near the east flank of the rise, near the bathymetric peak (Figure 13). But on profile BB' (Figure 14) the most reasonable anomaly symmetry axis is located on the western flank of the rise.

In addition we reemphasize that coherent, progressively older anomalies continue from the Rivera Ridge well into the bathymetric flank of the rise. This is particularly evident with respect to anomaly 2' of profile CC'.

A very interesting third possibility is that the anomaly identifications shown on profiles CC' and BB' are correct, and that the anomalies on the northern Rivera Plate become progressively older from the Rivera Ridge to the Rivera Trench. In this case, which we prefer, we must invoke the subduction toward the northwest of at least four to five million years of oceanic crust, older than about 3.5 MY, beneath the southeastern tip of Baja California in the Jimenez Trough. This is, of course, kinematically possible provided that at least the southern part of the peninsula be decoupled from the Pacific Plate for some time after the initial opening of the Gulf and during the time of subduction. More specifically, it would imply that right-lateral strike-slip motion must have occurred between the Pacific and North American (or California?) plates somewhere along the oceanic side of the peninsula in a manner similar to that proposed by Spencer and Normark (1980) to have occurred along the Tosco-Abreojos Fault.

The difficulty with our preferred hypothesis is that the magnetic anomalies over the Maria Magdalena Rise are not easy to identify. The correlations we make are not convincing. But even if the Rivera Ridge did jump toward the northwest, it is apparent from the symmetry of its bathymetry and from its flank anomaly pattern that the new axis of divergence (at about 3.9 MY on profile CC' and at about 3.5 MY on profile BB') would have had to be initiated exactly at the base of the continental slope of the peninsula. Note that no reversed anomalies are found near the base of the peninsular slope on any of the cross-gulf profiles used in this study. This means that the jump would have occurred at 3.9 MY on profile CC' and at 3.5 MY on profile BB', and presumably, at continuously proportional ages between the profiles. This rules out the possibility of a single, instantaneous ridge jump, but may be consistent with the propagation of the Rivera Ridge into the mouth of the gulf.

Finally, even if some sort of spreading, either diffuse or discreet, occurred, or is even still occurring north of the Esplandian F.Z., the umambiguous anomaly correlations on profile DD' (Figure 12) show progressively older crust extending without interruption from the Rivera Ridge to the Rivera Trench. This area is just south of the Esplandian F.Z. but is still well within the mouth of the gulf (it lies poleward of any reasonable cross-gulf plate trajectory connecting the Ulloa Trough with the Middle America Trench), and even here the Rivera Ridge is uncentered within the gulf.

In short, none of the relationships expected to follow from the Mammerickx hypothesis are found, other than the generally shallower bathymetry of the Maria Magdalena Rise and the difficulty of identifying magnetic anomalies older than anomaly 2' over the rise. The bathymetric expression of the rise is only slightly more pronounced than the expected outer trench swell seen on profiles EE' and DD'. It is just as reasonable to assume that no ridge jump has occurred, and that the rise on that part of the Rivera Plate north of the Esplandian F.Z. is caused by plate flexure in two directions -- into the Rivera Trench and obliquely beneath the Tres Marias Scarp.

Pacific/North American Motion

Profile AA' (Figure 15) was made midway between the Tamayo F.Z. and the Pescadero F.Z. and parallel to them, approximating a Pacific/ North American small circle of plate motion. Southwest of the Tamayo F.Z. the Rivera Ridge separate the Pacific Plate from the Rivera

Figure 15. Profile AA' taken between the Tamayo and Pescadero Fracture Zones. This narrow zone is the only place where the Pacific/North American plate separation rate can be measured using seafloor spreading anomalies. The anomalies shown are symmetrical out to about 3 MY as shown, but are difficult to identify.

(a) spreading rate plots for profile AA'. The upper plot is based upon the correlations shown in Figure 15. It yields symmetrical flank rates of about 34 km/MY. The lower plot is based upon an attempt to compress the anomaly correlations on the profile in an effort to obtain a slower spreading rate. The resulting age-distance points are badly scattered around the solid lines shown. The dashed lines present an alternative fit, but imply two spreading rate changes in the last 3 MY. The 68 km/MY spreading rate determination is preferred.

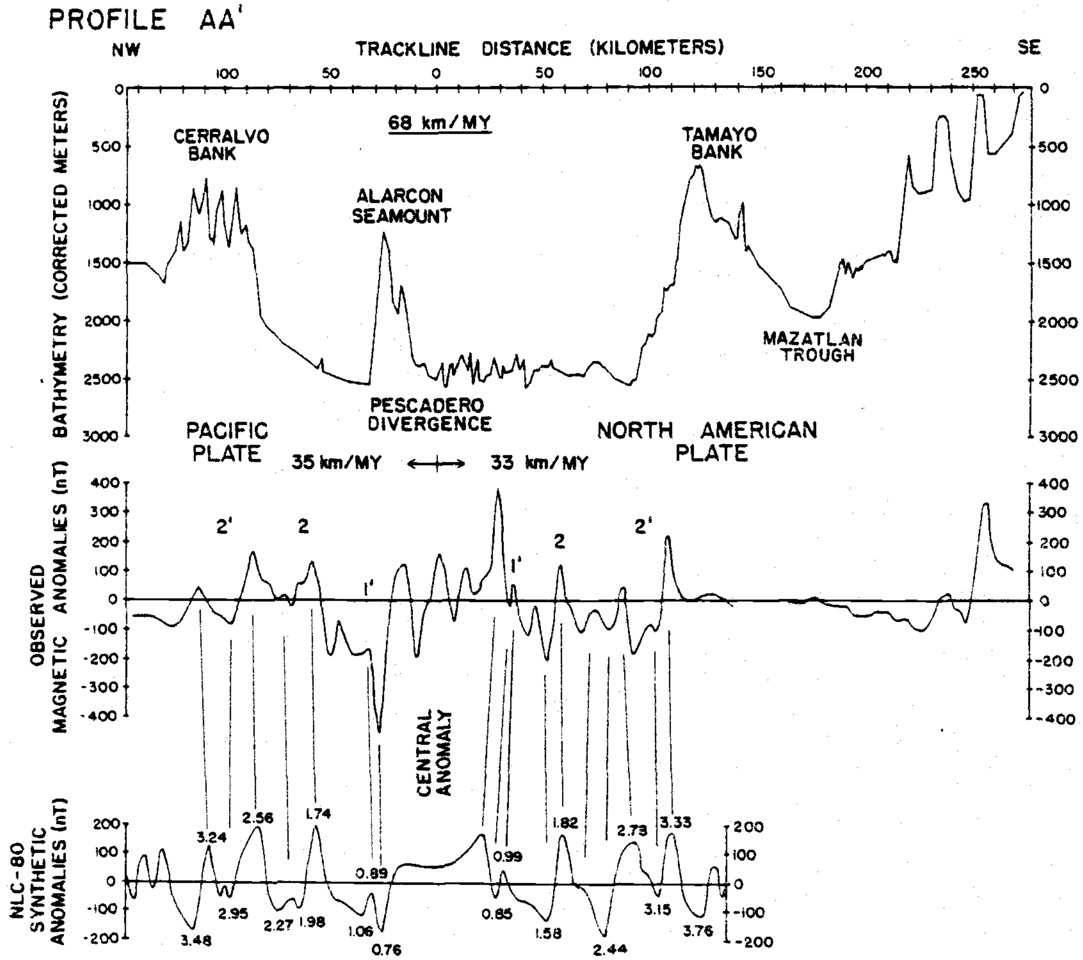

PROFILE AA'
NW
TRACKLINE DISTANCE (KILOMETERS)
SE
BATHYMETRY (CORRECTED METERS)
68 km/MY
CERRALVO BANK
ALARCON SEAMOUNT
TAMAYO BANK
MAZATLAN TROUGH
PESCADERO DIVERGENCE
PACIFIC PLATE
NORTH AMERICAN PLATE
35 km/MY
33 km/MY
OBSERVED MAGNETIC ANOMALIES (nT)
CENTRAL ANOMALY
NLC-80 SYNTHETIC ANOMALIES (nT)

Figure 15.

PROFILE AA'

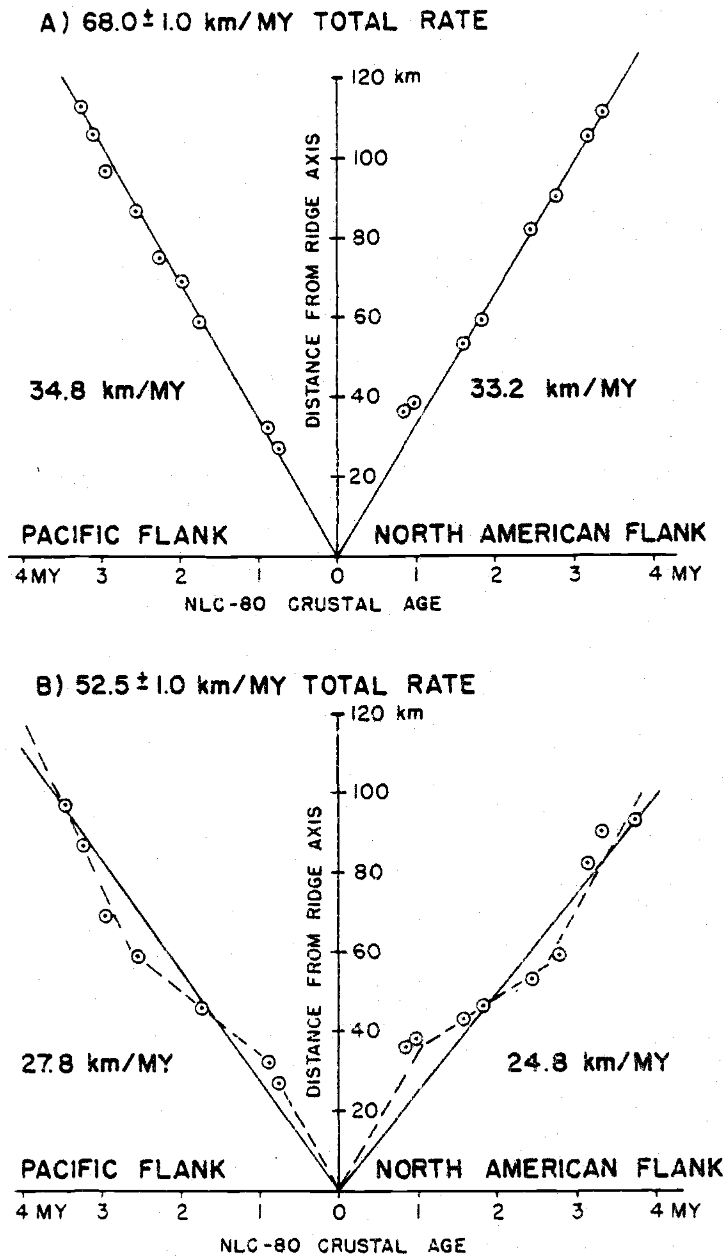


Figure 15a.

Plate and the spreading rates previously discussed are measures of Pacific/Rivera, not Pacific/North American, plate separation. Northwest of the Pescadero F.Z., in the Gulf of California proper, coherent seafloor spreading magnetic anomalies have never been convincingly identified (Larson et al., 1972). Thus, it is only within the narrow zone between the Tamayo F.Z. and the Pescadero F.Z. that it is possible to make a direct measurement of the Pacific/North American plate separation rate using marine magnetic anomalies.

The bathymetry along profile AA' indicates that only about 180 km of oceanic seafloor separate the continental crustal blocks of the Cerralvo and Tamayo Banks across the actively spreading Pescadero Divergence. This seafloor and the divergence itself are at the relatively shallow depth of 2400 m, plus or minus. On profile BB' (Figure 14) the Rivera Ridge, just south of the Tamayo F.Z., is at a depth of about 3000 m, plus or minus, and still has the elevated morphology expected of ridges. The Tamayo Bank is separated from the apparently block-faulted slope south of Mazatlan by the Mazatlan Trough which reaches a depth of almost 2000 m.

The magnetic anomaly profile in Figure 15 shows a very complicated central anomaly and a pattern of skewed peaks and troughs extending more than 100 km to either side of the divergence. The observed anomalies are difficult to identify, but are symmetrical. The correlations shown in Figure 15 yield nearly identical flank spreading rates of 35 and 33 km/MY (Figure 15a, top) and a Pacific/North American plate separation rate of 68 km/MY. This result is surprising. At this rotational latitude it is approximately twenty five percent faster than the commonly used (e.g. Minster and Jordan, 1978) Pacific/North American rate estimate.

By itself, this difference in the estimated Pacific/North American rate causes no particular problem. It simply means that the Gulf of California is opening faster, and that the San Andreas Fault System and the Queen Charlotte Island Transform Fault are slipping at an increased rate. However, if the 68 km/MY rate estimate is correct, it causes havoc with our present tenuous understanding of the mesoscale tectonics both of the Rivera Plate in the Mouth of the Gulf of California, and of the Gorda-June de Fuca-Explorer plate complex off of northern California, Oregon, Washington, and southern British Columbia.

Regarding the latter case, recent work on mapped northeast Pacific seafloor magnetic anomalies by Riddihough (1980) and his colleagues at the Pacific Geoscience Center in Canada, has provided a detailed history of the divergence, with respect to the Pacific Plate, of the Gorda-Juna de Fuca-Explorer plate complex. By adopting the local Pacific/North American plate motion vector provided by the geometrical-statistical model of Minster and Jordan (1978), they constructed a detailed history of the convergence of those small plate segments into North America. Over the last several million years most of the relative motion has been strike-slip, with only small components of convergence evident at any particular time. But even the small components allowed are eagerly accepted by most geologists and geophysicists who are studying the region because this limited geometrical evidence for convergence permits at least very oblique subduction to explain the active (recently explosive!) volcanism of the Cascade Range. No inclined seismic zone, which everywhere else is associated with the subduction of oceanic lithosphere, is found in the region. Yet there is active volcanism on land, active spreading ridges offshore, and fan-covered oceanic basement dipping beneath the foot of the continental slope between the two.

This has always been a particularly cloying problem since the seafloor west of the Cascades has probably been surveyed in greater detail, and is therefore better known, than almost any other deep-sea area of comparable size. It is also ironic in that the now-famous magnetic anomaly survey of Raff and Mason, the very survey that stimulated the Vine and Matthews (1963) hypothesis relating the zebra-striped seafloor spreading anomalies to geomagnetic field reversals, the survey that was one of the key elements leading to the acceptance of the theory of plate tectonics, was conducted over the Gorda-Juan de Fuca-Explorer region. And yet, because of numerous, anomalous fault orientations and the lack of Benioff zone seismicity, the area has never been completely or convincingly placed within the framework of rigid plate tectonics. Now, just when certain parts of the regional problem are beginning to yield to detailed analysis and explanation, a 68 km/MY Pacific/North America plate rate determination, made at the mouth of the Gulf of California, would lengthen the Pacific/North American vector near the Juan de Fuca region by about 25%. This implies that no subduction has been possible (for at least the last 3 MY) unless Oregon and Washington are not tectonically part of the main North American Plate. This is a thought provoking but not unreasonable qualification.

In the mouth of the gulf, the 68 km/MY rate determination leads immediately to the conclusion that the Pacific Plate is moving away from North America at a faster rate than the Rivera Ridge is generating oceanic crust. It follows directly that the Rivera Trench should be a zone of crustal extension. This is a very unsettling result. At least three alternatives come to mind:

First, slow diffuse spreading may be presently occurring on the Maria Magdalena Rise at a rate of at least slightly faster than the difference between the 68 km/MY Pacific/North America rate and the 52-57 km/MY Pacific/northern Rivera rates previously discussed. A 20 km/MY crustal generation rate on the Maria Magdalena Rise would satisfy the requirement that the northern Rivera Trench be a convergent, or at worst a strike-slip, plate boundary. In the latter case, the trench would have the form of a normal deep-sea trench but would act as a transform fault, similar perhaps to the Puerto Rico Trench, or to the westernmost Aleutian Trench which is parallel to a local Pacific/North American plate trajectory. The difficulty with this explanation is that there is no teleseismic activity associated with the Maria Magdalena Rise. There may be low magnitude seismicity ($M_b < 3.0$) associated with this spreading. We do not know. Another difficulty is that this explanation fails to solve the problem for the Rivera Trench immediately south of the Esplandian F.Z. (south of the Maria Magdalena Rise) where crustal extension would also seem to be required. Nor does it solve the convergence problem off of the Cascades, unless as we said, Cascadia is not part of the main North American Plate.

This leads to the second alternative. The difference between Pacific/North America and Pacific/Rivera rates could be explained by slow right-lateral strike-slip motion along the trans-Mexican volcanic belt similar to that suggested by Gastil and Jensky (1973). The existence of such a Trans-Mexican Plate would allow slow convergence at the Rivera Trench and satisfy the rate difference problem, provided that the strike-slip plate boundary enters the gulf very near the San Blas Trough (Figure 8). The difficulty here is that Gastil and Jensky (1978) feel that the major strike-slip faulting along the Trans-Mexican volcanic belt probably occurred prior to 10 MY.

The third and obvious alternative is that our profile AA' anomaly correlations, as shown in Figure 15, are incorrect. To examine this we have forced an alternative set of correlations intended to yield a slower Pacific/North American divergence rate by pushing the anomaly 2' correlations closer to the central anomaly from both flanks. This resulted in the age-distance plot shown on the bottom of Figure 15a, and a more sedate value for the overall divergence rate of only 53 km/MY. The difficulty with this result is that the points are very badly fit to the solid overall rate line shown. An explanation, an unacceptable explanation, for the bad fit would be to propose three different spreading episodes within the last 3.5 MY, as shown by the dotted lines. Nature may really work that way, but we lack confidence in straight lines fit to only two or three points. And so, although this explanation would certainly eliminate the rate difference problem, we favor the 68 km/MY anomaly correlation.

As a point in passing, if an episode of subduction has occurred at the southeast tip of the peninsula in the Jimenez Trough, as discussed earlier in this section, it more probably occurred prior to about 3.5 MY rather than since that time. The 68 km/MY Pacific/North American rate was determined across the Pescadero Divergence over the last 3 MY only. If subduction has occurred at the Jimenez Trough also within the last 3 MY, then the rate difference problem becomes even more pronounced and more difficult to explain. Better that it happened earlier.

SEISMO-TECTONICS

Oceanic Crustal Isochrons

By examining each of the magnetic anomaly profiles recovered over the deep seafloor, and by identifying particular anomalies in profile view and dating them using timescale NLC-80 as demonstrated, we have been able to construct a map of oceanic crustal isochrons for the mouth of the Gulf of California (Figure 16). This is similar to a crustal age map previously constructed for the area further seaward of this study area (Ness et al., 1981) except that here we have interpolated the crustal isochrons to million year values. In that earlier study we noted that the isochrons on the Rivera Plate (particularly, south of the Esplandian F. Z.) are fanned from a north-south orientation, gradually becoming parallel to the axis of the Rivera Ridge. Anomalies younger than about 2.5 to 3.5 MY are subparallel to the present axis. On the Pacific flank of this study area, the record of ridge reorientation is similar. Anomalies older than about 9 MY are oriented predominantly north-south reflecting an earlier Pacific/Farallon ridge azimuth. The Rivera segment of the East Pacific Rise began rotating clockwise at about 9 MY. This rotation may have slowed somewhat by about 6.5 MY, and ceased prior to about 2 MY. Thus, the isochrons younger than 9 MY on the Pacific and Rivera flanks of the ridge are approximately inverted, fanned images of each other. This sequence suggests that the Rivera Fracture

Figure 16. Earthquake activity, magnetic isochrons and faults within the Gulf of California. Note that many of the earthquakes in the gulf off of Topolobampo lie along apparent transform fault extensions. Note also the active faulting west of the peninsula.

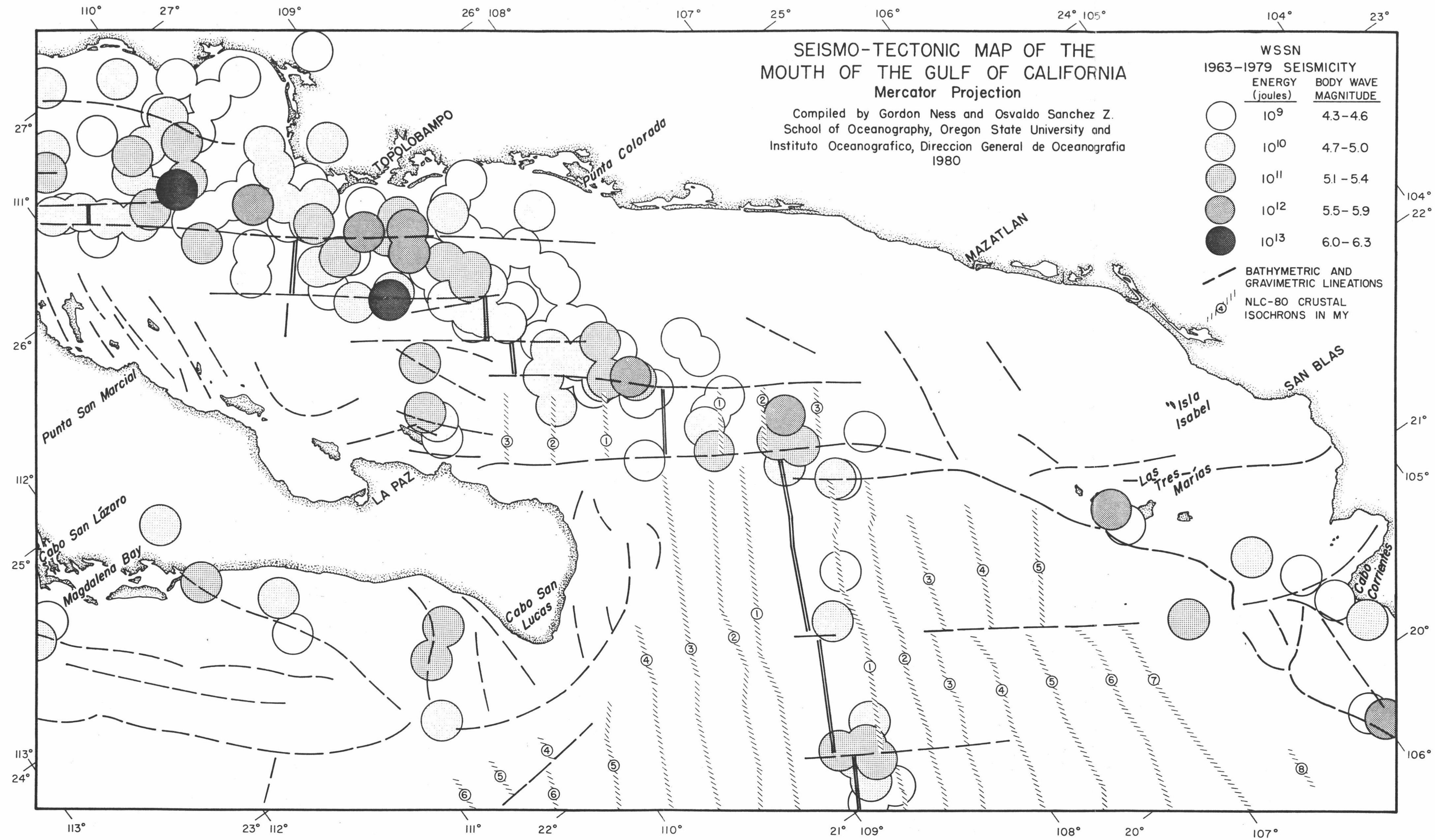

SEISMO-TECTONIC MAP OF THE
MOUTH OF THE GULF OF CALIFORNIA
Mercator Projection
Compiled by Gordon Ness and Osvaldo Sanchez Z.
School of Oceanography, Oregon State University and
Instituto Oceanografico, Direccion General de Oceanografia
1980
WSSN
1963–1979 SEISMICITY
ENERGY (joules)
BODY WAVE MAGNITUDE
10⁹ 4.3–4.6
10¹⁰ 4.7–5.0
10¹¹ 5.1–5.4
10¹² 5.5–5.9
10¹³ 6.0–6.3
BATHYMETRIC AND GRAVIMETRIC LINEATIONS
NLC-80 CRUSTAL ISOCHRONS IN MY
TOPOLOBAMPO
Punta Colorada
MAZATLAN
SAN BLAS
Isla Isabel
Las Tres Marias
Punta San Marcial
LA PAZ
Cabo San Lázaro
Magdalena Bay
Cabo San Lucas
Cabo Corrientes

Figure 16

Zone began reorienting, and that the Rivera Plate came into being as a separate unit, sometime around 9 MY.

North of the Esplandian F. Z. the anomalies older than 3 MY are poorly correlated, but we show 4 MY and 5 MY isochrons. These are over the Maria Magdalena Rise where, as discussed, spreading of some kind may have occurred, or may even be presently occurring. If no spreading has occurred on the Maria Magdalena Rise, then the age of the oceanic crust in the Rivera Trench is about 8 or 9 MY, as determined by continuous extrapolation using profile BB'. If an earlier episode of spreading has occurred on the Maria Magdalena Rise, then the crust in the Rivera Trench should still be about 8 or 9 MY, but there should be a reversal of ages over the rise.

Teleseismic Activity

In an effort to determine the neotectonic activity in and near the Gulf of California using a uniform data set, we sorted the earthquake files of NOAA/NGSDC for northwest Mexican and southern Californian events recorded since the establishment of the World-wide Standard Seismic Network in 1963. We then constructed a histogram of all events having listed body wave magnitudes (M_b) listed in the file (Figure 17). The record through the end of 1979 is about 17 years long. The histogram indicates that the network is reliably sensitive for regional events greater than about 4.3 M_b. On the assumption that these larger earthquakes would be better located, we then mapped their epicenters using circles with a diameter representing 25 km. This reflects our

Figure 17. A histogram of earthquakes for the region. The global network is apparently reliably sensitive to gulf earthquakes at the 4.3 magnitude level and above. We have therefore not plotted events smaller than that magnitude on Figure 16. We assume events of 4.3 magnitude and greater to be reliably located. The circles shown on Figure 16 are of 25 km diameter reflecting our estimate of the accuracy of the epicenter determinations.

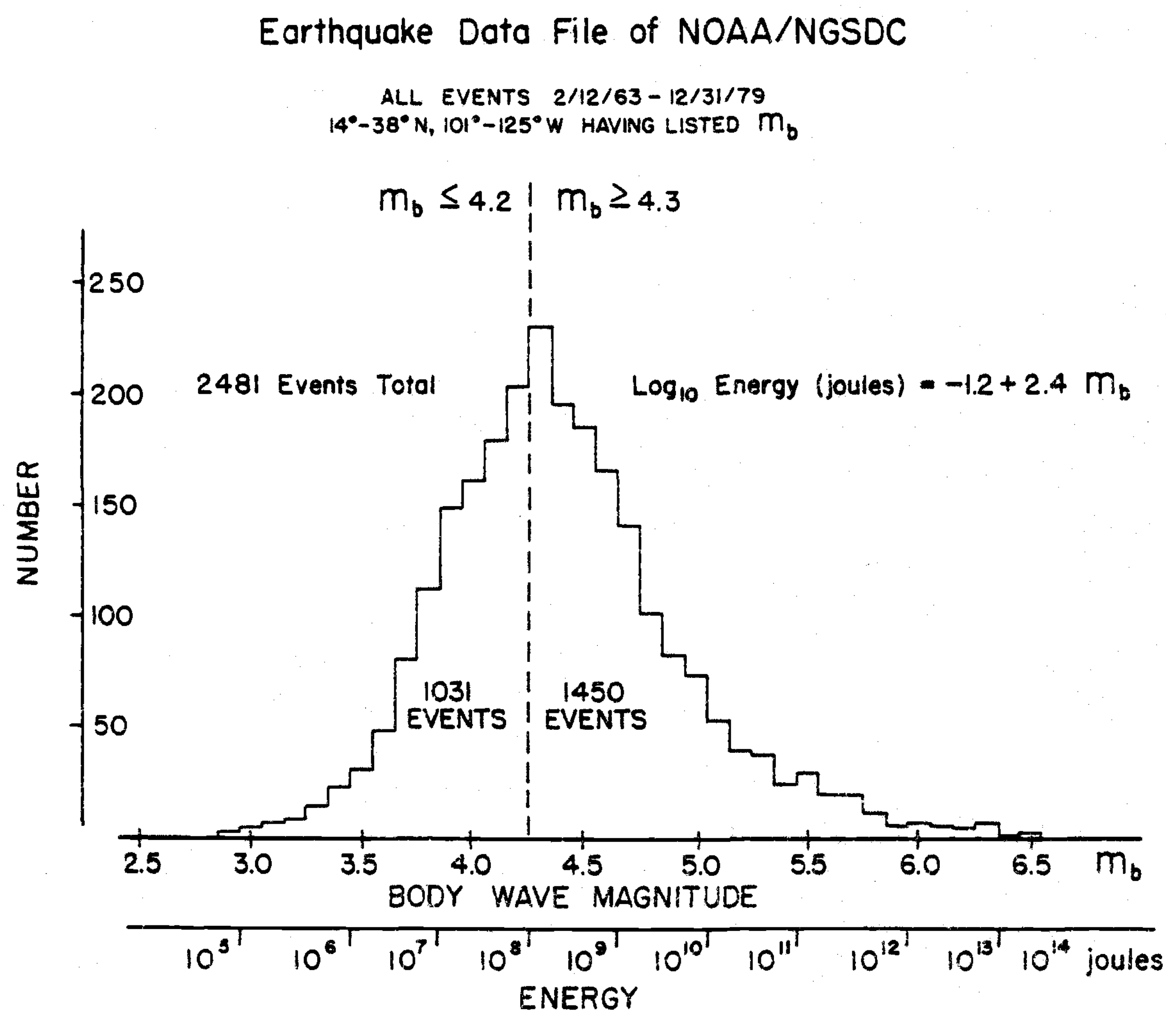

Earthquake Data File of NOAA/NGSDC
ALL EVENTS 2/12/63 - 12/31/79
14°-38° N, 101°-125° W HAVING LISTED m_b
$m_b \leq 4.2$
$m_b \geq 4.3$
250
200
150
100
50
NUMBER
2481 Events Total
$\log_{10}$ Energy (joules) = $-1.2 + 2.4\ m_b$
1031 EVENTS
1450 EVENTS
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
m_b
BODY WAVE MAGNITUDE
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14} joules
ENERGY

Figure 17.

nominal estimate of the accuracy of the epicentral locations. We next converted the body wave magnitudes, which are exponential, to equivalent energy in joules, using a relationship similar to that given by Richter (1958). We then filled the epicenter circles with progressively more dense matte patterns corresponding to the order of magnitude increases in energy. The result is shown in Figure 16 along with the crustal isochrons, the pronounced bathymetric and gravimetric lineations found on Figures 9 and 10, and with some few additional faults inferred from magnetic offsets and seismicity.

The first point we wish to make is that we believe the earthquake epicenters to be reasonably well located. Most of the largest magnitude event circles (10^{13} and 10^{12} joules) fall on obvious lineations. We do not show it here but this is particularly true over the Rivera F.Z. where there is a strong correspondence between the epicenter circles and the physiographic trace of the fracture zone. (We are preparing another study, similar to this one, for the entire central portion of the Pacific margin of Mexico, which will include the Rivera F.Z.). Note that the epicenter circles on the west side of Baja California are very closely related to the gravimetric and bathymetric lineations marking the trace of the Las Almejas Fault. Similarly, a string of epicenter circles of order 10 superimposes on the two closely spaced fracture zones within the Carmen Basin.

We infer, from the seismicity shown in Figure 16, that the short Montalvo F.Z. and, perhaps, the older and much longer Esplandian F.Z., are presently active. If the later inference is correct, then the northernmost portion of the Rivera Plate, including the Maria Magdalena

Rise, is a tectonic unit acting at least slightly independent of the main Rivera Plate. This in turn would seem to require that the Esplandian F.Z. extend across the Pacific Plate to either the Jimenez Trough or the Calafia F. Z., as we discussed in regard to the gravity anomaly map. However, there need be no Pacific extension of the Esplandian F.Z. if the eastern flank of the Rivera Ridge is spreading at slightly different rates on either side of the Esplandian F.Z. With the data available, we can neither support nor refute any of these options.

We have attempted no fault plane solutions for any events in the area. Obviously, it would be interesting to know the directions of slip vectors for the lower energy events off Cabo Corrientes. Minster (personal communication) finds a right (!) lateral strike-slip solution for a large magnitude event near the Tres Marias Islands. This implies that the northern Rivera Trench is primarily a transform boundary between the Rivera and North American plates. Alternatively the earthquake may be an expression of right-slip between North American and Trans-Mexican plates across the San Blas Trough.

The large cluster of epicenters within about 50 km of the Guaymas F.Z. extension at 26.5°N, 110°W indicates that the fault is active and not just a simple aseismic, transform fault extension. This in turn means that the piece of crust between the Carmen F.Z. and the Guaymas F.Z. (labeled the Carmen Block on Figure 8) is not acting as part of either the Pacific or the North American Plates.

A similar cluster of epicenters along the Farallon F. Z. transform extension indicates that the Farallon Scarp is an active fault bounding an independent Atl Block. A similar but less convincing case can be made for the smaller Murillo Block.

Farther south, the Pescadero and Tamayo Blocks, which are very prominent features in physiography and in gravity, appear now to be part of the North American Plate. No teleseismic activity is found between the blocks and the mainland toward the east. The Mazatlan Trough is aseismic, at the teleseismic level anyway. Although these blocks have every structural appearance of having been active horsts in the past, they have evidentially foundered. The aseismic extension of the Farallon Basin divergence toward the southwest, across the Atl F.Z. and to the Murillo F.Z. extension, also probably represents an aborted rift, and the crust between that rift and the Atl Basin once probably acted as an independent block - in this case on the Pacific Plate side. Note that at least four rifting axes may have been active between the Atl and Pescadero Fracture Zones from the Mazatlan Trough to the southern Farallon Basin.

There is no clear teleseismicity along the San Blas Trough, but the Banderas Canyon Fault, which is colinear with and perhaps somehow related to the Esplandian F.Z., could also be an active feature.

Finally, seismicity near Cerralvo Island at 24.3°N, 109.8°W and also near the base of the Tamayo Block at 23.2°N, 108°W indicates that the oceanic crustal segments on both sides of the Pescadero Divergence may possibly be acting independently of adjacent structural units, further complicating the Pacific/North American plate rate determination problem.

CONCLUSIONS

We have used a new, rigorously navigated, large volume, data set to examine the reconnaissance scale geophysical structures of the mouth of the Gulf of California. Four major conclusions result. Our confidence in these conclusions rests upon the quality of the data set, and upon agreement with other lines of evidence. We feel that our conclusions follow fairly directly from the evidence, but recognize that they may seem controversial to some workers. Other reasonable, but less encompassing, interpretations are possible, and we will attempt, in the following, to suggest tests for evaluating our interpretations.

The first conclusion we reach is that the rifting process responsible for separating Baja California from the mainland of Mexico acts very diffusely, over many divergent axes. The surprisingly extensive degree of faulting found by Ness et al. (1981) on oceanic crust west of the tip of the peninsula of Baja California is mirrored both on the continental crust of the southern peninsula, where active faulting persists, and within the southern Gulf of California, where the Pacific/North American plate boundary actually consists of many small blocks, some of which are still acting independently of either major bounding plate.

The San Blas, Tamayo, and Pescadero structural blocks appear, seismically, to have foundered and to have become part of the North American plate. In the past, however, they must have acted independently. Farther up into the gulf, the Murillo, Atl, and Carmen blocks are still bounded by seismically active extensions of main gulf transform faults. To argue otherwise would require that the WWSSN hypocenters be systematically mislocated to the east by as much as fifty kilometers and more. We have discussed this with Mike Reichle, who has done considerable work on the seismology of the gulf and peninsula, and we feel that such an extensive systematic mislocation of hypocenters would have to be demonstrated. This would require a local seismometer network. Such a network exists around the northern gulf, operated by the Mexican agency CICESE, the Center for Scientific Investigations and Higher Education at Ensenada. That agency plans to extend a telemetered seismic network into the central and southern gulf in the immediate future. So, within a few years, we may be able to better resolve the seismicity associated with these blocks.

The development of the gulf by rifting has also required a very long time to become organized. The Rivera Ridge began reorienting, by clockwise rotation, about 9 MY ago. It appears to have ceased rotating by perhaps 2 MY, at least within the mouth of the gulf proper. However the southernmost peninsula has acted as a number of small blocks in the past, and at least three of these are still seismically active and indepdent. Thus, we rule out as simplistic any notions that Baja California has ever acted as a large monolithic block. Trans-peninsular faults as proposed by Rusnak, Fisher, and Shepard (1964), seem quite possible to us, particularly in view of the probable existence of even larger faults such as the Tosco-Abreojos.

A truly detailed reconstruction of the opening of the gulf will have to address the problem of the motions of so many small blocks over so much space and so much time. We anticipate being very, very old when such a detailed history is finally, if ever, convincingly presented.

Our second major conclusion is that the Pacific/North American plate separation rate of Larson and Chase (1970), which is most commonly cited by other workers and which is the only Pacific/North American rate datum used in the benchmark, multiplate inversion model of Minster and Jordan (1978) is underestimated by 20-25 percent. We have illustrated and discussed the difficulties in estimating the divergence rate using our profile AA', which was made north of and parallel with the Tamayo Fracture Zone. We feel that our 68 km/MY rate estimate, determined for the last 3 MY, is the most direct and reasonable result that can be obtained from that profile. Other options would be statistically less well fit or would require special pleading. Actually Larson and Chase (1970) did not present data in support of their rate estimate, but instead cited an earlier report by Larson et al. (1968) where "data show a spreading half-rate of 2.9 cm/yr north of the Tamayo Fracture Zone inside the Gulf." An examination of the 1968 report reveals that the data were presented in map view (their Figure 2) by projecting magnetic anomaly profiles onto tracklines across the gulf. But the map is very small and no useful distance information is available at the scale required. A 2.9 cm/yr rate is not mentioned in the paper. Also, we question the navigational accuracy of those older profiles. Figure 1 of Larson et al. (1968) shows the western end of the Rivera Fracture Zone mislocated by at least a half-degree of latitude from its position as later mapped by Larson (1972) or by Mammerickx et al. (1978).

Our single profile is certainly subject to questions concerning the assumption of two-dimensionality for the source bodies and freedom from interference by seamounts, etc. We have recently acquired two additional profiles parallel to and astride the illustrated profile AA'. When we complete the renavigation process, to obtain gravity data from that cruise, we intend to compare, and perhaps to stack and model, the three profiles.

In the meantime, unless other convincing conflicting data are presented, our 68 km/MY Pacific/North American rate estimate lends strong support for (in fact it caused us to first consider) the possibility that an active Trans-Mexican Plate exists south of the Trans-Mexican volcanic belt. This is our third major conclusion. If southern Baja California (which is presumably on the Pacific Plate, although even this may be open to question) is separating from North America at 68 km/MY across the Tamayo Divergence, and if it is also separating from the Rivera Plate at approximately 52-57 km/MY (our profiles BB' and CC'), then the Rivera Plate should be separating from "North America" at Cabo Corrientes by about 14 km/MY. This would make the Rivera Trench a divergence zone -- an absurd result (perhaps, but see Allen (1981) on the subject of the Colima Graben).

Moreover, as Yeats and Haq (1981) reconstruct the history of the Maria Magdalena Fan it originated at or very near the mouth of the Gulf of California about 14 MY ago. If the fan is moved backwards along a Minster and Jordan (1978) Pacific/North American trajectory (we see no justification in arguing for a different PAC/NAM rotation pole position, only for an increased angular rate of motion), it would be positioned almost 1000 km to the southeast of its present position, corresponding to the present day location of the port of Manzanillo several hundreds of kilometers southeast of the present day mouth of the Gulf.

Our solution to these problems is to posit the existence of a Trans-Mexican plate moving right-laterally with respect to North America at a rate somewhere between 14 and 20 km/MY. Such motion is consistent with the sense and magnitude (but not the timing) of trans-Mexican displacement proposed by Gastil and Jensky (1973). It is also consistent with the sense (but not the timing) of the magnetic paleolatitude of Baja California proposed by Beck and Plumley (1979), with the approximate magnitude of the change in paleolatitude proposed by Marshall et al. (1979), and with the sense of Pliocene and Younger rotations of crustal blocks on Baja California proposed by Strangway et al. (1971).

A very interesting line of seismological evidence may also support our proposal that an active Trans-Mexican Plate is presently moving right-laterally with respect to North America. Larson and Chase (1970) and Minster and Jordan (1978) both compared predicted slip vectors for Cocos/North America plate motion with the fault plane solutions for Benioff zone earthquakes determined by Molnar and Sykes (1969). In both studies, although slightly different Cocos/North American pole positions were used, the observed slip vectors were consistently oriented more easterly than predicted vectors. This discrepancy is explicable if the fault plane solutions actually represent Cocos/Trans-Mexican relative motion and not Cocos/North American motion, as was assumed.

Additional, but less convincing, seismological evidence suggests that both our Pacific/North American plate rate estimate and, by extension, our speculation that a Trans-Mexican Plate is presently active are correct. Our 68 km/MY rate is only slightly greater than the 6.6 cm/yr slip rate calculated by Brune (1968) from the sum of seismic moments for three large ($M_b > 8.0$) earthquakes that have occurred along the San Andreas

Fault since 1800. This is certainly not compelling evidence since, as Brune pointed out, the particular earthquakes he used all occurred before modern instruments were in existence.

Thus, many very different kinds of evidence support both our second and third conclusions. We are presently working to establish a network of seven satellite laser ranging sites around the Gulf of California, at Manzanillo south of the trans-Mexican volcanic belt, and on Socorro Island which is umambiguously on the Pacific Plate. If and when such a widely spaced network is successfully established as part of the NASA Crustal Dynamics Program, and after a sufficient number of observations have been made (most probably requiring five to ten years), it should be possible to convincingly confirm or refute Trans-Mexican Plate motion, Pacific/North American rate estimates, the extent to which Baja California is acting as several small blocks, and which if any, of those blocks are bonded with the Pacific Plate. The satellite laser ranging technique is ideally suited for application to the problem of the Gulf of California.

Finally, our fourth conclusion. We have discussed in fair detail our thoughts that an episode of subduction has occurred beneath the southeastern tip of Baja California. We see the gravitational expression of a buried trench extending around the tip, and argue that the uncentered location of the Rivera Ridge within the mouth of the gulf is related to differing ages for the oceanic crust at the Rivera Trench and at the base of the slope of southeast Baja C lifornia. If the Mammerickx aborted ridge model is correct, in whole or in part, then our subduction model becomes questionable. The direct solution to this conflict is to drill a series of holes into the Maria Magdalena Rise, to determine paleotologically the ages of the basal sediments, and then to see which model those ages fit. A less direct but more economical test would be to determine by detailed surveying whether or not the Esplandian and Calafia Fracture Zones are connected. If they are, then many possibilities arise including different spreading histories on either side of those fracture zones. A well navigated and detailed magnetic survey of the Maria Magdalena Rise itself would also be illuminating. The problem for the moment is that the necessary navigation systems are not readily available.

Recently Lyle and Ness (1981) and Ness and Lyle (1981) have integrated the Deep Sea Drilling Project results from Legs 63 and 64 with the geophysical information presented here. This integration has allowed them to construct a history for the opening of the Gulf of California for the last 14 MY that is better constrained than would be the case if either the geological or the geophysical evidence were used separately. Of necessity this history is based upon a number of simplifying assumptions. It includes Trans-Mexican Plate motion, a rapid Pacific/North American plate divergence rate, and an episode of subduction beneath the southeast tip of Baja California. It is, however, consistent with, constrained by, and thus synergistically enhanced by the many lines of evidence available. It has been described by friendly, informal reviewers as "thought provoking". We suspect that a slight emphasis is placed upon the "provoking" part. The subduction idea is apparently the more difficult conclusion for people to accept. We make no limiting assumptions about plate driving mechanisms and so subduction becomes an obvious, kinematic explanation for the body of evidence.

Dixon and Farrar (1980) have illustrated some of the tectonic effects that can be expected for certain triple-point plate relationships. We have heard rumors that their paper was very critically reviewed and received, but we emphasize that the tectonic effects they postulated are not only possible, but are generally required for most ridge-trench interactions. The geometry of plate tectonics demands that such effects as oblique surface convergence and oblique surface divergence be possible. This is beyond contest. Pure strike-slip motion resulting from a ridge-trench collision would be fortuitous and rare. Thus the famous Atwater (1970) model for the tectonic evolution of western North America is only broadly correct.

At the scale of the mouth of the Gulf of California oblique subduction and divergence effects would have occurred beneath the unopened Gulf of California as the North American Plate overran parts of the East Pacific Rise. Typically, people have been reluctant, often even surly, about subducting a "ridge", which probably is an unconscious reflection of certain biases about plate driving mechanisms. The very fact of the Gulf of California, its very existence as an advanced continental rift, demands that sub-crustal divergent stresses be real. The subaerial valleys and depressions of the Salton Trough give way to progressively deeper, divergent marine basins in the central and southern Gulf, and become true oceanic ridges at the mouth of the gulf. Thus continental rift valleys become submarine basins become oceanic ridges in a continuous way reflecting the same probable cause. Ridge "jumps" behind the trench (where ridges are thought to be active, causal features) are not necessary. Instead continental crust can be thought to gradually override ridges (where "ridges" can be thought of as being simply the passive, shallow, surface expression, on oceanic crust, or a more broad, deeper divergence in the upper mantle). In that sense a ridge can be thought to migrate beneath the edge of a continent. All of this last discussion is intended to support and elaborate upon the Dixon and Farrar (1980) paper, which we feel is an important introduction into second generation, mesoscale, three-dimensional, geometrical plate tectonics. The concepts described there eliminate the difficulty with accepting subduction beneath the southeast tip of Baja California. Not only could Pacific/Baja California convergence have been possible at earliest rifting, it should have been occurring beneath the leading edge of North America prior to rifting and most probably was.

In summary, we have found complexity where, before, the problem was thought to have been solved. This, in itself, gives us confidence that we may be correct. The hope for simplification now seems to lie in accepting the possibility of a new three-dimensional geometrical kinematics. The old two-dimensional kinematics breaks down at the scale of this problem (and most other contemporary, meaningful tectonic problems). We now need to push a new mesoscale kinematics to its limit to find out where the rigid plate geometry will fail. That effort should yield much information about the dynamics involved in rifting and plate driving processes.

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