fraction analyses of bulk samples heated to between 200° and 1000°C. At no stage was a discrete manganese oxide phase observed although, from studies of amorphous manganese oxide gels (*4*), crystallization of some form of an oxide below 500°C is expected. Below 200°C, dehydration occurs and the nodules lose as much as 20 percent water by weight. Between 200° and 400°C the predominant iron-manganese oxide phase crystallizes as Mn-hematite with an empirical formula α-$Fe_{2-x}Mn_x$-O_3; simultaneously goethite from the ocherous matrix undergoes dehydroxylation to α-Fe_2O_3 (hematite). Above 650°C the Mn-hematite and hematite spinel (jacobsite); the transition is nearly begin to recrystallize, forming Fe-Mn complete at 870°C (Table 2).

Other workers (*5*) have shown that the lower limit for the formation of Fe-Mn spinel from stoichiometric mixtures of the oxides is approximately 1000°C. If manganese is diadochic in an iron mineral such as the Fe-Mn oxide phase observed in these nodules, jacobsite could be formed appreciably below 1000°C.

Differential-thermal analyses provide further evidence of the existence of a hydrous iron-manganese oxide phase. Thermograms of the nodules compare favorably with those reported by other workers (*6, 7*) for hydrated iron oxide gels. No observed reaction could be attributed to the crystallization of manganese oxide from a gel, although differential-thermal studies of prepared mixtures (*7*) clearly show a resolved exothermal doublet in the range 200° to 400°C, corresponding to the crystallization of iron and manganese oxides from their respective gels.

The ocherous matrix of the nodules consisted chiefly of cryptocrystalline goethite; their sediments and insoluble residues contained abundant illite, minor chlorite and kaolinite, and traces of montmorillonite, quartz, amphibole, plagioclase, and potassium feldspar. The nodules appeared to have no nuclei, although rare shards, and porcelaneous grains apparently pseudomorphic aftershards, were observed under the microscope. The porcelaneous grains were chiefly montmorillonite with minor phillipsite. No carbonate mineral was observed in nodules or sediment.

We suggest that formation of these nodules was contemporary with sedimentation and apparently related to volcanic activity; the basis for our argument is the occurrence within the nodules of large percentages of detrital silicates (from sedimentation) (see Table 1), and of rare shards and shard pseudomorphs from volcanic activity.

The nodules were enriched in iron and depleted in manganese relative to average values for the Atlantic Ocean (Table 1); nevertheless our values fall within the reported ranges for these elements (*8*). The Mn:Fe ratios of the nodules, differing appreciably, are considerably lower than most reported values for Atlantic nodules (*8, 9*).

Although the manganese content of the surface nodules is significantly greater than that of the 73-cm nodule (Table 1), no evidence suggests that manganese has migrated. Migration of manganese requires an environment that reduces manganese IV to manganese II (*10*), and there is no evidence in this core of such a reducing environment. The most probable oxidation state is manganese IV which has t_{2g}^3 electron distribution. The ligand-field stabilization energy associated with this electron distribution is $6/5\ \Delta_0$ (*11*), which is maximum. Manganese II has a $t_{2g}^3e_g^2$ electron configuration and no ligand-field stabilization energy; therefore the energy difference between the two states may be sufficient to deter the migration of manganese IV.

The contents of minor elements (Cr, Co, Cu, and Zn) were similar for the three nodules (Table 1), but our values for them are considerably less than average values for the Atlantic Ocean, with the exception of Cr which is greater by an order of magnitude than reported values (*8*). Our overall analyses suggest a similar history of formation of all three nodules.

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Gulf of California: A Result of Ocean-Floor Spreading and Transform Faulting

Abstract. *Ocean-floor spreading tore southern Baja California from mainland Mexico 4 million years ago and has subsequently rafted it 260 kilometers to the northwest along the Tamayo Fracture Zone. Magnetic-anomaly profiles indicate spreading at the mouth of the gulf at 3.0 centimeters per year and a rise-crest offset of 75 kilometers inside the gulf across the Tamayo Fracture Zone.*

The East Pacific Rise extends northward from the equatorial Pacific and disappears as a distinct bathymetric feature somewhere near the mouth of the Gulf of California (*1*). From the north, the San Andreas fault and a related system of parallel faults trend down through California and disappear under the Salton Sea Trough (*2*). The Gulf of California is generally assumed to have originated from motion on one or both of these structural features. Wilson (*3*) envisions the San Andreas fault as a dextral, ridge-ridge transform fault. As such, it forms a connecting link between the East Pacific Rise at the mouth of the Gulf of California and the reappearance of the rise in the form of the Gorda Rise and the Juan de Fuca Ridge in the North Pacific. Motion on the San Andreas fault is due to ocean-floor spreading from the rise crests. The Gulf of California is then a result of strike and cross-strike separation in relation to the San Andreas fault. The hypothesis has subsequently

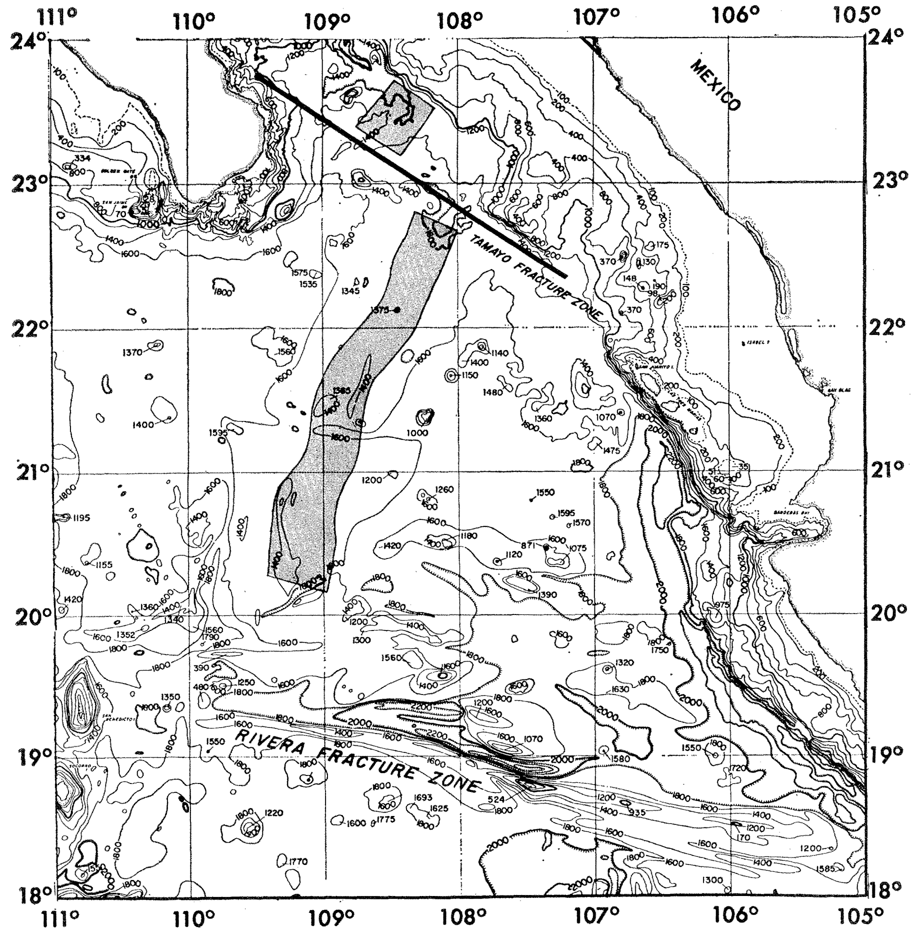
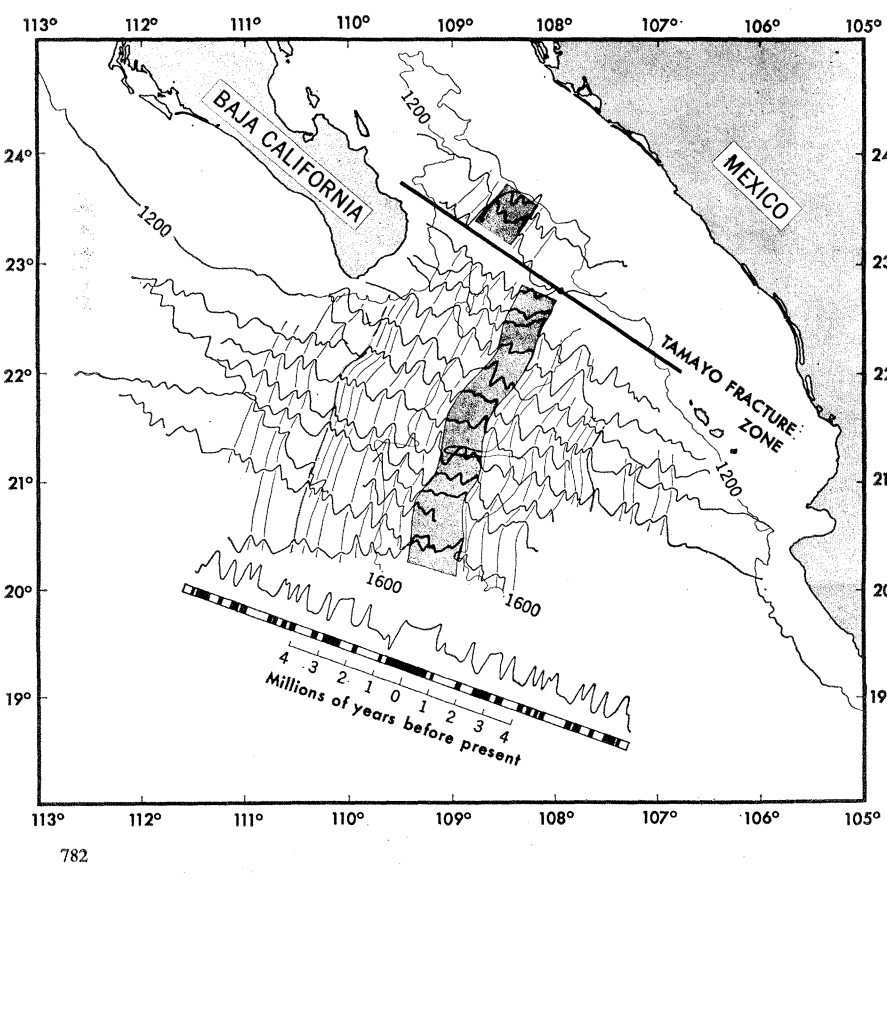


Fig. 1. Bathymetry in the region of the mouth of the Gulf of California (*19*). The darkened overlay indicates the extent of the central magnetic anomaly.



been slightly altered (*4, 5*) to include the possibility that there has been only strike separation along a series of parallel, offset transform faults in the gulf that trend slightly to the west of the trend of the gulf itself.

We now report, as judged from magnetic data, that the gulf is a product of ocean-floor spreading. The offset of the rise crest along the southernmost transform fault is also confirmed.

The portion of the East Pacific Rise considered here is that fairly continuous segment between the Rivera Fracture Zone and the mouth of the Gulf of California (Fig. 1). As a bathymetric feature it is a distinct swell in the ocean floor, even directly in the mouth of the gulf where it is sandwiched between Baja California and the mainland of Mexico. Occasional seamounts occur on the flanks and are distinctly more predominant on the eastern flank than the western one.

The magnetic profiles shown in Fig. 2 display a central anomaly occurring atop the rise crest as a low, broad, positive feature. This anomaly is a generally continuous feature observed on all but two of the profiles collected. One of the two questionable central anomalies is located over a portion of the rise previously thought to have been affected by faulting (*5, 6*), which may explain one of the problems. If such faulting has occurred, there was little or no associated rise-crest offset located on this survey. For a still unexplained reason, the central anomaly is a much more distinct feature north of the transform fault inside the gulf than it is to the south.

Moving to the flanks of the rise, the anomalies display the pattern of linearity, symmetry, and parallelism to the rise crest that depicts the ocean-floor spreading as described (*7*). The pattern indicates spreading at a rate averaging 3.0 cm/yr on each flank or a total of 6.0 cm/yr. It is especially clear on the western flank where anomalies representing polarity reversals can be traced away from the rise crest for 220 km. The picture on the eastern flank is not

Fig. 2 (left). Magnetic anomaly profiles at the mouth of the Gulf of California. The 1600-fathom contour outlines the East Pacific Rise crest, and the 1200-fathom contour locates the topographic edge of the continental blocks. The magnetic block model and corresponding anomaly profile were constructed with a spreading rate of 3.0 cm/yr (*19*).

nearly as clear, possibly because this flank of the rise is being forced against and under the mainland of Mexico and is presumably being disrupted in the process. The generally rougher bathymetry on the eastern flank may also be interpreted as additional evidence for such tectonic disruption.

The character of the anomalies on the western flank as they approach the eastern side of the tip of Baja California changes in a marked fashion. As the profiles come up on the continental shelf, the magnetic signature flattens out so that nothing of the ocean-floor spreading anomalies remains. Both the oceanic and continental anomaly patterns are remarkably clear in this region, and the boundary between them lies unmistakably at the topographic edge of the continental block. The lineated oceanic anomaly lying directly adjacent to the eastern edge of Baja in this region is correlated with the Gilbert reversed magnetic epoch. This epoch extends from 3.4 to greater than 3.7 million years ago (*8*). The four short positive anomalies occurring just west of this negative feature and truncated by Baja California are correlated with the short normal magnetic events recognized in sediments cored in the Antarctic Ocean (*9*). These events probably occurred between 4.0 to 4.5 million years ago.

The interpretation of these data leads to the following conclusions. The Gulf of California is the result of ocean-floor spreading from the crest of the East Pacific Rise. At the mouth of the Gulf of California, most of the spreading that has rafted Baja California away from the mainland of Mexico has occurred within the past 4 million years. Inside the gulf, the rise crest is offset 75 km along the Tamayo Fracture Zone, a transform fault whose trace is expressed as a distinct bathymetric lineation on the floor of the gulf. As the rise crest approaches the gulf, its trend swings around slightly to the east so that it meets this transform fault at right angles. The direction of spreading is then along the transform fault, and thus the manner in which southern Baja California has been displaced is in the form of strike separation parallel to this fault.

The fracture zone that is the expression of this transform fault is the southernmost of a family of major parallel, offset lineaments in the gulf that trend slightly to the west of the trend of the

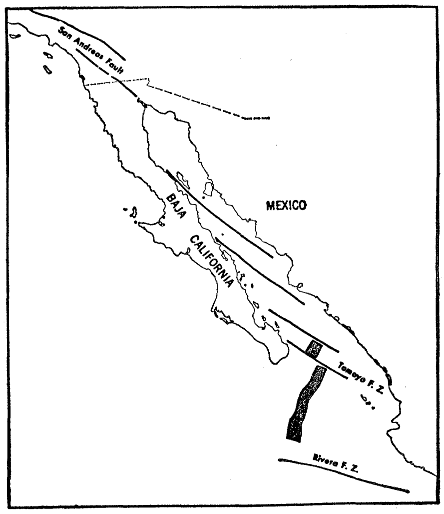


Fig. 3. Bathymetric lineaments of the Gulf of California and the fault system in southern California related as a family of parallel, offset structural features.

gulf. At the northern end of the gulf, this series of parallel, offset lineaments extends into southern California as the San Andreas fault system (Fig. 3). The offset of the rise crest now documented along the southernmost fault suggests that the crest is also offset along each of these fractures up into the gulf. Finally, at the northern end of the gulf, the San Andreas fault system becomes the northernmost member of this family of transform faults. Strike separation along each of these faults has resulted in the Gulf of California, and the strike separation along the San Andreas system is a result of the same phenomenon, ocean-floor spreading along a transform fault.

The conclusion that most of the motion at the mouth of the gulf has occurred within the past 4 million years is in direct conflict with former historical models which generally place the gulf opening somewhere in the Miocene (*10*) or even as far back in time as the Cretaceous (*11*). From paleontologic data acquired (*12*) in northern Baja California it can be argued quite firmly that the northern portion of the gulf was in existence in some form during the late Miocene. Nevertheless, the magnetic data at the mouth of the gulf indicate that most of the motion in that region has occurred in the last 4 million years. Possibilities that would resolve the dilemma could include allowing a very narrow, shallow gulf in the Miocene, or creating the gulf as a series of offsets starting in the north and working south to the present mouth of the gulf as has been proposed (*13*). This suggestion would make the northern portion of the gulf older than the southern portion, perhaps as old as Miocene.

The mechanism responsible for the gulf's formation now seems apparent, but it is much more difficult to prove the exact sequence of events that produced the feature. If, for the moment, the motion along the series of transform faults is considered synchronous, then this type of motion from the San Andreas system south to the mouth of the gulf is confined to the past 4 million years. This line of reasoning brings to mind what Taliaferro (*14*) stated about the importance of distinguishing between Quaternary strike separation measurements on the San Andreas and motion on the "ancestral" San Andreas fault which he regarded as "a profound normal fault developed in the early Eocene."

A large cumulative offset on the San Andreas that amounts to 560 km since Jurassic time has been proposed (*15*). Our data indicate that southern Baja California has been rafted away from mainland Mexico 260 km in the past 4 million years. If the amount of offset on the San Andreas is correct, more than half of it appears unrelated to the motion at the mouth of the gulf. This is clearly resolved if the excess San Andreas motion occurred previous to the opening of the mouth of the gulf, thereby creating the gulf from north to south.

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17. The horizontal dimensions of the magnetic block model are taken from Pitman and Heirtzler (*19*). The top of the model is placed 2.93 km (1640 fathoms) below sea level. It is 1.7 km thick. The blocks are assigned alternating effective susceptibilities of $\pm$ 0.01 emu cm^{-3} oersted^{-1} except for the central block which is +0.02. The blocks were then exposed to the ambient field with the following characteristics: intensity, 44,000 gammas (1 gamma = 10^{-5} oersted); inclination, 47° down; declination, 10° east. The geomagnetic time scale is taken from Cox *et al.* (*8*) and Doell and Dalrymple (*19*).
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20. Shiptime supported by NSF blockfunding. Research supported by ONR, Marine Physical Lab (SIO), and the U. S. Navy Oceanographic Office. During the past year, detailed magnometer and especially seismic profiling surveys have been conducted up and down the length of the Gulf of California at the same time that we have been carrying out magnetometer surveys at the mouth of the Gulf. These geophysical surveys by Moore and Buffington and our work are simultaneous, independent studies that reach similar conclusions based on different bodies of data. All the authors have thus requested publication of both articles at the same time as we believe them to be complementary.

5 April 1968

Magnetoencephalography: Evidence of Magnetic Fields Produced by Alpha-Rhythm Currents

Abstract. *Weak alternating magnetic fields outside the human scalp, produced by alpha-rhythm currents, are demonstrated. Subject and magnetic detector were housed in a multilayer magnetically shielded chamber. Background magnetic noise was reduced by signal-averaging. The fields near the scalp are about 1 $\times$ 10^{-9} gauss (peak to peak). A course distribution shows left-right symmetry for the particular averaging technique used here.*

Fluctuating magnetic fields around the human torso, produced by ion currents from the heart, have been detected (*1*, *2*) and studied (*3*). I now present evidence for the existence of a much smaller fluctuating magnetic field around the human head; the field is produced by the alpha-rhythm currents commonly seen on the electroencephalogram (EEG). The experiment, with some improvements, was similar to that for detecting the heart's magnetic field (*2, 3*); a subject with a sensitive magnetic detector near the field source, in this case the head, was situated inside an enclosure which was heavily shielded from external magnetic fluctuations. The high sensitivity of this experiment is due to the use of a low-noise parametric amplifier as part of the detector, and to the effectiveness of the shielding.

In theory, magnetic measurements at or near the surface of a living volume can yield some information about the internal charge distribution not possible to obtain with surface voltage or potential measurements. The potential measurements are limited because in general they cannot uniquely determine an internal charge distribution (*4*) which, in a living volume, contains the polarized charge layers of excitable muscle and nerve tissue. In electrocardiography, measurements of surface potential yield information about the state of heart muscles; the anatomical and electrical situations are relatively simple and well-understood, and the accepted electrical model of the heart is adequate for many purposes. As techniques improve, the information extracted with electrocardiography of any particular heart may soon approach the maximum allowed by this limitation. Because of this, measurements of the heart's magnetic field can eventually serve the auxiliary purpose of reducing this limitation. In electroencephalography, measurements of the brain's magnetic field may have a greater and more direct use. The information extracted by scalp potential measurements (the EEG) is far less than the allowed maximum because of the anatomical, functional, and electrical complexity of the source, for which no simple and effective model yet exists; the complexity is increased by the presence of the skull, a relatively poor conductor. Hence magnetic measurements around the head may supply fundamental information needed simply to evolve an effective electrical model of the phenomena which give rise to the EEG.

In an attempt to detect fluctuating or a-c magnetic fields from the brain, it makes sense to first use the alpha-rhythm currents. On instruction, the subject can produce or remove them by closing or opening his eyes; they yield some of the larger scalp potentials, and they are contained in the relatively narrow frequency band of 8 to 13 hz, with small harmonics; this is important because a narrower detector bandwidth means less detector noise, in which the weak magnetic signal is buried. By using a simplified geometry and formulas developed by Baule (*5*), one can theoretically predict the alpha-rhythm field several centimeters outside

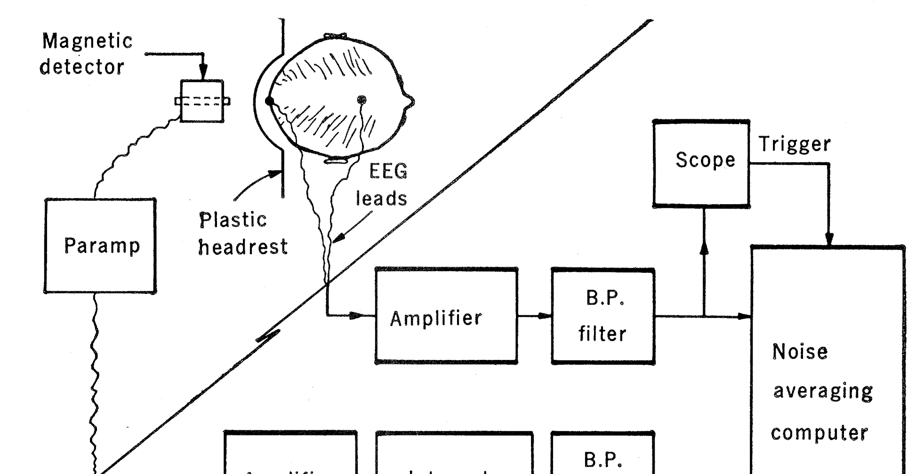

Fig. 1. Arrangement for magnetic alpha-rhythm detection. Subject and detector are inside the shielded enclosure, seen from the top; electronics are at an external station. The ferrite rod on the axis of the electrostatically shielded coil is in line with the subject's inion; this particular orientation detects the magnetic component normal to the scalp at the back of the head.