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Rift Activity in the Eastern Pacific

by

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S u m m a r y

The permanent rotation of the N.E.Pacific Rift is divided into three first-order rotations covering the whole rift between 20^{o} and 60^{o} N. during the last 80 mio years. The general movement of a clockwise rotation ($35-40^{o}$ altogether) was interrupted during the time between 40 and 20 m.y.b.p. by a weak counterclockwise one (8^{o} altogether). These superordinate rotations can be subdivided in smaller ones with an average duration of 10 m.y. only. It is to suppose that all these rotations are a readjustment of the rift to a changed position of the spreading pole. Compared to it, short-time, oscillatory rotations represent compensating movements of the rift and stabilizing efforts of the plate. For the S.E.Pacific Rift it is supposed that the counterclockwise rotation taking place there for the last 7 m.y. is continuing, as may be concluded from the distribution of earthquake epicentres.

Furthermore, the problems of pendulum movements and hinge zones at the S.E. and N.E.Pacific Rifts are discussed, which represent the magmatic activity of the rift. Hinge zones are lines of weakness of rifts, which can become fault zones. Up to now they were not mentioned in literature.

The internal deformations of the Pacific Plate and Juan de Fuca Plate off California indicated by kinks of the rift, fault-folding and strike slip faults became intense about 1-2 m.y.b.p.

Z u s a m m e n f a s s u n g

Die permanente Rotation des NE-Pazifischen Rifts während der letzten 80 Mill. Jahre ist in drei Etappen 1.Ordnung zu unterteilen, von denen der gesamte Rift zwischen 20^{o} und 60^{o}n.Br. erfaßt wurde. Die generelle Rechtsrotation des Rifts um insgesamt $35^{o}-40^{o}$ wurde vor 40 Mill. Jahren für einen Zeitraum von 20 Mill. Jahren unterbrochen durch eine schwache Linksrotation des gesamten Rifts um maximal 8^{o}. Diese übergeordneten Rotationen überlagern Drehungen des Rifts, die durchschnittlich nur 10 Mill. Jahre andauern. Beide ergeben sich offenbar aus der Reorientierung des Rifts während oder nach einer Verlagerung des Spreadingpols. Dagegen vertreten kurzzeitige, oszillatorische Rotationen Ausgleichsbewegungen des Rifts, die offenbar der Stabilisierung der Platte dienen. Die Verteilung der Erdbebenzentren am SE-Pazifischen Rift deutet darauf hin, daß die Linksrotation der letzten 7 Mill. Jahre noch anhält.

Pendelbewegungen einzelner Riftabschnitte an Störungen und Scharnierlinien spiegeln die magmatische Aktivität des Rifts wider. Bei den Scharnierlinien handelt es sich um Schwächezonen der Rifte, die sich zu Bruchzonen entwickeln können. Sie sind bisher in der Literatur nicht bekannt gewesen.

Die platteninterne Deformation der Pazifischen und der Juan-de-Fuca-Platte vor der Küste Californiens setzte intensiv vor 1-2 Mill. Jahren ein.

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Резюме

Постоянное вращение рифта северо-восточной части Тихого океана во время последных 80 милл. лет подразделяется в три этапа I порядка, которые охватывали весь рифт от 20° до 60° с.ш. Общее левое вращение рифта на всего 35° - 40° прервано незначительным левым вращением всего рифта 40 милл. лет тому назад длительностью 20 милл. лет на максимально 8°. Вращения I порядка накладывают вращения, продолжающиеся лишь I0 милл. лет. Оба движения, очевидно, вытекают из реориентации рифта до или после перемещения полюса спрединга. По сравнению с этим краткосрочные осцилляционные вращения представляют собой компенсирующие движения, способствующие, по-видимому, стабилизацию плиты. Распределение центров землетрясений рифта юго-западной части Тихого океана указывает на еще действующее левое вращение последных 7 милл. лет.

Колебательные движения определенных отрезков рифта по разломам и шарнирным линиям отражают магматическую активность рифта. Шарнирные линии представляют собой зоны ослабления рифта, из которых могут образоваться зоны разломов. В литературе они до сих пор не описывались.

Интенсивные деформации внутри плиты Тихого океана и плиты Хуан де фука, находящихся под берегом Калифорнии, начали I - 2 милл. лет тому назад.

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1. Introduction

The present paper deals with some geological processes taking place at rifts in the oceanic crust. They are by no means specific only to the Pacific Rift (Fig. 1), but the latter is the object of investigation, because detailed records of magnetic anomalies have been published for so large a coherent area that they could be used as initial data for our considerations.

An attempt is made to show the way in which the magmatic activity of the rift causes and influences tectonic processes. Magmatism forms the main parts of the ocean floor and, in the form of stripes having different ages, its spatial rhythm, producing the formation and activation of faults and fracture zones, that is to say, it stamps the development of active rifts. The rift must react on changes of pole positions, on the influence of other plates, and this in a variety of forms specific to the rift. On the other hand, it presents characteristics of activity (equidistance, behaviour of magmatic centres and fracture zones) to be found in the continental crust as well.

Finally, we are seeking general characteristics of tectonic movements, with the interpretation of magnetic anomalies as a method and the demonstration of block and rift rotations (the main subject of the paper) only as a means to an end. From the investigations results that, presumably for all processes to be described in this paper, regularities (to which no importance has been attached so far in part) seem to be valid within limits ranging from tens of m.y. to m.y., and covering extents from more than 1,000 km to 10 km. Just the differences from the general behaviour have excited our attention and, finally, made visible phenomena and relations characterizing real geological processes taking place in a well-ordered manner.

Although the aspect of rift tectonics, by the detailed processes of movements to be demonstrated (rift and block rotation, rift deformation, development stages of fracture zones), becomes more intricate, its appearance to a certain degree also becomes more geological in that line patterns in the form of magnetic anomalies do not move from the rifts across the ocean floor, but that geological bodies are on the move, living an intricate tectonic "life of their own", even at a relatively simple geometry.

For our investigations we used magnetic anomalies published by ATWATER (1970), HEIRTZLER et.al. (1966), HERRON (1971, 1972) and NAUGLER & WAGEMAN (1973).

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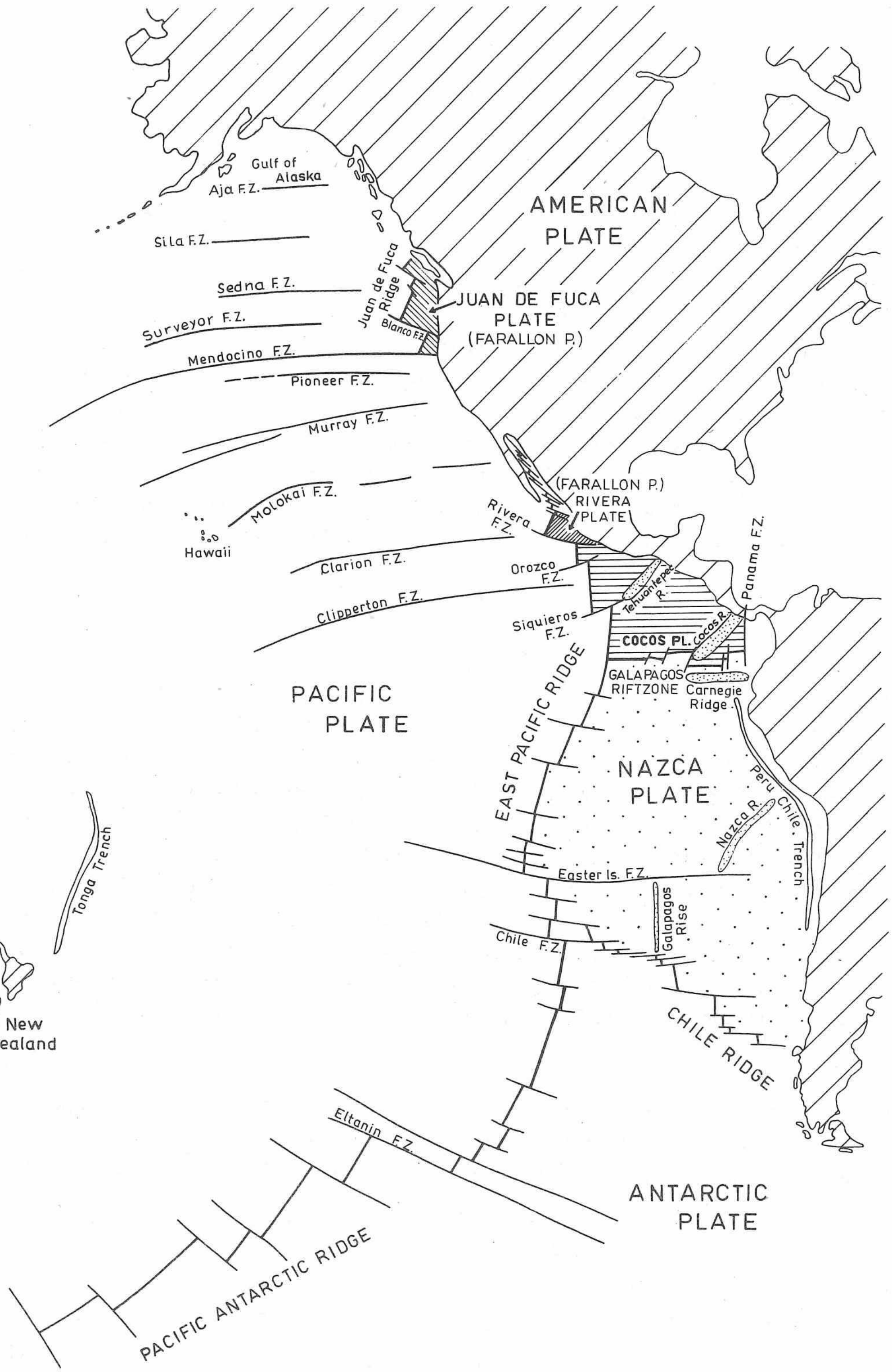

Fig. 1. Sketch map of the tectonic structures in the Eastern Pacific. Sources: ATWATER 1970, STOVER 1973, GIERLOFF-EMDEN 1970

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2. Superordinate rotations of the East Pacific Rift between 20° and 60° N.

The following considerations refer to the N.E. Pacific in the area between 20° and 60° N. as well as 105° and 170° W. (between the Clarion Fracture Zone and the coast of Alaska, Fig. 2). Numerous studies published on the tectonic development of the Pacific Plate are not to be discussed here. Rather the change of position undergone by individual magnetic anomalies is considered and compared with older adjoining anomalies, from which conclusions are drawn on rotations of the rift in the meantime. By VOGT et al. (1969) the possible mechanism for rift rotations is seen in the magmatic material injected obliquely within the main injection zones of the rift. The schematic representation given by these authors in Fig. 10B, p. 294, can be completed and varied by our observations of the anomalies between 52° and 56° N. (between the Sila and Aja Fracture Zones). In Fig. 14 the possible stages of rift sections rotating step by step are represented in the rows A and B, i.e., in a way as they might have preceded the changing positions and shapes of the anomalies 15 to 6, when we regard it as a premise that the positions, shapes and widths of the anomalies are generally a result of the magmatic activity at the rift, and are directly connected one with another.

2.1. The clockwise rotation of the N.E. Pacific Rift 80 m.y.b.p. (1st period)

The first clockwise rotation of the N.E. Pacific Rift which is demonstrated by numbered anomalies began north of the Surveyor Fracture Zone (F.Z.) with anomaly 32 A (80 million years ago) at (today) 42° N. South of this zone the clockwise rotation did not begin until it had diminished north of it, at the time of anomaly 31 (72 m.y.b.p.), but it continued up to 67 m.y.b.p. South of the Pioneer F.Z., at 37° N., the rift even rotated up to 65 m.y.b.p., that is, by 2 m.y. further. Fig. 3 shows schematically the beginning of this rotation in the individual rift sections between 20° and 55° N. (fault displacements are eliminated, numbers represent the corresponding anomalies), according to the representation of anomalies (Fig. 2). The width of anomalies was represented uniformly to compare directly between synchronous anomalies.

By this representation the rotations of the individual rift sections can be reduced to three groups (I, II, III) in which the rotations had proceeded from north to south. That means, about 80 m.y. ago the rotation nearly began at the same time:

north of the Surveyor F.Z. (46° N.),
south of the Mendocino F.Z. (39° N.),
south of the Molokai F.Z. (22° N.),

and continued there more than 10 to 15 m.y. for a differently long time. Within 6 to 8 m.y. next after the beginning, the rift rotation proceeded towards the south, and with a maximum delay of 9 m.y. attained the southern end of the blocks I and II, that means, the sections north of the Mendocino F.Z. and north of the Molokai F.Z. Thus, 9 m.y. after the beginning of these coinciding rift movements the whole East Pacific Rift, between 20° and 47° N., rotated in clockwise direction.

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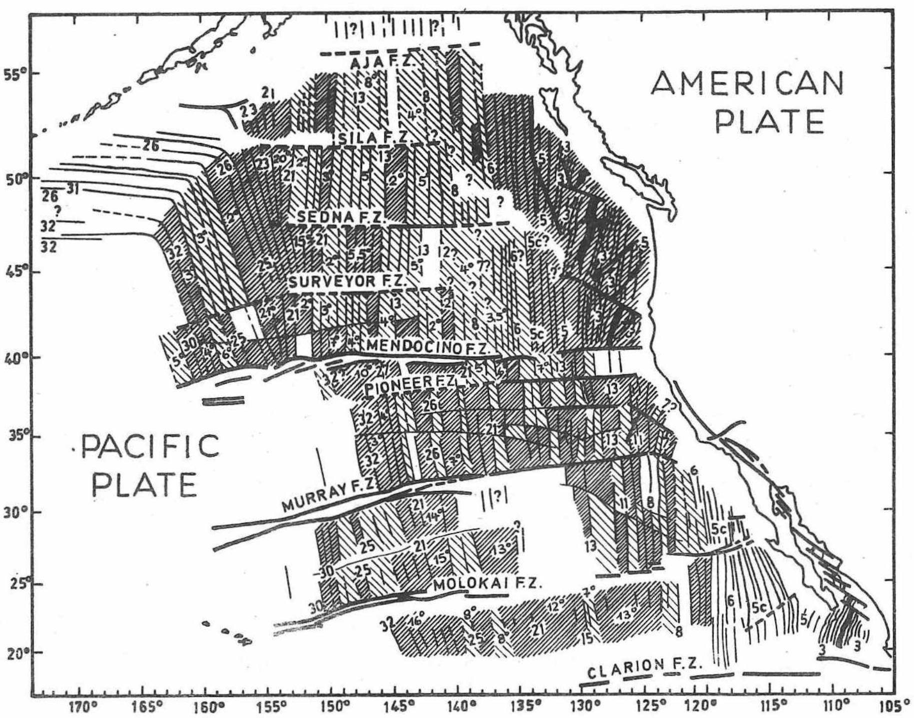

Fig. 2. Rotations of the East Pacific Rift. Anomalies after ATWATER & MENARD 1970. Clockwise and counterclockwise rotation: hatches inclined to the right and to the left. Additional faults or hinge lines, resp., between Surveyor and Molokai F.Z.s: fine lines. Numerals: numbers of anomalies; degrees: rotation rates of uniformly hatched areas. Black stripes off North America: East Pacific Rift

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The ceasing of these rift movements shows a delay from north to south, similar to that at the beginning, about 7 m.y. in group I (72 to 65 m.y.b.p.; anomalies 31 - 26), about more than 5 m.y. (70 to 65 m.y.b.p.; anomalies 29 - 26) in group II.

It should be noted that at the decay of the rotation the movement overlapped the next more southern group, which means that the rotation of groups I and II at the time of anomaly 26 only ceased south of the Mendocino F.Z. or south of the Molokai F.Z., respectively, instead of north of it.

From north to south, the time of rotation included in

group I: 8 m.y. (north of the Surveyor F.Z.),
10 m.y. (north of the Mendocino F.Z.),
12 m.y. (north of the Pioneer F.Z.);
group II: 12 m.y. (north of the Pioneer F.Z.),
10 m.y. (south of the Pioneer F.Z.),
8 m.y. (north of the Murray F.Z.),
4 m.y. (south of the Murray F.Z.),
3 m.y. (north of the Molokai F.Z.);
group III: 12 m.y. (south of the Molokai F.Z.).

In the area of the Mendocino and Pioneer F.Z.s (38° to 42° N.), and at the rift section south of the Molokai F.Z. (20° to 22° N.), the rotation of the rift was longest, i.e., about 12 m.y., with the following highest amounts of rotation: 10° in the area around 40° N., 18° in the area around 21° N., whereas at the other rift sections the maximum rotation was 5°.

The intensity of the first clockwise rotation was low, but with 1.5°/m.y. south and north of the Molokai F.Z. it attained values approaching such of the great clockwise rotation about 60 m.y.b.p. (Fig. 4). On an average, the rotations 60 to 50 m.y.b.p. south of today 40° N. (between Mendocino and Clarion F.Z.s) reached up to 1.1°/m.y., 80 m.y.b.p. the average rotation of the rift reached 0.88°/m.y., the lowest values being between 0.3° and 0.5°/m.y. (individual values cf. Fig. 3).

2.2. The counterclockwise rotation of the N.E. Pacific Rift from 71 to 63 m.y.b.p. (2nd period)

The end of the clockwise rotation was identical with the beginning of the immediately following counterclockwise one. Owing to the time delay of the beginning these rift rotations between 20° and 52° N. comprised altogether 8 m.y. (anomalies 30 to 25). The maximum period of rotation on a single rift section varied, however, between 4 and 1.5 m.y. only (71 to 63 m.y.b.p.). In spite of the short duration the rotation was remarkably intense. At the rift sections from north to south the average angles of rotation (individual values cf. Fig. 3, right) were: 3° - 6° - 7° - smaller than 2° - smaller than 2° - 9° - 12° - 8° (3° - 5.3°/m.y., with the exception of the rift section between the Murray and Pioneer F.Z.s, which exhibits special characteristics). Thus the rate of rotation 70 m.y.b.p. has been greater than 60 to 50 m.y.b.p., at the time of the great well-known clockwise rotation. The rift almost made a jump, or ra-

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ther, it jumped in its individual sections. However, the average rate of rotation of the individual rift sections exceeded, with 3.08°/m.y. 70 m.y. ago, the highest value of 3°/m.y. attained by the rift section north of the Mendocino F.Z. 50 m.y. ago (average rate of rotation of all individual parts at this time: 1.63°/m.y.).

The end of this rift movement shows the same time delay from north to south (about 4 m.y.). During this time, about 65 m.y. ago, the Pioneer F.Z. separated the East Pacific Rift between 20° and 50° N. into a northern and a southern half (Figs. 3 and 8), with a coherent rotation.

It is striking that the delay with which a rotation began always became shorter. The average value was at the

- beginning of clockwise rotation (80 m.y.b.p.) 9.m.y.,
- end of clockwise rotation/beginning of counterclockwise rotation (70 m.y.b.p.) 6.m.y.,
- end of counterclockwise rotation (about 65 m.y.b.p.) 4.m.y.,
- end of compensating rotations (about 60 m.y.b.p.) 2.5 m.y.,
- end of great clockwise rotation (about 50 m.y.b.p.) 2 m.y.

One out of many factors reducing the periods of time in which a new rift rotation started could be the increasing decoupling of the Pacific Plate from the Kula Plate. Owing to the N.E. movement of the triple point the Kula and Farallon Plates became more and more smaller and, consequently, their effects as a stabilizing element decreased. It may be that as a result of this process the Pacific Rift was more easily mobilized, which applied above all to the time following anomaly 24 (60 m.y.b.p.). The Kula Rift more and more came into the position of a subduction zone, and the Farallon Plate remained less and less clamped in the angle between the Kula-Farallon Rift and East Pacific Rift.

2.3. Rotations of the rift during a transitional stage about 65 to 60 m.y.b.p. (3rd period)

The movements of the rift between 65 and 60 m.y.b.p. differed essentially in their intensities, durations and directions of rotation. They must be attributed to a transitional stage preceding the beginning of the great clockwise rotation 60 to 50 m.y.b.p.

In Table 1 the rotations of this time are specified for the whole N.E. Pacific Rift from 20° to 45° N. and include a period from 3 to 7 m.y. The rotations, for example, are

(a) slow, persisting then somewhat longer, e.g., anomalies 27 - 24 north of the Surveyor F.Z., 7 m.y. with a rotation rate of 0.3°/m.y.,

(b) intense, but often of a short duration only, e.g., anomalies 26 - 25 north of the Molokai F.Z., 1.5 m.y. long with a rotation rate of 4°/m.y.

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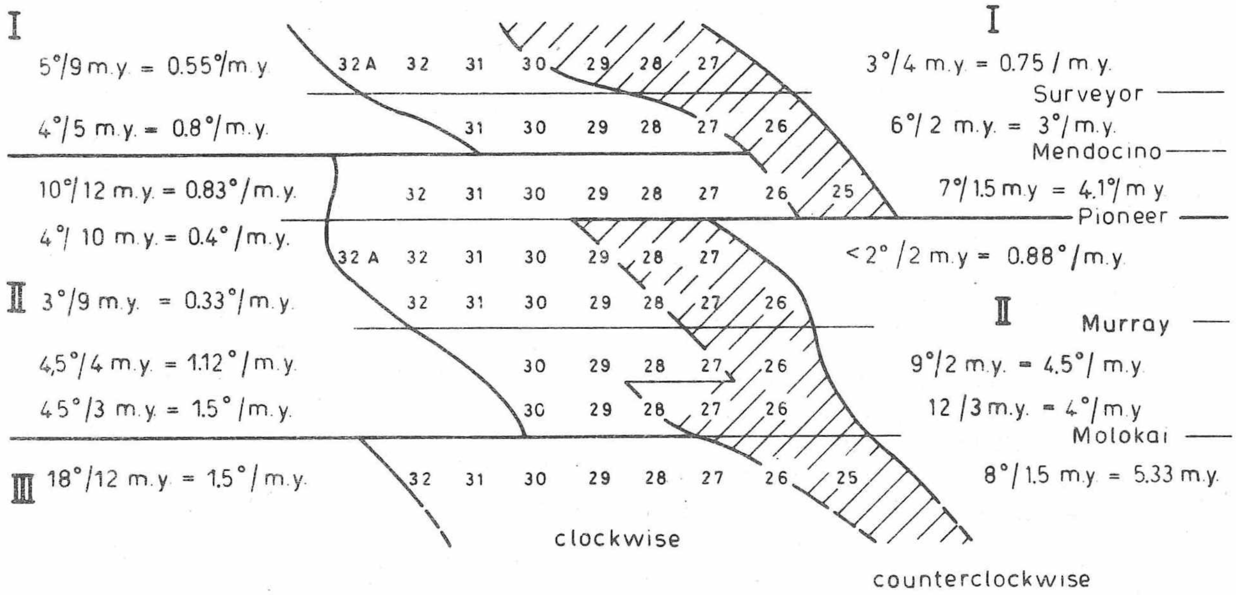

Fig. 3. Time scheme of rift rotations between 80 and 63 m.y.b.p. (1st and 2nd periods). Numerals: numbers of anomalies; left-hand side: clockwise rotation; right-hand side: counterclockwise rotation (hatched)

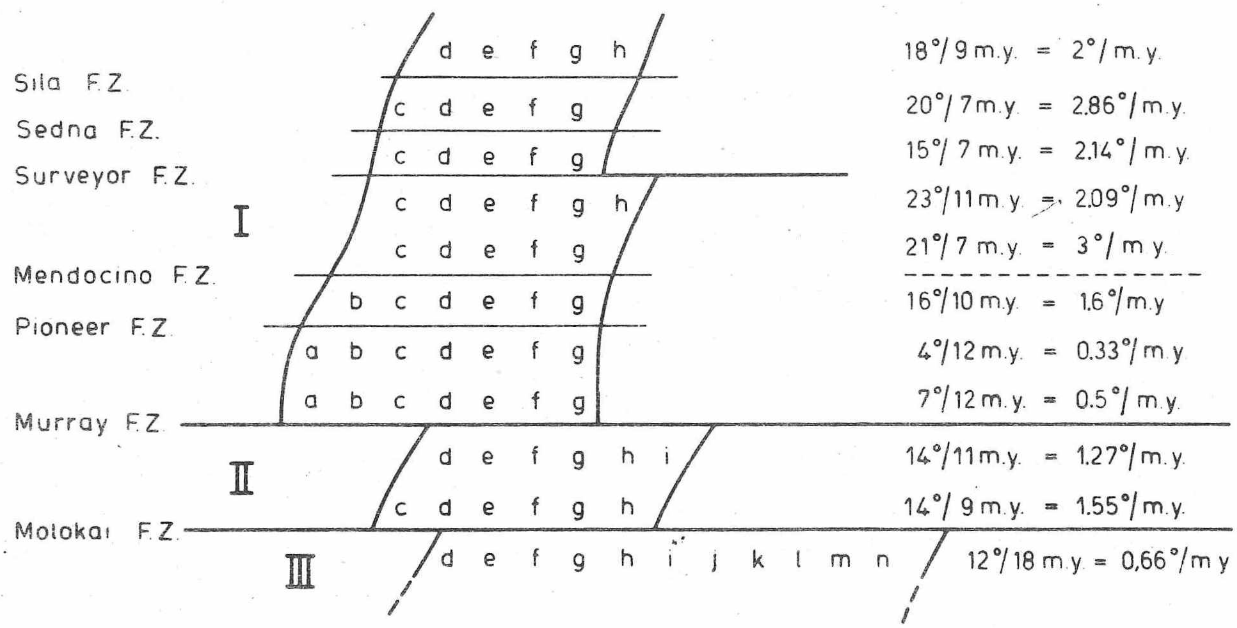

Fig. 4. Time scheme of the great clockwise rotation of the East Pacific Rift between 63 and 50 m.y.b.p. Letters: anomalies (a, b = 26, 25; g = 21; n = 15)

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Table 1. Transitional stage 65 - 60 m.y.b.p. (3rd period)

	Anomalies	Time [m.y.b.p.]	Type of rotation	Angle	Rotation within 1 m.y.	Duration [m.y.]	
Surveyor F.Z.	27-14	67-60	right	2°	$0,3^{\circ}$	7	
	26-25/25-24	64.5-63.5/63.5-60.5	right/-	1.5°/-	$0,5^{\circ}$/-	3/1.5	—
Mendocino F.Z.	25-24	63.5-60.5	right/left	$4^{\circ}/6^{\circ}$	2°?/6°?	3	
	25-24	63.5-60.5 the great clockwise rotation is beginning		5°	3.3°	1.5	
Pioneer F.Z.	27-15	67-50 only compensating rotations				17	
	28-11	68-34 only compensating rotations				24	—
Murray F.Z.	26-25/25-23	64.5-63.5/63.5-58.5	right/left	$2^{\circ}/6^{\circ}$	$1.33^{\circ}/1.2^{\circ}$	1.5/5	
Molokai F.Z.	26-25/25-24	64.5-63.5/63.5-60.5	right/left	$6^{\circ}/6^{\circ}$	$4^{\circ}/2^{\circ}$	1.5/3	
Clarion F.Z.	26-23	64.5-58.5 compensating rotation				6	

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In general, they were not only of a shorter duration but also changed their sense of rotation within a short time, so that they eliminated each other in part, or almost completely, for example, the rotation at 27° N. north of the Molokai F.Z., about 64 to 60 m.y.b.p. A clockwise rotation of 6° (anomalies 26 - 25) within 1.5 m.y., which means a rotation of 4°/m.y., was followed by a counterclockwise one of 6° (anomalies 25 - 24) within 3 m.y. (2°/m.y.).

For the rift parts altogether then the great clockwise rotation in the area of the Pioneer and Mendocino F.Z.s was already initiated (cf. Fig. 4). In our opinion, it may be recognized that this time interval of 65 to 60 m.y.b.p. was already a kind of precursory phase for the following great clockwise rotation, because

(1) north of the Surveyor F.Z., between 44° and 55° N., a slow but continuous clockwise rotation of the rift took already place during the time of the anomalies 27 to 24;

(2) south of the Mendocino F.Z., at 38° to 40° N., the great clockwise rotation already began with anomaly 25 (Fig. 2) 63.5 m.y.b.p. (3.3°/m.y.!);

(3) the central rift section in spite of the oscillating movements of the rift rotated at 32° to 38° N. between the Murray and Pioneer F.Z.s about 4° to the north (0.8°/m.y.), and this on account of the residual amounts of the oscillating movements.

From 80 to 40 m.y.b.p. this central rift section was affected by a continuous clockwise rotation superimposing all its pendulum movements (Fig. 8). As a result, 60 m.y. b.p., the position of the rift at 40° N. again appeared to be kinked more considerably at the Pioneer F.Z., the rift to the north shifted in a counterclockwise rotation. The same is valid for the rift sections south and north of the Molokai F.Z. at 25° N. During this superordinate clockwise rotation of the total rift the kink points were shifted in an eastern direction. The amount of rotation of the rift movements is represented in Fig. 8 and seems equally to be realized step by step on a large distance along the rift, as we suppose it for a single rift section (Fig. 14, series A and B).

2.4. The great clockwise rotation of the N.E. Pacific Rift 63 to 50 m.y.b.p. (4th period)

Together with the clockwise rotation 7 m.y.b.p., the second clockwise rotation of the rift 60 m.y.b.p. was the most intense of its movements. At first, between 63 and 60.5 m.y.b.p., the triple point of the Kula and North Pacific Rifts jumped when about more than 2.5m.y.) the Kula Rift shifted in a northern direction by about 150 km. At that time, the hypothetical Kula-Farallon Rift had so much approached a subduction zone, and had so much been reduced, that a greater degree of freedom of motion of the N.E. Pacific Rift might have been involved. This is the time (about 61 m.y.b.p.) when the great clockwise rotation began (anomalies 24 to 21 - 20).

Fig. 4 shows the time delay at the beginning of this rift rotation. The Mendocino F.Z. did not mark a difference in this rift rotation; 60 m.y.b.p. the Murray F.Z. has subdivided the movement at (today) 33° N. North of the Murray F.Z. the rift formed a coherent block (I) with a continuous movement, where the rotation began in the south

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and, in the course of time, proceeded in a northern direction (BANKWITZ & BANKWITZ 1972). The maximum time delay of the beginning rotation was 7 m.y. (from 65 to 58 m.y.b.p.). Then the rotation reached the rift section (II) between Murray and Molokai F.Z.s, beginning to rotate with anomaly 24 (61 m.y.b.p.) only 4 m.y. later than the great northern block (I), its northern partial section even at about 58 m.y. only, i.e., 7 m.y. later.

Therefore, the rift sections south of the Murray F.Z., between 20° and 33° N. (present-day position), reacted with a clearly visible delay towards the northern part of the plate between 33° and 56° N.

The duration of this rotation was different for the individual rift sections (7 to 12 m.y.). The angle of rotation was between 23° and 12°, and north of the 40th degree N. was greater than south of it (Fig. 8). This also applies to the intensity of movement, being north of 40° N. 2° - 3°/m.y., south of it 1.6° - 0.7°/m.y. (for individual values cf. Fig. 4). The average rate of rotation of this period was at 1.63°/m.y.

A special reaction is shown again by the section between the Murray and Pioneer F.Z.s, between 33° and 38° N. (present-day position), with the longest rotation period of 12 m.y., the smallest angles of rotation of 4° and 7°, and the smallest intensities of 0.5°/m.y. and 0.33°/m.y.

It is obvious that the end of the clockwise rotation again was retarded from south to north, just as during the slow counterclockwise rotation 53 to 47 m.y.b.p. (anomalies 21 to 19) immediately following along the total rift between 20° and 60° N. From 80 to 60 m.y.b.p. all rotations in the north of such a block began and proceeded towards the south. Since the East Pacific Rift has no longer been so intensely stabilized by the progressive subduction of the Kula-Farallon Rift, it seems that the movements adopted an opposite course from south to north.

During the great clockwise rotation 60 to 65 m.y.b.p. the southernmost section between 21° and 22° N. lost its rhythm and the rotation lasted here for 18 m.y. (58 to 40 m.y.b.p., anomalies 23 - 15; Fig. 4). Thus the synchronous rhythm of rotation of the rift was interrupted between 20° and 60° N. As a result, this rift section "missed" some events of the following 5th and 6th periods. This ceased in the successive counterclockwise and clockwise rotations (anomalies 15 - 14, 14 - 10), at today 23° N. and 130° to 123.5° W. between the Clarion and Molokai F.Z.s (Table 2), simultaneously corresponding, with some delay, to (1) the counterclockwise and clockwise rotations normally following (generally anomaly 20 to about 15) the great clockwise rotation, (2) on the other hand, already synchronously proceeding with the great counterclockwise rotation north of 40° N. from 42 to 38 m.y.b.p. (anomalies 16 - 13), as well as with the clockwise rotation south of 40° N. from 39 to 22 m.y. (anomalies 14 - 10, Table 2) and further (Fig. 5). In this way a synchronous behaviour of the rift sections was again attained.

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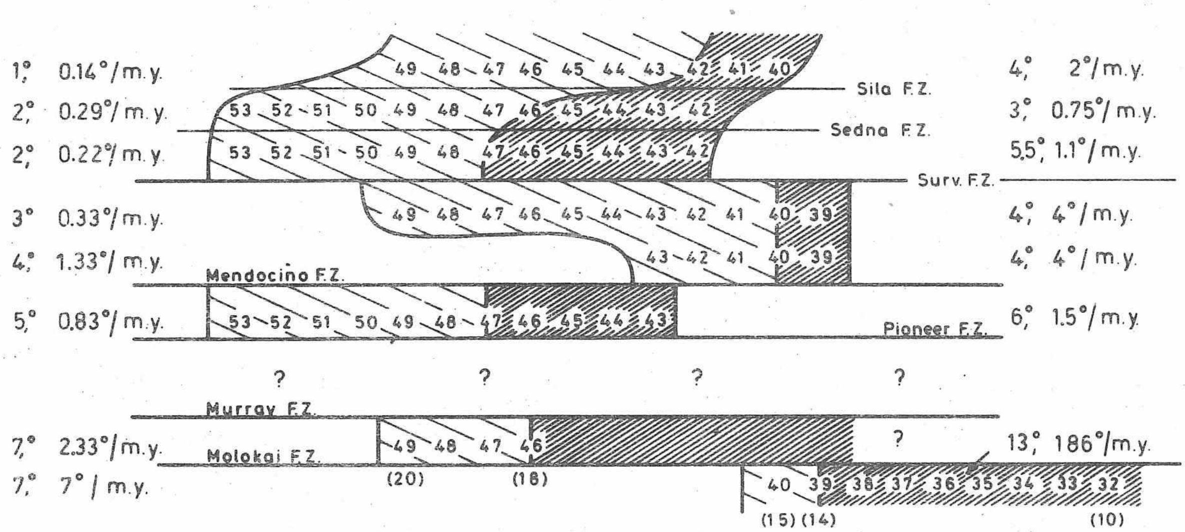

Fig. 5. Time scheme of compensating rift rotations between 53 and 39 m.y.b.p. (5th period). Hatches inclined to the right and to the left: clockwise or counterclockwise rotation, resp.

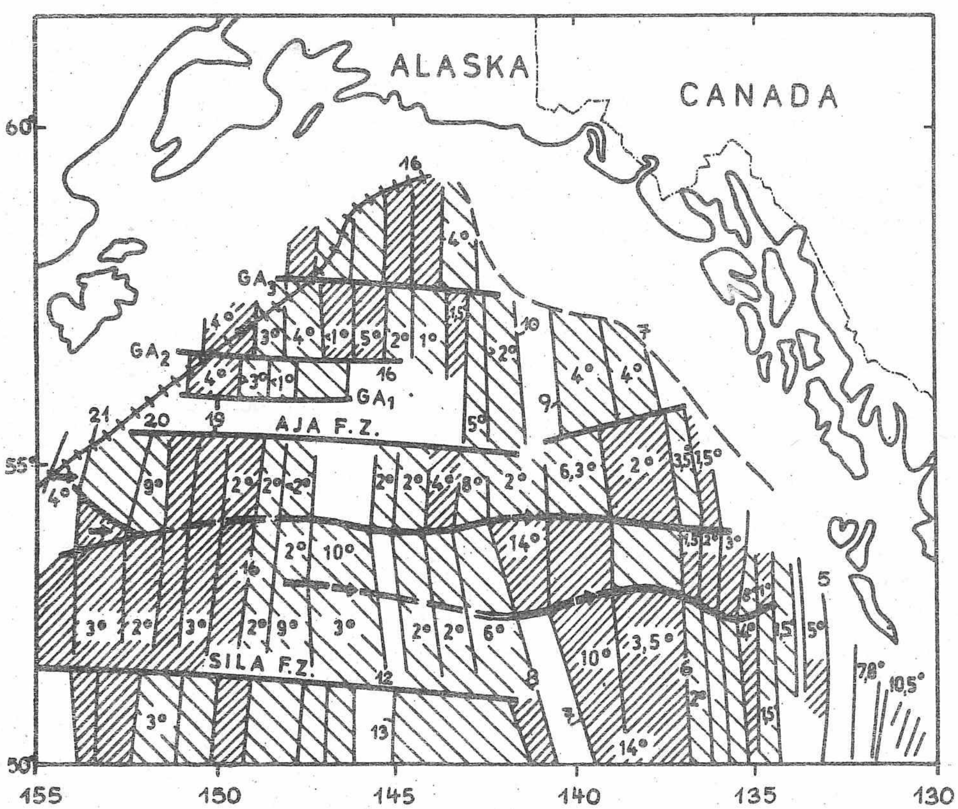

Fig. 6. Rotations of the East Pacific Rift in the Gulf of Alaska. Anomalies after NAUGLER & WAGEMAN (1973). Numerals: numbers of anomalies; degrees: rotation rates; two curved hinge lines between Aja and Sila F.Z.s after BANKWITZ. GA_{1-3}: faults

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Table 2. Superordinate rotations with a stabilizing function (5th period)

	Counter-clockwise	Rotation in 1 m.y.	Anomalies	Time [m.y.b.p.]	Duration [m.y.]	Clock-wise	Rotation in 1 m.y.	Anomalies	Time [m.y.b.p.]	Duration [m.y.]
North of Sila F.Z.	1°	0.33°	20–16	49–42	7	4°	2°	16–15	42–40	2
North of Sedna F.Z.	2°	0.31°	21–18	53–46	7	3°	1° 0.75°	18–17 18–16	46–43 46–42	3 4
North of Surveyor F.Z.	2°	0.33°	21–19	53–47	6	5.5°	1.1°	19–16	47–42	5
South of Surveyor F.Z.	3°	0.33°	20–15	49–40	9	4°	4°	15–14	40–39	1
North of Mendocino F.Z.	4°	1.25°	17–15	43–40	3	4°	4°	15–14	40–39	1
North of Pioneer F.Z.	5°	0.83°	21–19	53–47	6	6°	1.5°	19–17	47–43	3
South of Pioneer F.Z.										
North of Murray F.Z.										
South of Murray F.Z.										
North of Molokai F.Z.	7°	2.16°	20–18?	49–?46	3	13°		?18–?	?46–?	
South of Molokai F.Z.	[7°	7°	15–14	40–39	1]	[13°	1.88°	14–10	39–32	7]

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2.5. Rotations with a stabilizing function in a transitional stage from 50 to 40 m.y.b.p. (5th period)

The great clockwise rotation was followed by a kind of transitional stage in the period between approximately 50 and 40 m.y. before the rift entered the new period of a great counterclockwise rotation north of the 40th degree N. (Mendocino F.Z.) and of a new clockwise rotation later on south of it. The rotations of this transitional period proceeded in a synchronous way along the whole rift (apart from the central section between 33° and 38° N. already mentioned repeatedly). The durations, angles of rotation and intensities are listed in Table 2.

A slow, long-lasting counterclockwise rotation (with an average duration of about 6 m.y. and an average rate of rotation of 0.8°/m.y.) is replaced by a more intense, shorter clockwise rotation (with an average duration of 2.7 m.y. and an average intensity of 2°/m.y.). In both cases the angle of rotation increased from north to south (Table 2). The clockwise rotation began at a later date, about 43 m.y. ago, nearly eliminating the preceding counterclockwise one at about 50 m.y. ago. By the remaining residual angles the rift was again clockwise rotated by about 1° to 6° altogether.

In our opinion the function of these rift rotations between about 50 and 40 m.y. ago was a compensating one and stabilized the plate (slowing down, inter alia, the clockwise tendency). These rotations, although having an oscillating character effective for more than 10 m.y., belong to those being superordinate because they were related to the whole rift described here from 20° to 60° N. along several thousand km.

2.6. The great counterclockwise rotation 43 to 20 m.y.b.p. (6th period)

The great counterclockwise rotation only covered the northern part north of 38.5° and 40° N. (today), respectively, where it lasted for more than 20 m.y. (anomalies 17 to 6). At first, the southern part maintained an indifferent attitude during this time, with compensating movements at the individual rift parts for more than 3 m.y. from 43 to 40 m.y.b.p. (anomalies 17 to 15). Then a slow but uniform clockwise movement began.

The great counterclockwise rotation simultaneously started 43 m.y. ago at (today) 38.5° and 52.5° N., i.e., north of the Pioneer and north of the Sedna F.Z.s. From there the rotation proceeded in two groups (I and II) towards the north, where the last rift sections, south of the Sedna F.Z. and south of the coast of Alaska, were included in this rotation at 58.5° N. 3 m.y. later. In the area around 56° and 57° (Aja F.Z.; Fig. 6) identified anomalies are missing (NAUGLER & WAGEMAN 1973). Therefore, it cannot be decided whether the area north of the Aja F.Z. formed an independent unit of movement. Fig. 7 shows the anomalies with a counterclockwise rotation (small letters) and the clockwise rotation presented in inclined hatches. The counterclockwise rotation overlapped the Mendocino F.Z. southward as far as the Pioneer F.Z.

A northern and a southern half of the rift can be recognized: from 43 to 38 m.y.b.p. at (today) 38.5° N. divided by the Pioneer F.Z., and from 38 to 0 m.y. at (today) 40° N. divided by the Mendocino F.Z. (Fig. 7).

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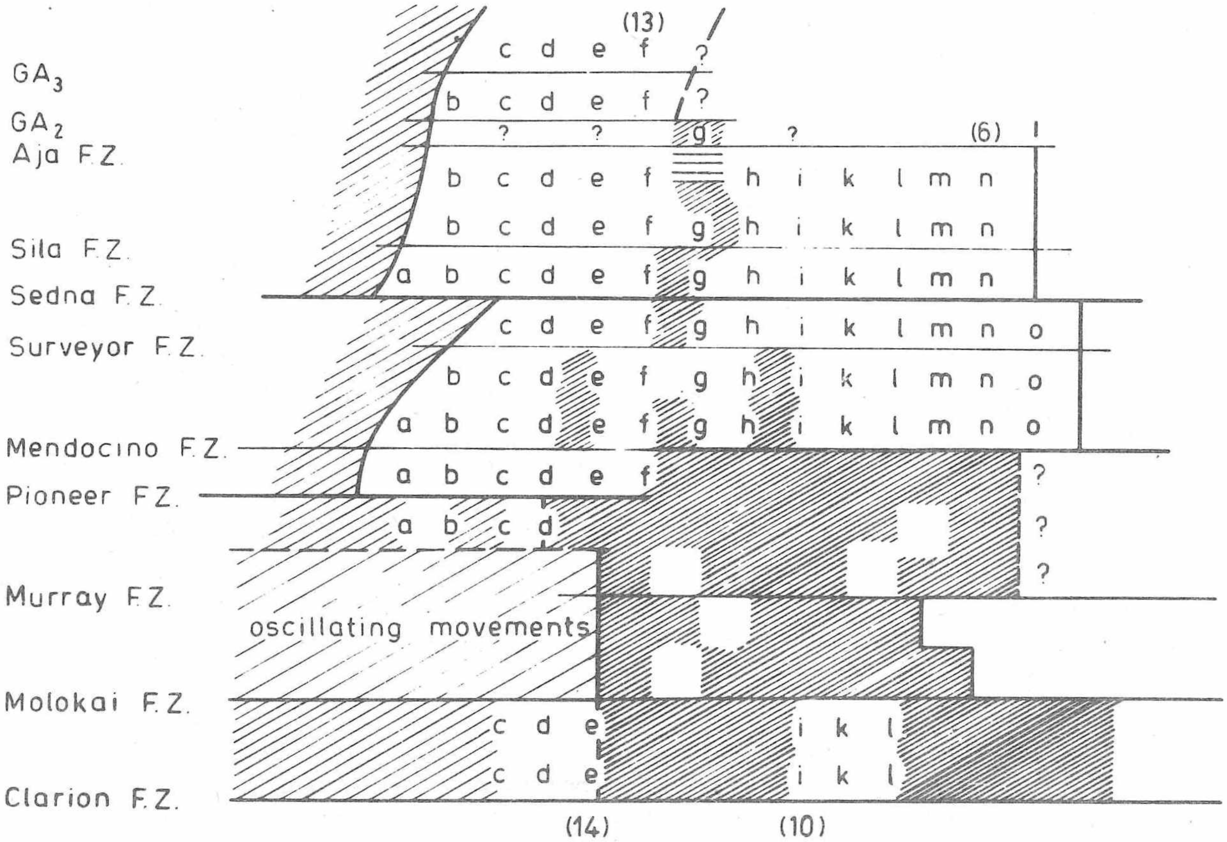

Fig. 7. Time scheme of the great counterclockwise rotation of the East Pacific Rift between 43 and 20 m.y.b.p. (6th period). Letters: anomalies; numerals in brackets: numbers of anomalies; hatched: periods of clockwise rotation of rift sections

Thus there is again a hint on the special character of the double structure of the Pioneer and Mendocino F.Z.s, both of which share the function of an internal plate boundary, a function which definitely was accepted by the Mendocino F.Z. from 38 m.y. b.p. As a result, the two rift parts were widely decoupled and almost independently reacted one upon another. This decoupling process began at 40 m.y. (anomaly 15) at the latest, and was terminated at 38 m.y. (anomaly 13). From 40 m.y. onwards the two parts were subjected to a reorientation, however, with an opposite sign.

The great counterclockwise rotation north of 38.5° and 40° N., respectively, was interrupted by a stop of 3 m.y. only (at 38 to 35 m.y. as a rule), and was divided into two stages (anomalies 13 to 12), obviously as an effect of the clockwise rotation beginning at that time south of 40° N. The beginning of the clockwise rotation south of 38° N. (with 2°/m.y. almost an abrupt one) is marked by another short stop within the counterclockwise rotation 40 to 39 m.y.b.p. (anomalies 15 to 14).

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Table 3 shows the angles of the rift rotation and their velocities as approximate values. Although the rotation proceeded from south to north, the angles of rotation in the north (51.5° to 54° N.) being 14° - 10° - 24° are three times those in the south (40° to 44° N.), 4° - 3° - 7°. The increase towards the north was a continuous one.

It should be noted that, in spite of a much shorter duration of rotation of only 5 m.y., the section between the Pioneer and Mendocino F.Z.s also rotated by 7°, just as the more northern sections in an interval of 21 and 22 m.y. It seems that a rotation by 7° was the minimum amount during the great counterclockwise rotation. The rotation of the 1st stage from 43 to 38 m.y. was considerably more intense (1° to 2.5°/m.y.) than that from 38 to 21 m.y. (0.3°to 0.4°/m.y.). The stage 43 to 38 m.y. coincided with a counterclockwise rotation at the Reykjanes Ridge. There, the rotation proceeded from north to south, at the N.E. Pacific Rift it proceeded from south to north.

The clockwise rotation from 40 to 32 and 27 m.y., respectively, south (today) 40° N. has different durations, namely,

between 40 and 30° N. up to anomaly 9: 30 m.y.b.p.,
between 30 and 27° N. up to anomaly 7: 27 m.y.b.p.,
between 27 and 22° N. up to anomaly 10: 32 m.y.b.p.
and up to anomaly 6: about 23 m.y.b.p., respectively.

32 m.y. ago the Farallon Plate broke into two parts (ATWATER 1970). At the same time the rift south of the Pioneer F.Z. abruptly rotated to N.E. by 30° and 15°, respectively, within 2 m.y., which hints at a complete separation of the Farallon Plate and the Northeast Pacific Rift, respectively.

The amounts of the clockwise rotation (Table 3) along the southern half of the rift are low, lying between 2° and 5°, with average velocities from 0.2° to 0.4°/m.y., except for the sections at 38° and 23° N. with rotations of 16° and 13°, respectively, and rotation rates of 2°/m.y. and 1.71°/m.y. In the superordinate rotations we do not include that of the anomalies 10 to 9 by 30° north of Murray F.Z.

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Table 3. The great counterclockwise rotation 43 - 20 m.y.b.p. (6th period)

	Anomalies	1st stage	Counter-rotation	2nd stage	Angle of rotation: 1st stage	Angle of rotation: c. rot.	Angle of rotation: 2nd stage	Angle of rotation: sum	Rotation in 1 m.y.: 1st stage	Rotation in 1 m.y.: 2nd stage	Duration [m.y.]	Time [m.y.b.p.]
	15-13?		-								?2	40-38?
	16-10?	16-13?	13-12	12-10?							?10	42-32?
	?- 7	?	-	12- 7							?6	?33-27
Aja F.Z.												
	16-6'	16-13	13-12	12- 6	3°	-	12°	15°			22	42-ca.20
	16- 8	16-12	12-11	11- 8	14° 8°		10° 4°	24°(1) 12°(2)	2°	2°	13	42-29
Sila F.Z.												
	17 -6	17-13	13-12	12- 6	5°	2°	5°	10°	1°	0.36°	22	43-21
Sedna F.Z.												
	15- 6	15-13	13-12	12- 6	5°		4°	9°	2.5°	0.29°	19	40-21
Surveyor F.Z.												
	?16-6	?16	-	6				~7°	~ 0.58°		21	?42-21
	?17-6	17?-13	13-12	12- 6	4°	2°	3°	7°	1.5°	0.44°	22	43-21
Mendocino F.Z.												
	17-13	17-13	13 - 11					7° / 4°	1.4°	0.66°	5 / 4.5	43-38 / 38-33.5
Pioneer F.Z.												
	15-10	15	-	10				16°	2°		8	40-32
	14-10	14-13	13-12	12-10				3°	0.37°		8	39-32
Murray F.Z.												
	14-9	14-12	12-11	11- 9				< 2°	0.2°		8	39-30
	doupled rift											
	14- 7	14-13	13-12	12- 7				5°	0.42°		12	39-27
Molokai F.Z.												
	14-10	14	—	10				13°	1.71°		7	39-32
Clarion F.Z.												

(1) after NAUGLER & WAGEMAN (1973);

(2) after ATWATER (1970)

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3. Total rotation of the East Pacific Rift between Clarion and Aja Fracture Zones

Rifts are able to perform various movements at the same time (cf. Section 5.1.). VAN ANDEL (1974) assumes that the East Pacific Plate rapidly shifted its boundary towards east from 50 m.y.b.p. to about 25 m.y., with the rift shifting from 115° to 105° W. LARSON & CHASE (1972) presume a shift of the East Pacific Rift towards the east from 150 m.y.b.p. till today (Fig. 11). According to ATWATER (1970), an additional northward movement of the rift took place from 80 to 20 m.y.b.p. These movements were connected with rotations, as can be concluded from geometrical features of the anomalies between 20° and 60° N. Fault displacements (Fig. 8) were eliminated as being able to stress the importance of rotation for the movement of the total rift. Thus the general direction of the rift and its change due to rotations can better be reviewed.

3.1. Sum of rotations of the rift

Three superordinate tendencies can be distinguished in the total behaviour of the rift:

(1) the period from 80 to 40 m.y.b.p.: stage of a clockwise rotation of 24° to 11°,
(2) period from 40 to 20 m.y.b.p.: stage of a counterclockwise rotation of 8° to 2.5°, and
(3) period from 20 to 0 m.y.b.p.: stage of a clockwise rotation of 28° to 24°.

From 80 to 40 m.y.b.p., the rift in its whole length rotated at nearly the same time, in spite of its displacements at the fracture zones. From 40 to 20 m.y.b.p. the northern and southern halves of the rift reacted in an opposite rotation sense. The reason is obviously not to be found in the rift displacement at the Mendocino F.Z., as it is demonstrated by the readjustment of the rift to a shift of the Pole of rotation with a general clockwise rotation of the rift from 10 m.y.b.p. up to now, which again covered the rift still existing: in the north the Juan de Fuca Rift, in the south the Rivera Rift. - It may be supposed that the cause of reorientation of the rift during the 2nd stage of rotation was more subordinate in nature than that of the 1st stage.

During the 1st stage, from 80 to 40 m.y.b.p., a clockwise rotation of 24° superimposed the different movements of the whole rift during five periods of rotation (Chapter 2). It is obviously a readjustment to a shift of the pole of rotation permanently going on, slowly for 20 m.y., jumping from 60 to 50 m.y.b.p. with a rotation by 19°, gradually finishing 50 to 40 m.y.b.p. (Fig. 8). For the time of the great clockwise rotation (anomalies 24 to 20) this means a shift of the rift by 4.5 cm/y., in addition to the spreading rate of 3 to 4 cm/y. 1,500 km north of the Mendocino F.Z. The Mendocino-Pioneer double structure behaved like a separating line that divided the rift into two parts reacting differently, with the southern half taking part in the rotation from 80 to 40 m.y.b.p., however, by about 11° only.

Apart from the displacements the rift, 80 m.y.b.p. (anomaly 32), was kinked two times, towards the east in the area of the Mendocino F.Z., towards the west in the area of the Molokai F.Z. The intense clockwise rotation of 18° south of the Molokai F.Z. with the rate of 1.5°/m.y. (anomalies 32 to 26) caused a straightening of the

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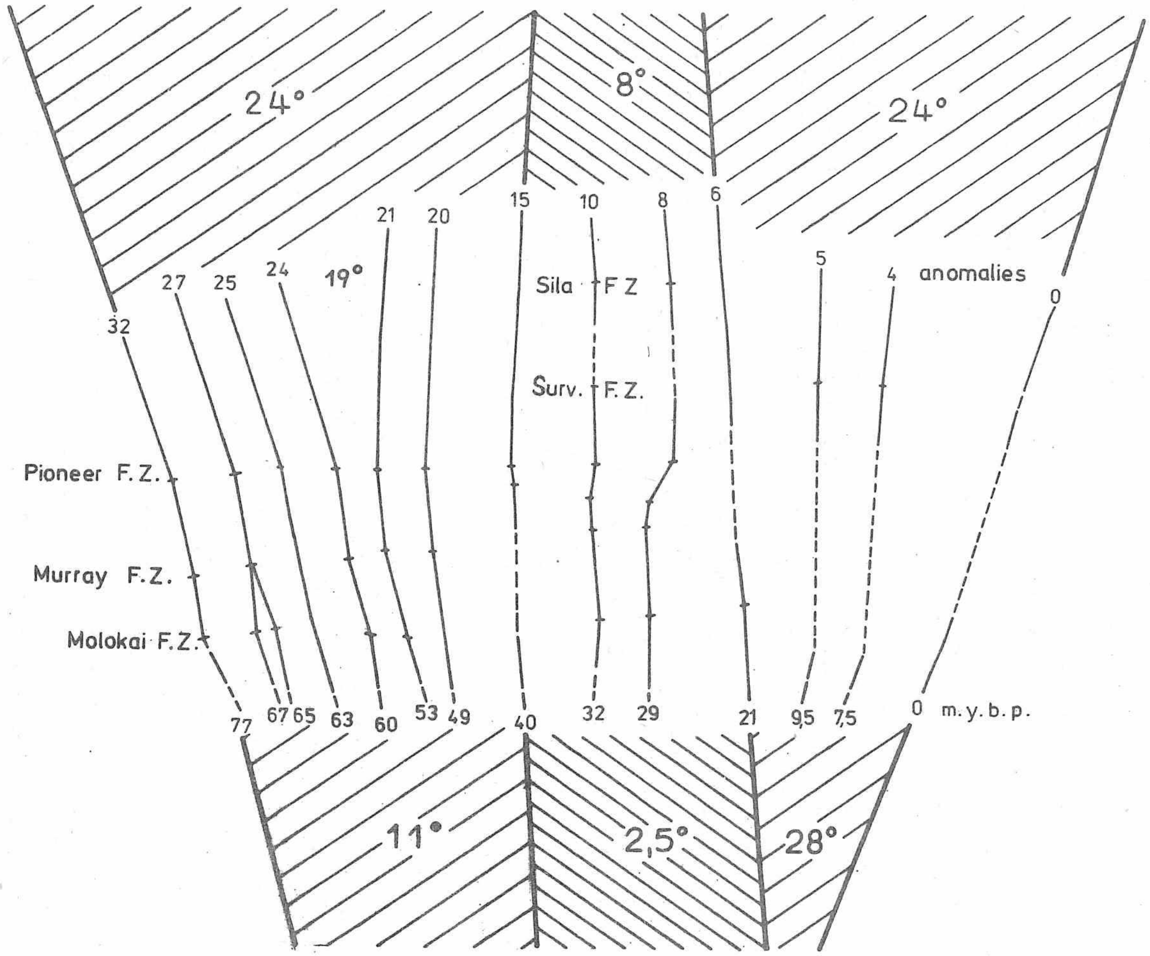

Fig. 8. Configuration of rift sections in the N.E. Pacific according to Fig. 1 of ATWATER 1970. Displacements are eliminated. Distances between rift positions are not taken into account; three main rotations of the whole rift occurred: clockwise rotation between 77 and 40 m.y.b.p. (anomalies 32 – 15), counter-clockwise rotation between 40 and 21 m.y. (anomalies 15 – 6), clockwise rotation between 21 m.y. and today – with different rotation rates north and south of the Pioneer F.Z.

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rift for 15 m.y., just as the intense counterclockwise rotation of 12° to 8° with a rate of 4° to 5°/m.y. (anomalies 26 - 25; Figs. 3 and 8). The rift, 63 m.y. ago, was the best straightened; this character was only attained again at 21 m.y.b.p. (anomaly 6), that is, 42 m.y. later.

For the whole time the rift altogether newly orientated itself to maintain a position adjusted in the best way possible towards the pole of rotation, obviously shifting continuously step by step. It is the question, however, (a) of the rate of delay in which this action took place, (b) of whether the three counterclockwise and four clockwise rotations directly reflect variations of the pole position, 80 to 42 m.y. b.p., or (c) if they must be attributed to other global processes, or (d) of whether the clockwise rotation resulting definitively by 24° and 11°, respectively, only represented a readjustment to the changing position of the pole. In this case intercalated counterclockwise rotations would only represent pendulum movements of the rift having a stabilizing effect, or secondary movements at hinges of the rift. This relationship seems to be probable.

The manner in which a rotation of the whole rift is realized speaks in favour of this opinion. First of all, the rift moved just as along hinges, that is to say, at definite fault places the rift rotated reversely at the southern and northern flanks, relatively, in the way as along a hinge, e.g., during the times of anomalies 27 - 24 (67 - 60 m.y.b.p.) at the Mendocino F.Z. and 67 - 65 m.y.b.p. at the Molokai F.Z.: north of them moving in counterclockwise direction and south of them in an opposite direction (1st phase). At these hinges the rift synchronously shifts eastward, which is all the more conspicuous as at these points the rift is separated by considerable displacements. In this way the counterclockwise rotation of the northern limbs pretends to be a secondary or compensating rotation. In the 2nd phase only all sections of the rift were covered by a continuous clockwise rotation.

General rotations of the whole rift (cf. Fig. 8):

1st phase anomalies	Time [m.y.b.p.]	Duration [m.y.]	2nd phase anomalies	Time [m.y.b.p.]	Duration [m.y.]	Resultant
32-24	80-60	20	24-15	60-40	20	clockwise rotation
15-10	40-32	8	10- 6	32-21	11	counterclockwise rotation
6 - 5	21-10	11	5- 0	10- 0	10	clockwise rotation

During the 2nd stage with superordinate counterclockwise rotation of the whole rift, 40 to 20 m.y.b.p., the northern part rotated by 8° altogether, the southern part by 2° only. Owing to the consequent clockwise rotation from 38 to 32 m.y.b.p. (anomalies 14 - 10) south of the Mendocino F.Z. and the continuous counterclockwise rotation north of it, the rift again moved along the Mendocino-Pioneer structure like on a hinge (Fig. 8). As a result of the hinge movement the rift previously kinked westward became kinked eastward, almost completely straightening itself at the time of anomaly 6 (21 m.y.b.p.) when all parts occupied a uniform position towards the spreading pole.

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The 3rd stage began 21 m.y. ago. It may be accepted that at that time, on account of the divisioning of the Farallon Plate, the rotation of the Rivera Rift in the south, 14° and 18°, at anomalies 5 and 4 was twice as much as in the north (6° and 12°). Only recently the rotation of the Juan de Fuca and Gorda Rifts (24°) has almost reached that of the southern Rivera Rift (28°), which means that in the last 4 m.y. the northern rift rotated by 3°/m.y., whereas in the south it seems that the fast rotation already finished 4 m.y. ago. The high amounts of rotation are obviously due in part to the collision between the Pacific and American Plates.

3.2. Special position of the plate section between 33° and 37° N.

An activity somewhat differing from the other part of the rift is shown by the section between the Murray and Pioneer F.Z.s between 33° and 38° N., where the anomalies are arranged in a more regular and parallel manner. A remarkable rotation is missing, the section being covered by the first clockwise rotation only of 80 to 70 m.y.b.p., with short rotations having an oscillating character, which we consider to be compensating movements of the rift, carried out for 30 m.y. The rotations are slow (e.g., 0.75°/m.y. for the time of the counterclockwise rotation of 69 to 65 m.y.b.p.), or rather of a short duration. As a rule, they were partly compensated in an opposite direction immediately afterwards.

In spite of these pendulum movements residual amounts are summed up to a clockwise rotation conforming the dominant tendency of this rift section. Thus it rotated by 15° from 77 to 32 m.y.b.p. altogether (anomalies 32 to 10; Fig. 8) still during the time of the general counterclockwise rotation of the whole rift from 40 to 20 m.y.b.p. Consequently, this rift section lived a "life of its own" for 70 m.y. (anomaly 29), but fitted into the tendency of the whole rift and was, to a certain extent, the stabilized centre of the rift solely reflecting the real rates of rotation of the whole rift. The short-time counterclockwise rotations inserted in this clockwise rotation may be regarded as movements stabilizing this plate section.

About 42 m.y. ago, the adjacent more southern section between the Murray and Molokai F.Z.s presumably took upon itself the function of compensation by means of pendulum movements. During the following time a second rift was formed parallel with it, which later became extinct again. This is a peculiarity of the rift under discussion.

3.3. The significance of the Mendocino-Pioneer double structure

By the large faults known from the N.E. Pacific the rift is divided into parts displaced along these faults, i.e., by which they are morphologically separated from one another. Regardless of this separation several sections often reacted simultaneously and coincidingly, unlike another group of rift sections. Figs. 3 to 5 and 7 show the faults having an additional function to separate such groups which exert a uniform movement.

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Special importance must be attributed to the Mendocino F.Z., which separated the rift into two differently active parts, a role which it shared with the Pioneer F.Z. running parallel with it at a distance of 150 to 200 km. Both faults reacted like a double structure belonging to one another, whose external margins are formed by the Mendocino F.Z. and Pioneer F.Z., between them, however, a short section of the rift has always formed a new ocean floor. A similar result was obtained by VOGT & AVERY (1974) for the Gibbs F.Z. in the Atlantic. A third double structure with spreading in the central stripe is the Eltanin F.Z. (HEIRTZLER 1968). We should like to include in this type the Mendocino-Pioneer zone, whose character is emphasized by Fig. 8.

The rift sections north of this zone behaved by far more synchronous and in the kind of movement they were much more in conformity than south of it. In its movements 80 to 50 m.y.b.p. the small rift section between the Mendocino and Pioneer F.Z.s was connected more to the north, later on more to the south, but changed and, in part, performed deviating movements. This stripe at least formed a transitional area between the northern and southern parts of the Pacific Rift.

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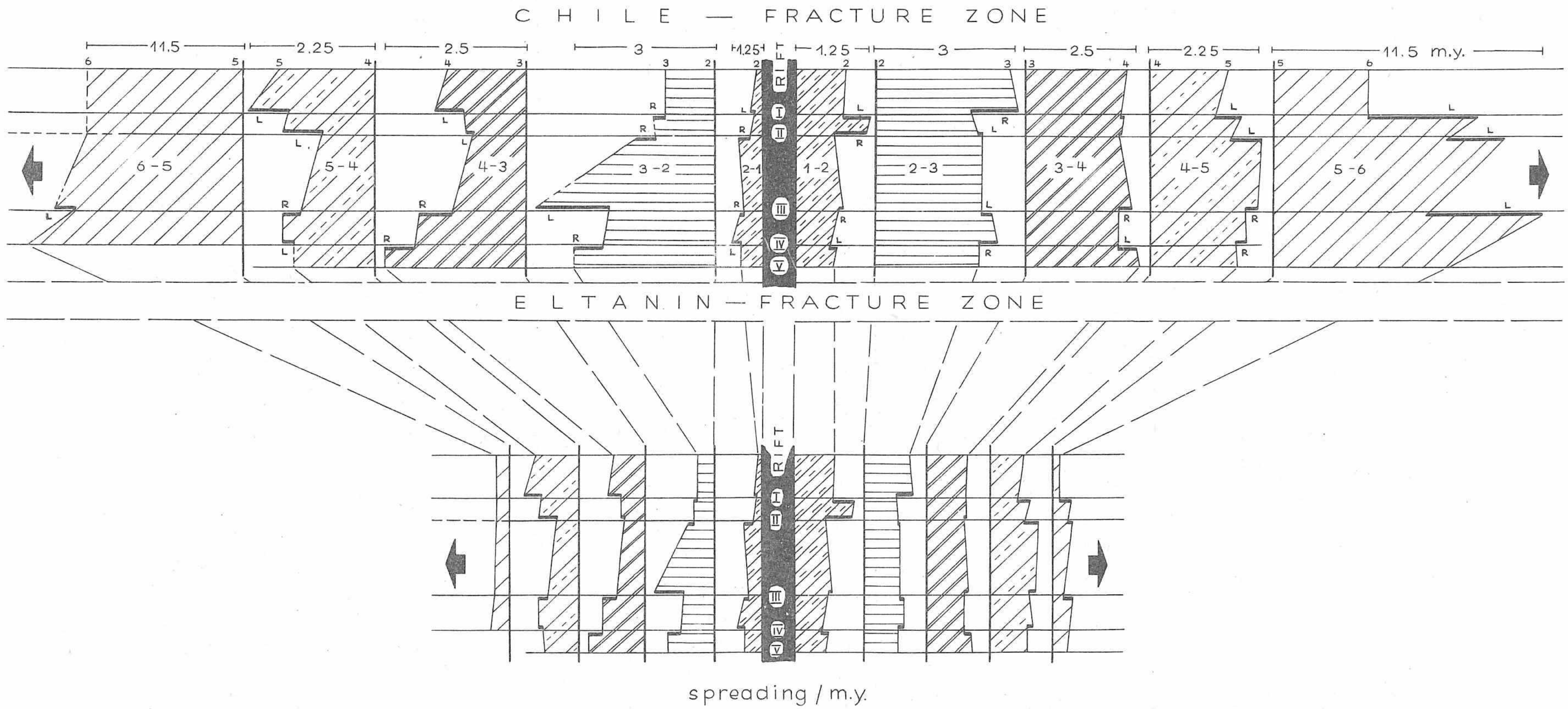

Fig. 9. South Pacific Antarctic Rift between Chile and Eltanin F.Z.s (30° - 65° S.). A: Width of the anomalies 1 - 6: columns (the length of the rift ist reduced 1 : 10). B: width of anomalies/1 m.y. Source: HERRON 1971

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4. Rotations of the Pacific-Antarctic Rift between 30° and 65° S.

4.1. Complex movements of the rift

According to HERRON (1971), the part of the Pacific-Antarctic Rift between the Chile F.Z. and Eltanin F.Z. shows almost all characteristics of a rift activity as mentioned in Chapter 5: rift drift, rift rotation, obliquity of anomalies without rotation, etc. The different rates of spreading (rift axis shortened, displacements eliminated) are demonstrated in Fig. 9. The thin centre line of the blocks in Fig. 10, series A and B, corresponds to anomaly limitations towards the rift in Fig. 9.

Fig. 9 indicates the variations of the fault activity for the individual faults at any time having another value and, for the most part, another direction of shift (R: rotating clockwise, L: rotating counterclockwise). The fault activity at the fault sections is mainly outside the transform sections. The lower row of Fig. 9 shows the spreading rate, a small general west drift of the rift indicating itself by higher spreading rates on the east side.

In Fig. 10 (rows A and B), for example, the presumable position of the rift at the beginning of the time between anomalies 5 and 6 is recorded as a thick line. Thin arrows indicate the direction in which the rift obviously rotated during this time, till it reached a position presumably occupied 9.5 m.y.b.p. Thick arrows suggest the lateral shift to be simultaneously supposed for the rift, whose position, from 9.5 m.y.b.p., was to be within the formed stripe, in the range of the thin central axis, because it marks the limitation of synchronous stripes east and west of the rift.

The northernmost section (Fig. 10) presumably drifted eastward from 20 to 7 m.y. b.p., taking a reverse direction 7 m.y. ago. At first, it slowly drifted westward, then, 5 m.y. ago, faster, a tendency slowing down since 2 m.y. It seems that this section, directly south of the Chile F.Z., was most intensely shifted laterally.

The central stripe between the faults II and III obviously drifted westward since 9.5 m.y.b.p.; thus, this movement began 3 m.y. before the east drift of the northern part has ended and also turned into a west drift. With respect to drift and rotation, the parts north of the Eltanin F.Z. behaved most quiet. Between 5 and 2 m.y.b.p. the rotation of the central part of the rift and the west shift of its northern part point at a general counterclockwise rotation of the rift for 3 m.y. In the last 2 m.y.b.p. a general west drift definitely covered the whole rift. These lateral shifts of the rift were partly accompanied by rotations of the sections.

The row C in Fig. 10 schematically indicates differences in the activity of the individual rift sections (intrusions intensified above the average: basis of wedges; average production: apex of wedges). Here, too, areas with an intensified intrusive activity mostly lie at the end of a rift part, i.e., near fracture zones, e.g., at the southern end of the central section between faults II and III for 7.5 m.y. (9.5 to 2 m.y.b.p., anomalies 5 to 2).

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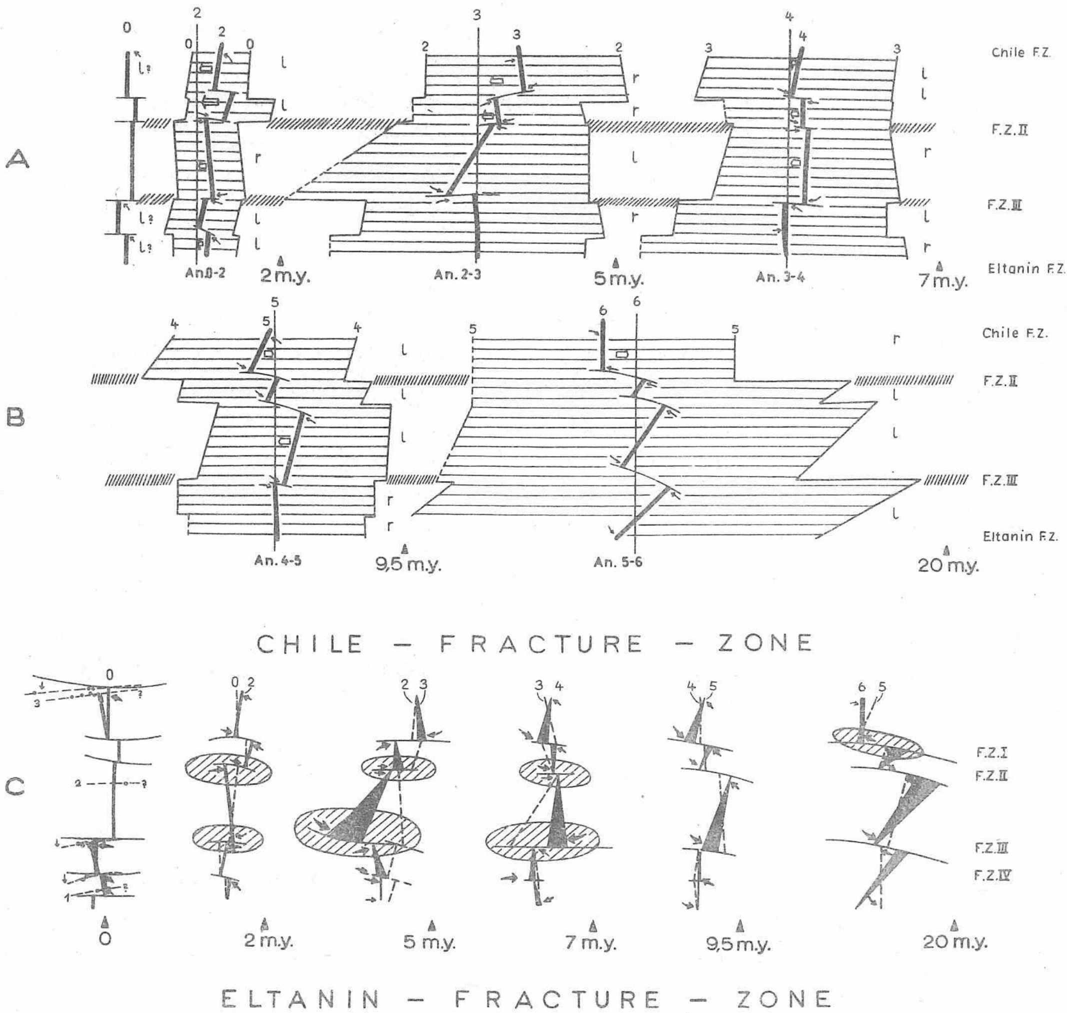

Fig. 10. Location and anomalies as in Fig.9. A and B — faults with the function of hinge lines: obliquely hatched; thick vertical lines: direction of the rift at the initiation of the creation of anomalies; fine vertical lines: direction of the same rift at the final stage of creation of anomalies; small arrows: rotation sense; r, l: clockwise or counterclockwise rotation, resp.; thick arrows: lateral rift shifting. C — base of wedges: intensified intrusion activity along the rift; top of wedges: average rift activity; dashed lines: reorientated rift position; arrows: rift rotation; hatched areas: faults with temporary hinge line function. Column 0 m.y. — points: earthquakes (GIERLOFF-EMDEN 1970); dashed rift: presumed recent rift rotation; dashed fracture zones: presumed positions in the future; points 1 - 3: presumed additional faults, eventually initial stages. Numerals above all colums: numbers of anomalies.

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A counterclockwise rotation of the rift with a simultaneous westward shift for 15 m.y. still continued in the central section for 3 m.y., up to 2 m.y.b.p.; it covered, however, the northern section south of the Chile F.Z. 9.5 m.y. later. Moreover, at that time this section still moved eastward, and showed, therefore, a certain independence. Afterwards, the rift parts were covered by a clockwise rotation 5 to 2 m.y.b.p., except for the central section, which again passed to a counterclockwise rotation already 2 m.y. earlier (7 m.y. ago, anomaly 3). Thus this rift section shows a special behaviour, rotating since 7 m.y.b.p. in a direction opposite to that of the N.E. Pacific Rift. This was left unchanged also during the last 2 m.y. The whole rift between 30^{o} and 65^{o} S. was covered by a new counterclockwise rotation, whereas the central section rotated in a clockwise direction, which means that since 7 m.y. the whole rift has moved at the faults II and III just as on hinges, as is shown by Fig.8 for the N.E. Pacific Rift at the Mendocino-Pioneer zone, or at the Molokai F.Z., performing pendulum movements that might be designated as a roll of the position of the rift. By this roll the rift is obviously stabilized.

In general, the Pacific-Antarctic Rift has thus been subjected to a counterclockwise rotation for 20 m.y., with the exception of the 3 m.y. from 5 to 2 m.y.b.p., and is in contrast to the clockwise rotation of the rift in the N.E. Pacific 21 m.y.b.p. till today.

4.2. Recent tendencies

We suppose that, at recent times, this counterclockwise rotation is still active, and will continue also in the future, as may be concluded from a distribution of recent earthquakes occurring at this rift, almost all of which lie west of the rift sections and in a particular abundance south of the fracture zones. This may point at a future shift of the fracture zones in a southern direction (striking S.S.W.), which has already begun. In three cases additional fracture zones may exist, or may be formed (points 1 to 3; Fig. 10, row C). At the same time, it may be supposed that five earthquakes west of the rift will effectuate another shift of its parts by rotation. Such considerations may result in the prediction of a general tendency of the occurrence of earthquakes at the rifts and fracture zones respectively, on the prerequisite, however, that epicentres are exactly determined.

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5. Magmatic activity of the rift

A great deal of ocean tectonics must directly be attributed to the magmatic activity of the rift. The width and shape of anomalies as well as the activity of faults, inter alia, vary as dependent on the spreading rate. This, conversely, permits to draw conclusions on the activity of the rift in geological time.

From detailed studies of the individual anomalies in the N.E. Pacific north of 38° N. and at the Pacific-Antarctic Rift between the Chile and Eltanin F.Z.s it results that the widths of anomalies with different ages vary just as the widths of those originated synchronously at different places. Such variations, already at a distance exceeding 10 km, can also be recognized at the Reykjanes Ridge (58° to 62° N., 24° to 33° W.; Fig. 16), in the area around the Juan de Fuca Rift and south of the Aleutian Trench between 170° and 180° W.

5.1. Characteristics of rift activity

(1) The magmatic activity pulsates (a) at the same time at different places of the rift, or of a rift section, which means that more than an average quantity of magma intrudes there; (b) in consecutive intervals at one and the same place of the rift, times of a particularly intense intrusion activity are alternating with those of particularly weak ones.

(2) Pulsating manifests itself in macrorhythms and microrhythms with an average duration of ca. 1.5, 6 and 12 m.y. (BANKWITZ & BANKWITZ 1972, Fig. 5). In the course of time centres of magmatic activity having a superordinate significance will shift; at the N.E. Pacific Rift, for example, they did so from north to south 80 to 60 m.y.b.p., from south to north 60 to 20 m.y.b.p. (Section 2.4.).

(3) Areas showing an intense intrusive activity often occur at the end of a rift section, (i.e., bordering a fracture zone), where the synchronous anomalies do not run parallel to one another (rather have a trapezoidal form), originated without a rotation of the rift (Fig. 12A). At the S.E. Pacific Rift, 7 to 5 m.y. ago, such a centre was situated north of 50° S. (recent position). In Figs. 9 and 10, row A, the central part of the anomalies 3 to 4 has the shape of a trapeze, just like the part between the faults III and IV of the anomalies 2 - 3. The unequal activity at the rift is schematically represented in Fig. 10, row C.

(4) The centres are mostly cut off by faults. As a rule, they do not continue beyond a fracture zone (Figs. 10, 12 B); accordingly, the efficacy of faults is very deep. Examples: (a) There were centres of activity for more than 10 m.y. in the S.E. Pacific (today) north of 50° S. each time at the end of three rift sections (Fig. 10, from 20 to 9.5 m.y.b.p. between faults I and IV), without continuing beyond the faults; (b) the Reykjanes Ridge at 60° N. 8 to 10 m.y.b.p.: one of its centres north of the fault 9 (Fig. 16, column a).

(5) Centres of additional magmatic activity are preferably developed at intersections between rift zones and fracture zones, or at fault-like points. This caused a fault activity also outside the transform sections, because on both flanks of the fault stripes of anomalies with unequal widths spread away from the rift, as is exemplified by displacements of the limitations of anomalies 6 to 1 (Fig. 9) during the last 20 m.y. in the area between the Chile and Eltanin F.Z.s in the S.E. Pacific.

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(6) From (5) it follows that a stepwise shift of the fault flanks is possible even outside the transform sections (a left-handed displacement alternating with a right-handed one). Thus the displacements originating can almost, or totally, be eliminated in the following time, a movement, however, almost continuously taking place at the faults (BANKWITZ & BANKWITZ 1972, Figs. 2 and 3).

(7) If such an additional production extincts, the rift section (a) may uniformly continue its magmatic production in its whole length, or (b) at this place may produce less than at the remaining rift. The latter is the rule. - Example: anomaly map of the Reykjanes Ridge at 60^{o} N. and of the Juan de Fuca Ridge, e.g., anomaly 4 west of the mouth of the Columbia River. This is recognized by interlocking stripes magnetized normally and reversely (there is an extension in addition to a constriction, cf. Fig. 12 C).

(8) This behaviour also applies to whole rift parts where the spreading was occasionally faster than in other rift sections. The greater a maximum of intrusion, the smaller is the minimum following chronologically. - Examples: (a) Reykjanes Ridge 8 to 10 m.y.b.p. between faults 3 and 4, 9 and 10; the areas between the faults 1 - 2, 12 - 12a and 16 - 17 are more compensated ones (Fig. 16, column a); (b) the central section between the Chile and Eltanin F.Z.s 2 to 4.5 m.y.b.p. (Fig. 9, anomalies 3 - 4, rows A and B), clearly above all west of the rift; (c) the section between the Mendocino and Surveyor F.Z.s in the N.E. Pacific 40 m.y.b.p. (cf. Fig. 1, BANKWITZ & BANKWITZ 1972).

(9) There is available, obviously for a long time, a constant mean amount of magma over a large length of the rift, which, by a self-regulating principle, intrudes occasionally and locally at the rift in an irregular way. If more than the mean quantity intrudes, the intrusion in the same area is reduced in the following time interval or in the adjoining area, respectively. This compensating rhythm of 1 to 6 m.y. is superimposed by macrorhythms and by increased spreading towards the equator.

(10) If the intrusions mainly took place on one side of the older main intrusion zone (Fig. 12 D), the rift is shifted laterally. - Examples: Pacific-Antarctic Rift between Chile and Eltanin F.Z.s (Fig. 10, rows A and B). Thick arrows indicate the supposed shifting, which must have happened up to the thin vertical line each time in the midst of the blocks. This auxiliary line indicates the limitation of the anomaly towards the rift.

(11) Rotations of the rift took place if the magmatic bodies only intruded partially or only at a point on one of its sides. The anomalies then run parallel on both sides of t rift, but in an oblique direction in comparison to the preceding anomaly (Fig. 12 E). An intrusive zone obviously never shifts unilaterally. The orientation of the intrusions presumably shifts only partially and, in most cases, probably only at one end of the rift section. The basic idea of the diagonal intrusion by VOGT et al. (1969) proves, however, to be suitable for a reconstruction of processes of rotation (Fig. 14, row B). - Example: rift between the Chile and Eltanin F.Z.s (Fig. 10). Small arrows indicate the presumable direction of rotation partly opposite at the individual rift sections (cf. Chapter 4).

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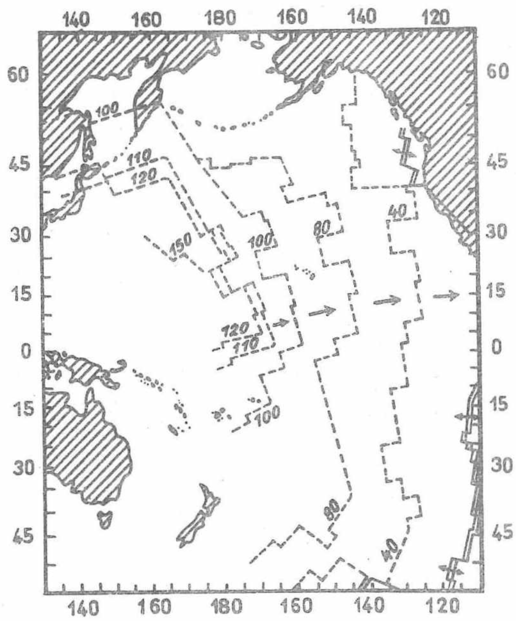

Fig. 11. Lateral rift shifting towards the east from 150 m.y. until today (LARSON & CHASE 1972)

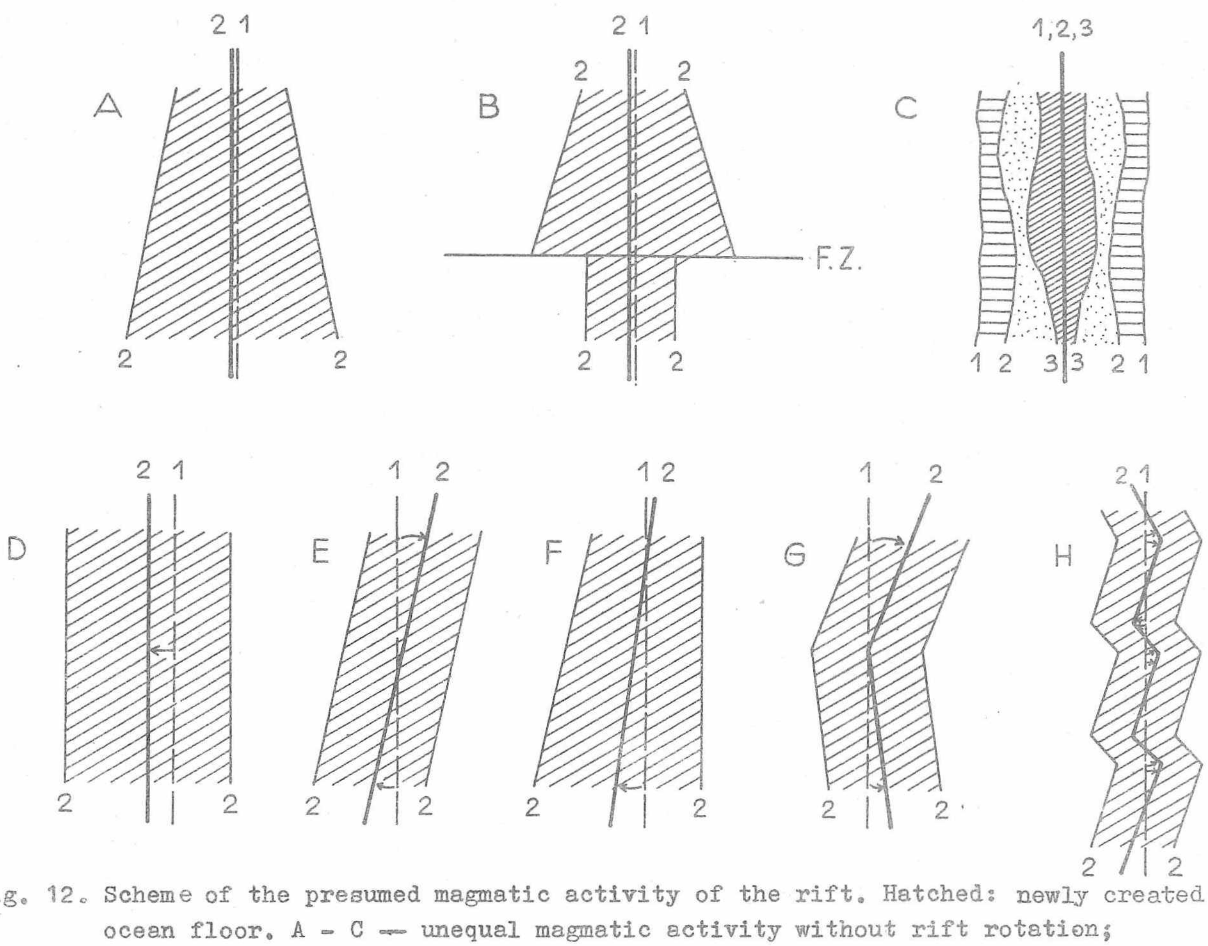

Fig. 12. Scheme of the presumed magmatic activity of the rift. Hatched: newly created ocean floor. A – C — unequal magmatic activity without rift rotation; D – H — intensified at one side of the former main injection zone; E – H — connected with rotation; G – H connected with creation of hinge points; G without shifting of the kink point; H connected with shifting of the kink points.

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(12) Kinks of the rift observable in the following time as anomaly kinks (Fig. 12 G) were formed if places with intrusions shifted unilaterally are not situated close to fracture zones. If such a spot with a tendency towards an injection zone shifting unilaterally was maintained at the rift for a long time (5 m.y. and longer), kinks arranged laterally originate, which are connected by nodal lines. - Examples: in the Gulf of Alaska the rift between the Aja and Sila F.Z.s (Figs. 6, 13 and 14). Particularly numerous narrow kinks are shown by the Reykjanes Ridge at (today) 60° N., the Kula and East Pacific Rifts at (today) 59° N. and 170° to 180° W., as well as the Rivera Rift south of Baja California. They also occur at the Juan de Fuca Rift, however, with minor angles. One of the two sections forming a kink is often longer than the other (Fig. 12 H). At the Reykjanes Ridge (Fig. 16) the kink distances are 10 to 25 up to 50 km.

(13) The different consequences of the rift activity may simultaneously occur in a combined way at the same point, or part of the rift, such as drift, rotation, or kinking of the rift. Example: the Pacific-Antarctic Rift between the Chile and Eltanin F.Z.s (Fig. 10; cf. Chapter 4).

5.2. Hinge zones of the rift rotations

Hinge zones s.l. were already mentioned in the sections dealing with the total rotation of the N.E. Pacific Rift and with the rotations of the Pacific-Antarctic Rift. In these cases hinge zones are faults where the rift is displaced considerably. This may suggest that an increased activity causing eastward rift shiftings (expressed in kink dislocations towards the east) may take place as a result of increased mobilization in the upper mantle in definite distances, not only at the intersection points of the rift and fracture zones, but also within these zones themselves. This increased intrusive activity giving rise to shiftings of the rift towards the east is in good accordance with its shift generally supposed towards this direction. Times in which the kink of the rift relatively shifts westward (Fig. 8) would then be regarded as times in which the magmatic activity of the hinge zones has become extinct.

From the simplified representation of Fig. 8 three intervals of activity and three of quiescence are obtained for the Mendocino-Pioneer zone:

Duration [m.y.]	Time [m.y.b.p.]		Anomalies
15	quiescence	80-65	32-26
5	activity	65-60	26-24
20	quiescence	60-40	24-15
8	activity	40-32	15-10
16	quiescence	32-?16	10-5C
6.5	activity	?16-9.5	5C-5

Thus the quiet intervals durations 15 to 20 m.y. are twice to three times as long as the activity intervals durations (5 to 8 m.y.).

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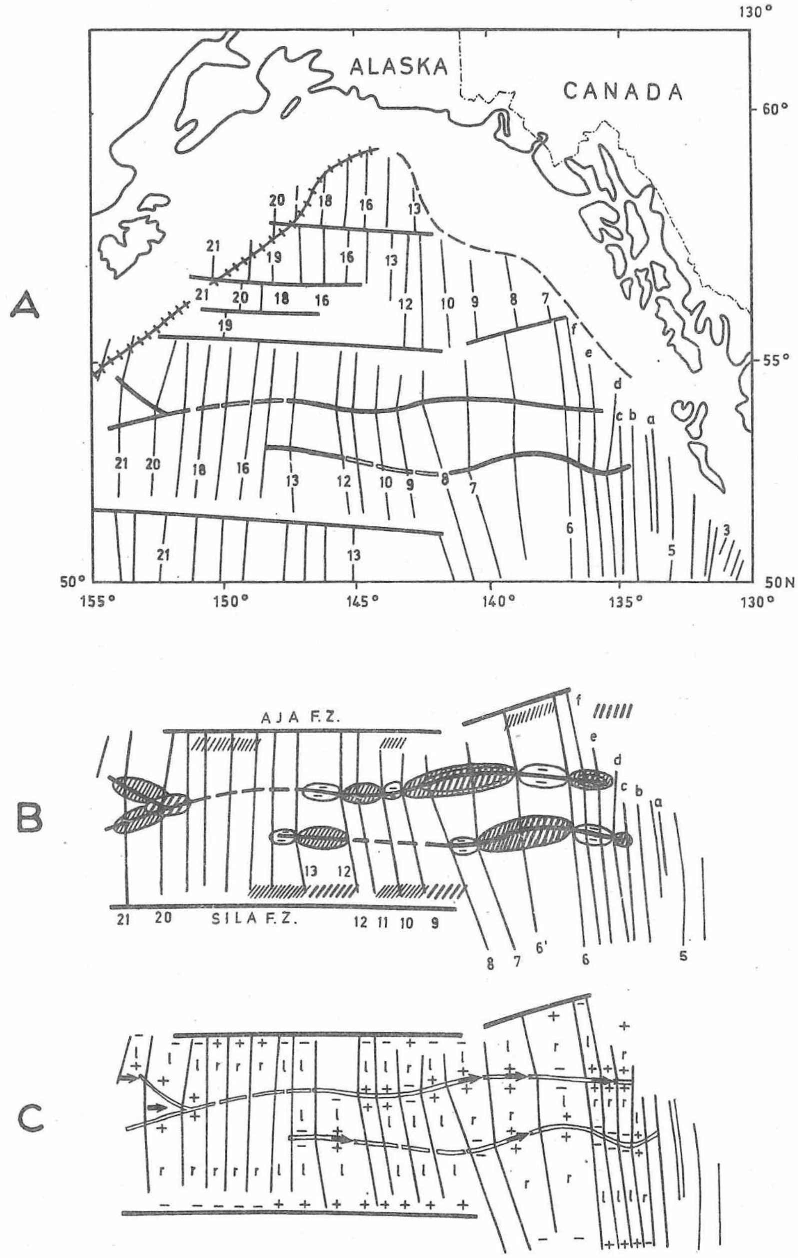

Fig. 13. Hinge lines in the Gulf of Alaska between Aja and Sila F.Z.s. A — configuration of anomalies and positions of kink points (NAUGLER & WAGEMAN 1973) and both hinge lines; B — hatched areas: intensified intrusion activity, minus: reduced activity on the west flank of the rift; the maximum activity changes from the southern to the northern hinge and vice versa, exept the time of anomaly 7 - 6'. C — r, l: clockwise or counterclockwise rotation, resp.; +, -: intensified or reduced intrusion activity, resp., on the west side of the rift; arrows: shifting of kink points

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Places at the rift having a fault-like character often reacted as hinge zones, without being realized as faults. At these points the rift is not displaced, but is only kinked. This statement may be relied on for the area south of the Aleutian Trench from 163° to 180° W. (distance of track lines of magnetic data interpreted by GRIM & ERIKSON 1969: 18 km); this statement may also hold true for other areas with a similarly low distance of track lines.

The magmatic activity of such a hinge point represents the anomalies of the rift section between the Sila and Aja F.Z.s in the area between 52° and 56° N. in the N.E. Pacific. Fig. 13 shows the characters of this hinge zone, viz.:

(1) All kinks are situated almost on the same geographical latitude, originated at one point at the rift, and can be connected by nodal lines approximately running parallel with the fracture zones.

(2) This rift section between fracture zones has two hinge points roughly dividing it into three parts. They became active 40 and 38 up to 20 - 10 m.y.b.p. The northern hinge point has obviously existed already 53 m.y. ago and was inactive from 47 to 38 m.y.b.p. The southern hinge point, too, occasionally was inactive.

Hinge activities between the Sila and Aja F.Z.s:

Duration [m.y.]		Time [m.y.b.p.]	Anomalies
(a) Northern hinge zone			
6	activity	53-47	21-19
9	quiescence	47-38	19-13
18-28	activity	38-20(10)	13-6(5)
(b) Southern hinge zone			
4	activity	39-35	14-12
6	quiescence	35-29	12- 8
9-19	activity	29-20(10)	8- 5(6)

(3) The nodal lines and hinge zones, respectively, are curved arch-like on account of a temporary, small shift of the kink towards the south and north, respectively. Provided these shiftings are real ones, the N.-S. shifts are due to the respective rotation connected with the E.-W. shift of a kink. The kink is the result of a rotation of one of the two adjacent rift parts, with the kink point shifting towards the north, or south, as dependent on the circular arc. It often occurs that an adjacent rift part only rotates, or one part rotates more than another, with the curvature produced by the more intense rotation (Figs. 6 and 13).

(4) By means of these hinge points the rift rotated stepwise. It was readjusted to a new position of the pole by way of small steps, which may be equal in value to the principle of the smallest working effort (VOGT et al. 1969). These steps are represented in Fig. 14 for the anomalies 13 - 5 in this area.

(5) The magmatic production may obviously become more asymmetric at a hinge than in other places of the rift (cf. Figs. 12 F and 14, rows A and B), that is, on one side preponderantly, however, north and south of the nodal point. At a fault intrusions are mostly unilateral at one flank only. If so at both flanks, the fault also reacts like a hinge.

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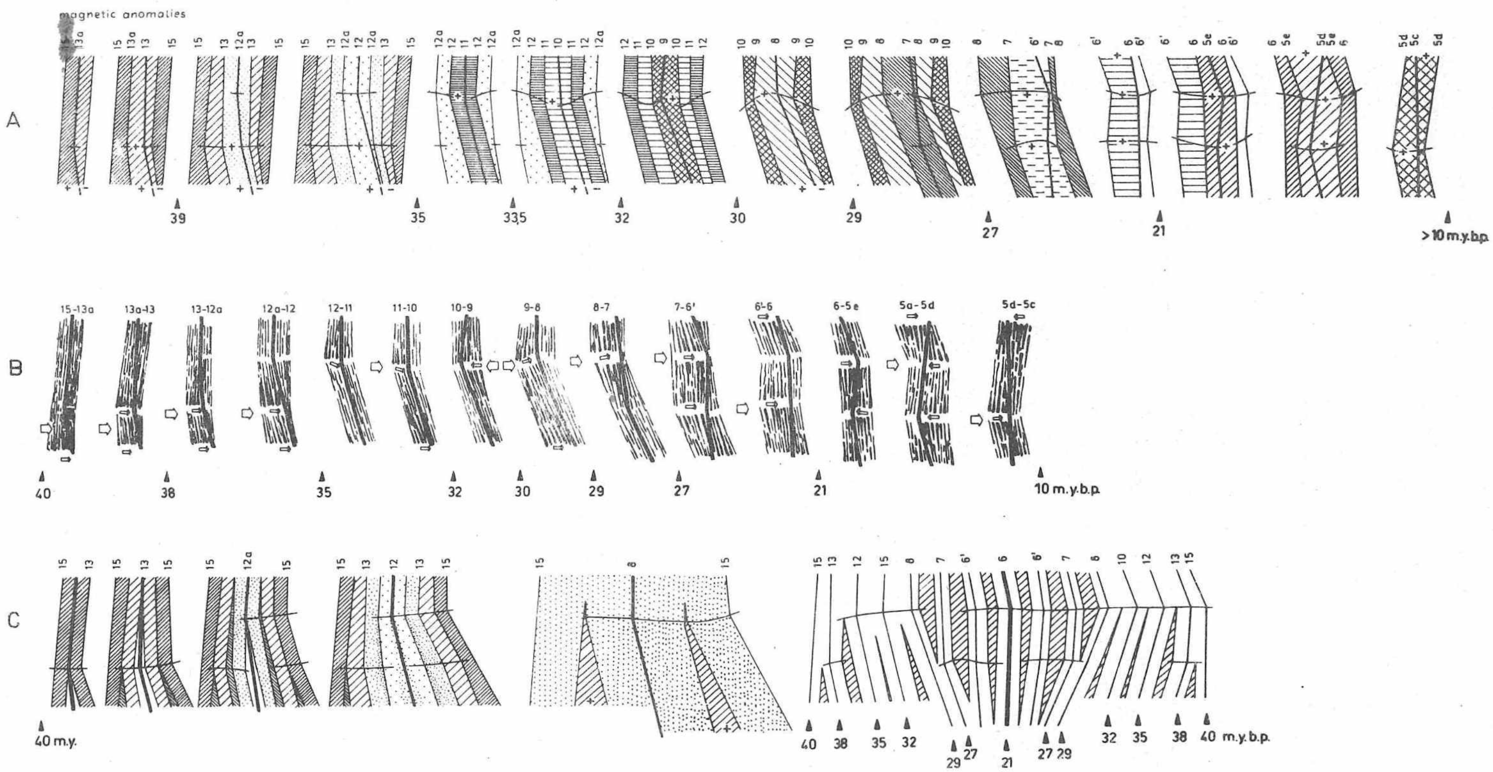

Fig. 14. Location and configuration of anomalies as in Fig. 13. A — step-by-step rotation of single parts of this rift section which is to be supposed on the strength of the kinks, provided an equal magmatic activity along the whole rift section, but unequal distribution of the intrusions at one side of the rift (+). B — one-sided main intrusion zone causes the change of rift position or of the kink, resp. (arrows). C — rift rotation on the understanding of an unequal magmatic activity along the rift section. Hatched areas: intensified intrusion. Only if the anomalies at both sides of the rift are preserved, it may be determined which case (A or C) is present.

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(6) The kink is either fixed at the hinge and rotates at the free ends (Fig. 14: anomalies 15 to 12; another place of the rift has a major magmatic activity), or is shifted in the hinge area due to a particularly intense activity (anomalies 12 to 7; Fig. 14, rows A and B). In Fig. 13 B the first case is characterized by a minus sign and the second case by a plus sign.

(7) The nodal point shifts together with the rift (Figs. 13 and 14).

(8) The nodal point couples the two rift parts, compels them to react in common, or prevents a fault displacement.

(9) Kinks may occur at narrow distances, such as at the Reykjanes Ridge (Fig. 16), Gorda Ridge, Pacific and Kula Ridges (anomalies 29 to 25). They shorten the rift in its longitudinal direction.

Differences of the rate of spreading are transferred from the rift sections into the plates as unequal displacements of faults. Either the energy will be absorbed by deformation or transmitted through the whole plate. The latter case seems improbable, because it can be realized only when the plates are divided into independent strips. But the point-like centres of activity must cause deformations in the older intrusions. According to our opinion, tectonically deformed basalts may occur especially in the hinge zones of rifts as they were described above.

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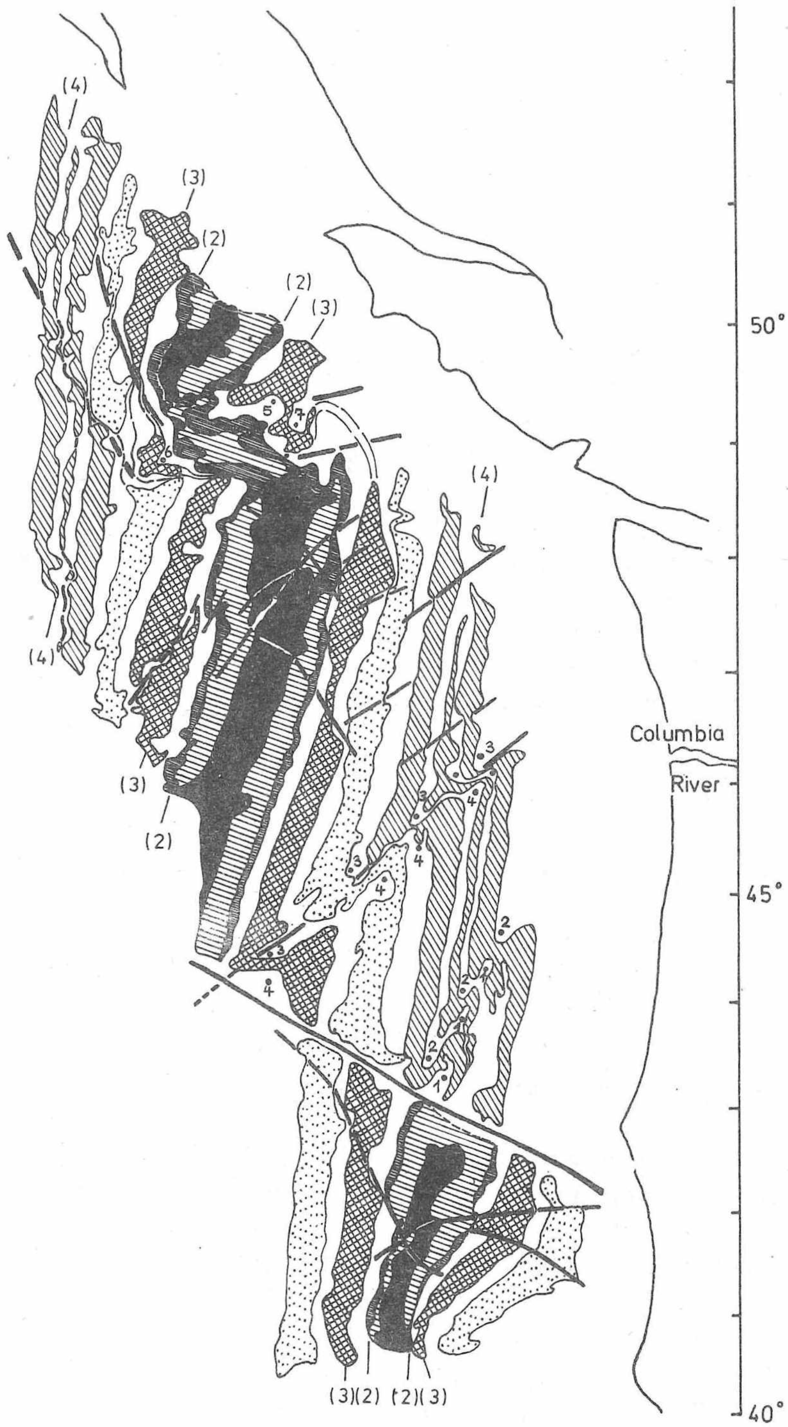

Fig. 15. Deformation of the Juan de Fuca and Gorda Rifts between 40° and 50° N. fault-folding and fault displacements. Black: rift area; numerals in brackets: numbers of anomalies. Source for the configuration of anomalies: RAFF & MASON 1961. Fold-like bending of the rift at 49° N., and of the anomalies 3 and 4 between 44° and 46° N. Points 1 - 7: bendings. Right-hand side of the rift: compression connected with rift rotation; left-hand side: dominating extension

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6. Plate deformation

Out of the various signs indicating a deformation of plates with an oceanic crust two phenomena only will be discussed here.

6.1. Rift rotation at a collision of plates

The Farallon Plate in the N.E. Pacific may be widely subduced, the small remains only known being the Juan de Fuca Plate and the Rivera Plate. There some extremely intense rift rotations seem to be traceable to a collision between the Pacific and the American Plates. According to our opinion, the remaining residual sections of the two rifts were influenced and carried along during the collision by the south-west movement of the American Plate. This is valid already for the southern part of the Farallon Plate, when the East Pacific Rift got into the immediate proximity of the American Plate. The rift, 32 m.y. ago, by 15° and 30° N., respectively, jumped towards the N.E. south of the Pioneer F.Z., i.e., with 7.5° to 15°/m.y., presumably as a reaction upon the southward drifting American Plate. There is, in our opinion, a deformation of the oceanic plate in the time before, or during, the subduction. In the following 3 m.y. the rift was able to "reorganize" itself once more, that is to say, from 30 to 27 m.y.b.p. this rotation partially was eliminated by 6°, but from 27 to 21 m.y. b.p. this rift already rotated by 15° towards the north-east. This anomaly is the last that has been preserved.

The intense counterclockwise rotation of the anomalies 6 - 5, west of Baja California, is a result of the plate collision, just as the extreme clockwise rotation by 13° to 40° in 11.5 m.y. continuing from anomaly 5 till present time. The amount of rotation always increases from south to north (Rivera 14°, Gorda 18°, Juan de Fuca Rift 20° to 40°; cf. Fig. 15). The asymmetric position of anomaly 3 at the Rivera Rift is due to a distinct decrease of the intrusive activity at the rift from S.W. to N.E.

6.2. Rift shortening due to compression

A primarily active internal deformation of the plates and rifts can be observed in addition to this secondary, passive rotation of the rift and Farallon Plate during the collision. Owing to the intense compression to be ascribed to the Pacific and American Plates moving towards each other, the rift system was compressed and shortened together with the adjacent anomalies, so that a large-area fault-folding took place. We distinguish several phases:

(a) Rift shortening due to manifold kinking. This is the present-day stage of the Rivera Rift, and is also shown by the Reykjanes Ridge at 60° N., although developed to a minor degree (cf. Fig. 16). It is the type of a compression continuously increasing slowly.

(b) Shortening due to some few large kinks laterally evading in fold-like bends and forming a fault-folding (cf. Fig. 15 after Fig. 1 in RAFF & MASON 1961, and Fig. 4 in VINE 1968). It is due to an intense constriction rapidly increasing. In this area the folding may only have begun more than 2 m.y.b.p., because the stripes magnetized normally (3.5 to 2.5 m.y.b.p.) at 45° N., which originated prior to

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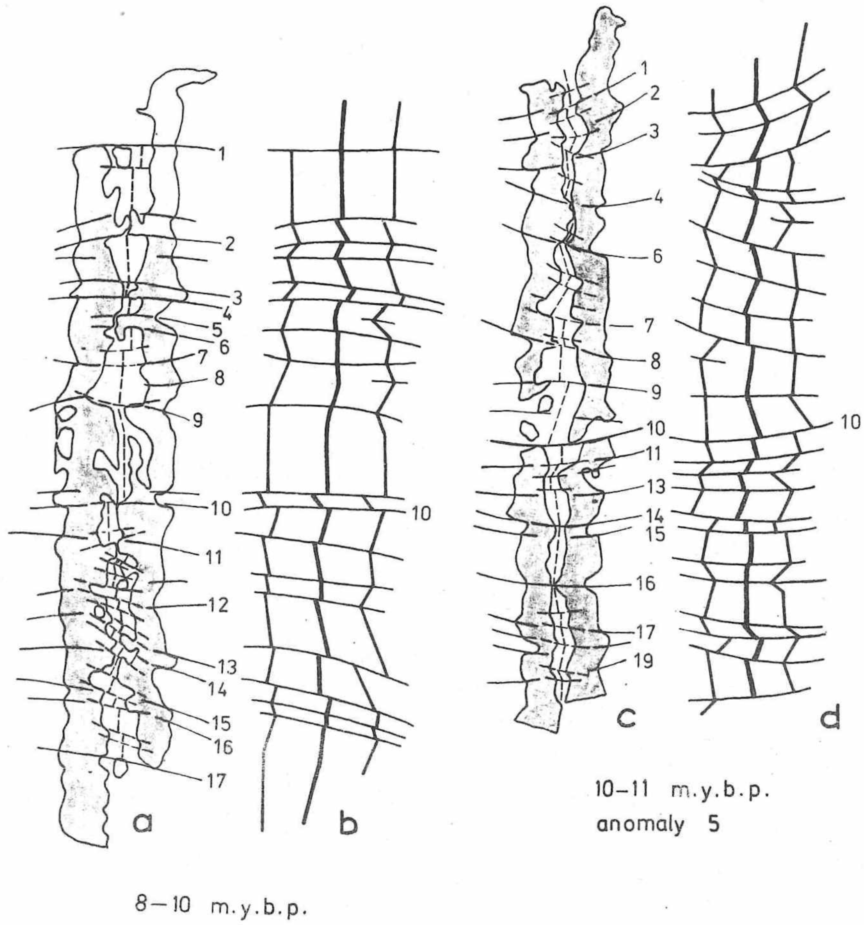

Fig. 16. Reykjanes Ridge at 60° N. (HEIRTZLER et al. 1966). a and c: the distances between two simultaneous stripes with normal magnetization at both sides of the rift were eliminated. The central areas show the initiation of new stripes with reverse magnetization. Dashed vertical lines: supposed position of the main injection zone before 8 and 10 m.y.b.p.; horizontal lines 1 - 17 and 1 - 19: minor faults (e.g. 10) or hinge lines active 10 m.y. (a) and 11 m.y. (b) ago. b and d: shapes of the columns a and b representing kinks of the rift during the creation of the stripes of ocean floor

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the anomaly 2, were also folded. At 49° N. the rift shows a weaker stage of bending (sigmoidal fold), at 45° N. a more intense one (zigzag fold). In places, a small-dimensioned additional folding must be assumed, as otherwise it is only known from the continental crust (points 1 - 6 in Fig. 15). With the bending north and south of the Blanco F.Z. the northern end of anomaly 3 also points at a previous fault-folding prior to the shearing and displacement of the bending for more than 100 km. This displacement may have been realized 2.5 m.y. ago only, i.e., after formation of the stripe normally magnetized; it may, however, still continue today. This means a horizontal shift by 5 cm/y. (since the beginning of the Pleistocene). -

The late beginning of the fault-folding at 45° N. results from the supposition that the rift did no longer produce in such an "overturned" position as it is today (N.W. limb). A production in such a position must be demanded if the bending had already taken place 3 or 4 m.y.b.p. At 49° N. we suppose that in the E.-W. bending the anomaly 2 is still completely developed, whereas the anomaly 1 represents the last stripe formed. The recent stripe magnetized normally could not originate, which means that 1 m.y. ago the fault-folding became so intense that this rift section was no longer productive. This degree of folding supports the assumption that the fault-folding at 45° N. only began intensely about 2 m.y.b.p.

(c) Origin of additional fractures and of the clockwise-rotating displacement: Not only the rift but also the remainder of the Farallon Platte and a stripe about 100 km wide of the Pacific Plate (north of 48.5° N.) were rotated in a clockwise direction, widening the Pacific Plate and compressing (shortening) the Farallon Plate with the rift. West of 47° N., however, the shortening encroaches as far as the Pacific Plate, with the area north of 48.5° N. rotating on kinked faults (VINE 1968), or on listric surfaces (described by PAVONI 1966), which represent a later bending stage. The faults striking W.N.W. or N.W. must be regarded as primary ones and correspond to the compression rotating clockwise of this area. The faults running N.E. secondarily result from a further compression of the fault-foldings and represent its latest stage. There the folds were sheared and neighbouring anomalies were also displaced.

By eliminating all bendings and kinks, it is shown (cf. Fig. 17) that the anomalies 2 and 3, east of the rift of Cape Blanco to the Juan de Fuca Strait, have nearly the same extension as the anomaly 4, 7 m.y.b.p. Today, at the Juan de Fuca Rift (with the great bending at 49° N.), the anomaly 2 is shortened by about 1/7 to 85.3 per cent of the original length, which must widely have taken place during the last 2 m.y.

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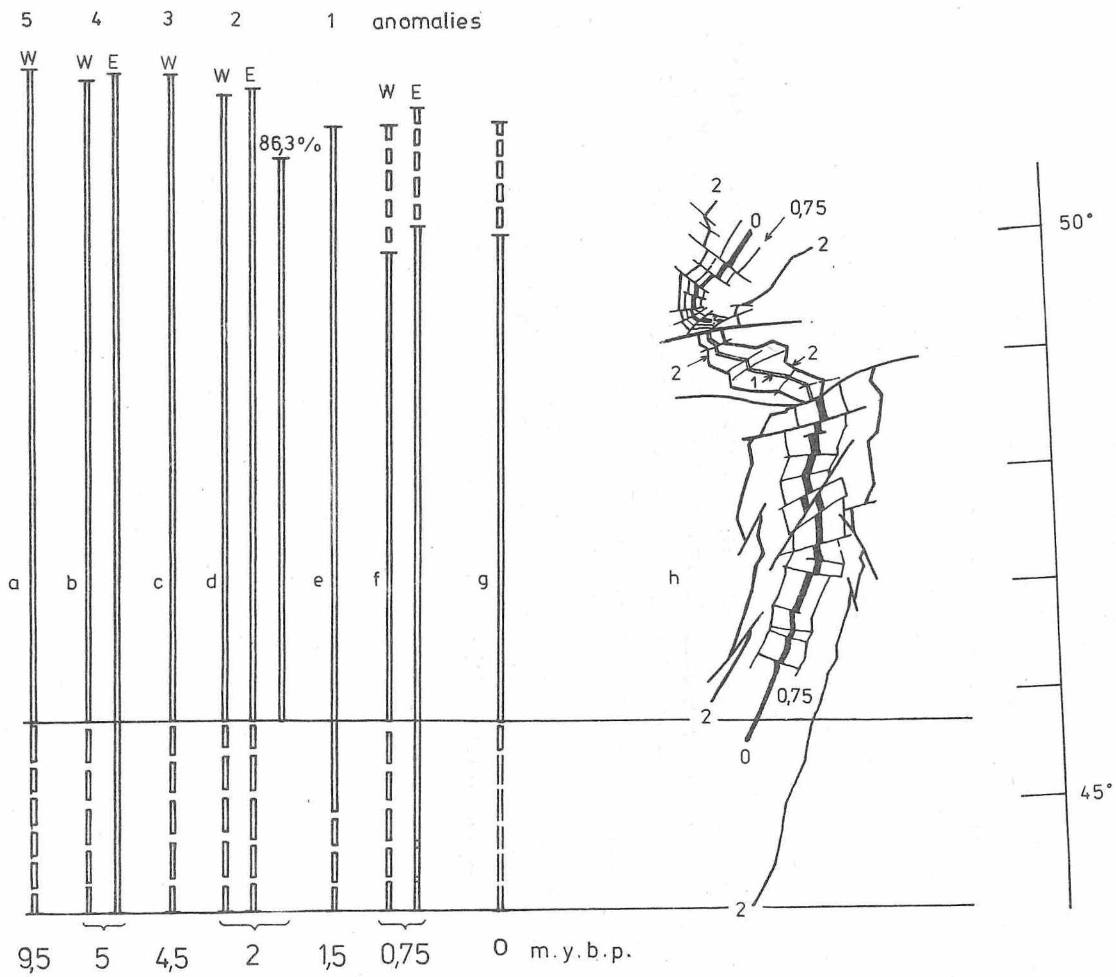

Fig. 17. Juan de Fuca Rift between 45° and 50° N. a - g -- elimination of the rift kinks of the anomalies 1 - 5 (a - f: W -- west of the rift, E -- east of the rift); d: the most right column is shortened regardless of the minor kinks to 86.3 %. f - g: last anomaly with normal magnetization which is missing in the bending at 49° N. This dead rift section is added in the upper part of f and g (dashed); f: outer contour of the stripe h; g: recent rift axis; h: configuration of the Juan de Fuca Rift with anomalies 1 (1.5 m.y.) and 2 (2 m.y.) after RAFF & MASON 1961; numerals: m.y.b.p.

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7. Conclusions

It should be noted that the rift sections always have migrated to another position since 80 mio years b.p. The permanent rotation of the East Pacific Rift (Fig. 2) must be divided into three stages of first-order rotations lasting about 40, 20 and again 20 m.y. The general clockwise rotation covering the whole rift (35 - 40^{o}) was interrupted between 40 and 20 m.y.b.p. by a weak counterclockwise one (8^{o}; Fig. 8). The stages are composed of six periods of changing rotations with average durations of 10 m.y. only. It may be supposed that all these rotations are a readjustement of the rift to a changed position of the spreading pole.

Contrary to these rotations the plate was stabilized by short-time oscillatory rotations representing compensating movements of the rift. They may concern the whole rift, or may be limited regionally.

There exists a connection between hinge zones and faults, resp., and such pendulum movements. Hinge zones are zones of weakness of the rift (Fig. 13), which can become fault zones. They may be observed at the N.E. and S.E. Pacific Rifts as well as the North Atlantic Rift. Up to now they were not mentioned in literature.

The internal deformation of oceanic plates is demonstrated by the Pacific and Juan de Fuca Plates off California representing kinks of rift, fault-folding and strike slip movements on faults which became intense about 1 - 2 m.y.b.p. (Fig. 17).

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References

[1] ATWATER, T.: Implications of the plate tectonics for the Cenozoic tectonic evolution of western North America.
Geol. Soc. Amer. Bull., Boulder 81 (1970) 12, p. 3513-3536

[2] ATWATER, T.; MENARD, H.W.: Magnetic lineations in the northeast Pacific.
Earth and planet. Sci. Lett., Amsterdam 7 (1970) 5, p. 445-450

[3] BANKWITZ, P.; BANKWITZ, E.: Zur tektonischen Entwicklung des Nordostpazifik.
Geologie, Berlin 20 (1972) 4/5, S. 393-408

[4] GIERLOFF-EMDEN, H.G.: Tektonisch-geologische Übersichtskarte der Ozeane der Erde.
Dt. hydrogr. Z., Hamburg 23 (1970) 3, S. 118-120

[5] GRIM, P.J.; ERICKSON, B.H.: Fracture zones and magnetic anomalies south of the Aleutian Trench.
J. geophys. Res., Richmond 74 (1969) 6, p. 1488-1494

[6] HEIRTZLER, J.R.: Sea-floor spreading.
Sci. Amer., New York 219 (1968) 6, p. 60-70

[7] HEIRTZLER, J.R.; LePICHON, X.; BARON, J.G.: Magnetic anomalies over the Reykjanes Ridge.
Deep-Sea Res., Oxford 13 (1966) 3, p. 427-444

[8] HERRON, E.M.: Crustal plates and sea floor spreading in the southeastern Pacific.
Antarctic Res. Ser., Washington 15 (1971), p. 229-237

[9] HERRON, E.M.: Sea-floor spreading and the Cenozoic history of the East-Central Pacific.
Geol. Soc. Amer. Bull., Boulder 83 (1972) 6, p. 1671-1692

[10] LARSON, R.L.; CHASE, C.G.: Late mesozoic evolution of the western Pacific Ocean.
Geol. Soc. Amer. Bull., Boulder 83 (1972) 12, p. 3627-3644

[11] MOLNAR, P.; ATWATER, T.; MAMMERICKX, J.; SMITH, S.M.: Magnetic anomalies, bathymetry and the tectonic evolution of the South Pacific since the late cretaceous.
Geophys. J. Res. astr. Soc., Oxford 40 (1975), p. 383-420

[12] NAUGLER, F.P.; WAGEMAN, J.M.: Gulf of Alaska: Magnetic anomalies, fracture zones, and plate interaction.
Geol. Soc. Amer. Bull., Boulder 84 (1973) 5, p. 1575-1584

[13] PAVONI, N.: Tectonic interpretation of the magnetic anomalies southwest of Vancouver Island.
Pure and appl. Geophys. 63 (1966) 1, p. 172-178

[14] RAFF, A.D.; MASON, R.G.: Magnetic survey off the west coast of North America, 40° N. latitude to 52° N. latitude.
Geol. Soc. Amer. Bull., Boulder 72 (1961) 8, p. 1267-1270

[15] STOVER, C.W.: Seismicity and tectonics of the east Pacific Ocean.
J. geophys. Res., Richmond 78 (1973) 23, p. 5209-5220

[16] VAN ANDEL, T.H.: Cenozoic migration of the Pacific Plate, northward shift of the axis of deposition, and paleobathymetry of the central equatorial Pacific.
Geology, Boulder 2 (1974) 10, p. 507-510

[17] VINE, F.J.: Magnetic anomalies associated with mid-ocean ridges. In: PHINNEY, R.A. (Ed.), The History of the Earth's Crust, p. 73-89.
Princeton: Princeton University Press 1968

[18] VOGT, P.R.; et al.: Discontinuities in sea-floor spreading.
Tectonophysics, Amsterdam 8 (1969) 4-6, p. 285-317

[19] VOGT, P.R.; AVERY, O.E.: Detailed magnetic surveys in the northeast Atlantic and Labrador Sea.
J. geophys. Res., Richmond 79 (1974) 2, p. 363-389

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DOI: http://doi.org/10.2312/ZIPE.1978.046