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[1] Sinnott, E. W., and Bailey, I. W., *Amer. J. Bot.*, **2**, 1 (1915).
[2] Zimmermann, W., *Die Phylogenie der Pflanzen*, second ed. (Fischer, Stuttgart, 1952).
[3] Melville, R., *Nature*, **211**, 116 (1966).
[4] Ettingshausen, C. R. von, *Die Blattskelete der Dikotyloden* (Staatsdruckerei, Wien, 1861).
[5] Foster, A. S., *Not. Roy. Bot. Garden Edin.*, **23**, 1 (1959).
[6] Foster, A. S., *J. Arn. Arb.*, **49**, 52 (1968).
[7] Pray, T. R., *Amer. J. Bot.*, **42**, 611 (1955).
[8] Foster, A. S., *Amer. J. Bot.*, **37**, 159 (1950).
[9] Foster, A. S., *Amer. J. Bot.*, **37**, 848 (1950).
[10] Asama, K., *Sci. Rep. Tohoku Univ., Sendai, Japan*, **4**, 252 (1960).
[11] Hammen, L. van der, *Blumea*, **6**, 290 (1948).
[12] Feistmantel, O., *Palaeontologia Indica, Mem. Geol. Surv. India*, Parts 1–2 (1880), 3 (1881), 4 (1886).
[13] Plumstead, E. P., *Trans. Proc. Geol. Soc. S. Africa*, **59**, 211 (1956).
[14] Plumstead, E. P., *Palaeobotanist*, **11**, 106 (1962).
[15] Plumstead, E. P., *Transantarctic Exp. 1955–8, Sci. Rep.*, No. 9 (Geol. 2) (London, 1962).
[16] Plumstead, E. P., *Proc. Intern. Union Geol. Sci. Symp. Gondwana, Mar del Plata, Argentina*, 1967 (in the press).
[17] Plumstead, E. P., *Symp. Flor. Stratig. Gondwanaland* (Sahni Institute Palaeobotany, Lucknow, 1966).
[18] Arnott, H. J., and Tucker, S. C., *Bot. Gaz.*, **125**, 13 (1964).
[19] Croizat, L., *Adansonia*, **6**, 217 (1966).
[20] Plumstead, E. P., *Trans. Proc. Geol. Soc. S. Africa*, **61**, 81 (1958).
[21] Plumstead, E. P., *Trans. Proc. Geol. Soc. S. Africa*, **55**, 281 (1952).
[22] Melville, R., *Nature*, **188**, 14 (1960).
[23] Melville, R., *Kew Bull.*, **17**, 1 (1963).
[24] Bailey, I. W., *J. Arn. Arb.*, **30**, 70 (1949).

Evolution of Triple Junctions

by

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The simple geometric ideas of plate theory are extended to include some forms of plate evolution. The most important of these occurs where three plates meet. Such triple junctions are divided into two groups, stable and unstable, according to whether or not they can retain their geometry as the plates move. These ideas suggest an explanation for some of the major changes which have occurred in the North Pacific during the Tertiary.

A PRECISE version of the hypothesis of sea floor spreading[1,2] has recently been suggested. This new formulation[3–6] requires that all aseismic areas of the Earth's surface move as rigid spherical caps, and for this reason it is often called "plate tectonics". The instantaneous relative motion of any two plates on the surface of a sphere can be represented by a rotation about an axis, and so problems of present day tectonics reduce to determining the plate boundaries and relative rotation vectors of all plates on the Earth's surface. There are various methods of obtaining such information. If two plates are separating and new oceanic crust is being generated, the rate can be obtained from the magnetic lineations[7,8], which can also be used to map the plate boundaries[7]. Where the ridge axis is offset by transform faults the relative motion vector must be parallel to the strike of the faults[9]. The most general method of mapping plate boundaries, however, is by their seismicity[6,10], and earthquakes can also be used to measure the direction[3,6,11] and magnitude[12] of the relative velocity between the two plates involved. The agreement between these methods is striking, especially in oceanic areas[6], and demonstrates that aseismic regions are indeed rigid. It is now clear that the principal features of ridges, trenches and transform faults are a direct consequence of the relative motion of rigid plates.

There are two main reasons why plate tectonics does not yet provide a complete theory of global tectonics. The first is that the mechanism by which the motions are maintained is still unknown, though it now seems that some form of thermal convection can provide sufficient energy[13]. This problem will not be discussed further. The other is that the original ideas only apply to motions at present taking place, and are not concerned with either the slow evolution of plate boundaries or with changes in their relative motion through geological time. For example, the break-up of Gondwanaland was presumably caused by stresses within the original plate, and cannot be understood using geometry alone. Two causes of plate evolution, however, are the geometric consequences of the motion of rigid plates, and it is with these that this article is concerned.

The simplest example of such evolution is that of the trench shown in plan view in Fig. 1*a*, and occurs because a trench consumes lithosphere on only one side. The upper part of the trench *ab* consumes the plate Y, whereas the lower part *bc* in the figure consumes X. The arrows show the relative motion vector between X and Y, and are on the plate which is being consumed. As the motions continue in the directions of the arrows, Y is consumed between *a* and *b*, but not between *b* and *c*. *bc* must therefore be steadily offset from *ab* to form two trenches joined by a transform fault (Fig. 1*b*) the length of which increases at the consumption rate. The Alpine fault in New Zealand is an example of such a transform fault joining two trenches which consume different plates[6,14] (Fig. 1*c*). To the north of North Island the Kermadec trench consumes the Pacific plate, whereas the shallow and intermediate earthquakes beneath South Island and Macquarie ridge demonstrate that the Tasman Sea is being consumed in this region. This example is particularly simple because the slip vector does not change anywhere on the boundary between X and Y. More complicated effects can occur when the point at which three plates meet moves along plate boundaries. Evolution of such triple junctions can produce many of the changes which would otherwise appear to have been caused by a change in the direction or magnitude of the relative motion between plates. In particular, sudden changes in tectonic style are more likely to be caused by the movement of such junctions than by a change in relative velocity. It is especially difficult to alter the motion of large plates in a short time ($\sim$1 million years) because of the long thermal time constant ($\sim$ 50 million years or more) of any mantle convection driving the plates[13].

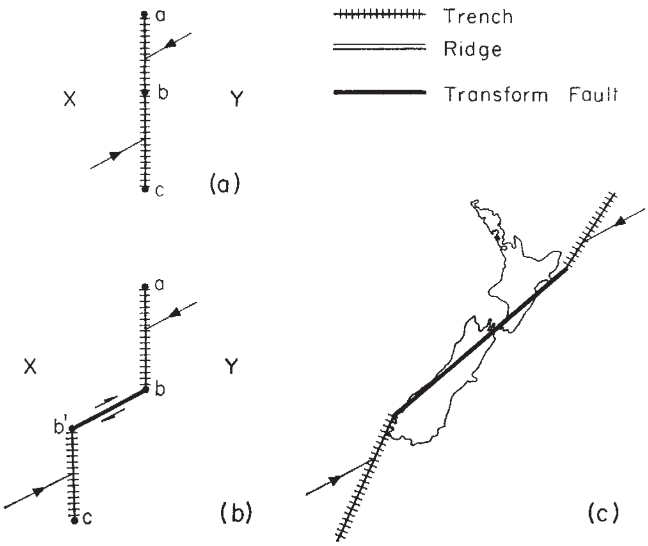

Fig. 1. The evolution of a trench. The arrows show the relative motion vector and are on the plates being consumed. Thus Y is consumed between a and b, X between b and c. The trench evolves to form two trenches joined by a transform fault. (c) is a sketch of New Zealand, showing that the Alpine fault is a trench–trench transform fault of the type in (b).

The discussion which follows is easier to follow if trenches, ridges and transform faults are defined in terms of destruction and creation of plates, rather than in terms of topographic features. Trenches are therefore defined as structures which consume the lithosphere from only one side, and ridges as structures which both produce lithosphere symmetrically and lie at right angles to the relative velocity vector between two separating plates. Transform faults are defined as active faults parallel to the relative slip vector. It is easy to modify the arguments which follow to take account of the complications of the real Earth where these definitions are not exactly true[15,16]. This is not done in general because the basic principles would then become obscure.

For the purposes of plate tectonics, the surface of the Earth is completely covered by a mosaic of interlocking plates in relative motion. There are many points where three plates meet, but, except instantaneously, none where four or more boundaries meet. The relations between the relative velocities of the plates at triple junctions have been discussed previously[3]; they are a consequence of the rigidity of the plates and do not impose any restrictions on the orientation of plate boundaries or on the relative velocity vectors. If, however, the triple junction is required to look the same at some later time, there are important restrictions on the possible orientations of the three plate boundaries. Unless these conditions are satisfied the junction can exist for an instant only, and for this reason is defined as unstable. If evolution is possible without a change in geometry, then the vertex is defined as a stable junction. The distinction between the two types is important because movement of stable junctions alone permits continuous plate evolution.

An example of a triple junction is the point at which three trenches meet (Fig. 2a). The arrows are on the plates which are being consumed, and show the relative velocity vector between plates. These vectors are not in general perpendicular to the boundaries. Consider the evolution of this junction relative to A which is taken as fixed. The positions of the plates B and C at some later time are shown in Fig. 2b. The dashed boundaries show where the plates would have extended if they had not been consumed by the trenches AC and AB. The trench BC, however, has migrated up the boundary, consuming B during the process, to reach the position shown. A point such as x on the boundary AB will show a sudden change in motion direction as the triple junction passes. This apparent change in spreading direction of the plates is easily distinguished from a real change in motion of one of the plates because it takes place at different times at different places along the plate boundary. Fig. 2 also shows how an unstable junction may become a stable one. The original orientation in Fig. 2a is unstable unless the slip vector ${}_A\mathbf{v}_C$ is parallel to the boundary BC. This condition is satisfied if BC does not move relative to A, and does not require any of the trenches to turn into transform faults. The slip vector ${}_A\mathbf{v}_C$ in Fig. 2a does not satisfy this condition, and therefore the trench BC does not remain on the apex of A but moves upward. Once the geometry in Fig. 2b occurs, the junction is stable and further evolution causes no change in geometry as BC moves along AB with a velocity with respect to A given by $\mathbf{v}_T$. If therefore the triple junction is watched by an observer moving with no rotation and with velocity $\mathbf{v}_T$ with respect to A, the triple junction will be stationary in his frame of reference. If all the boundaries are straight, the angles between them will not change. In the first example of a stable junction of three trenches the geometry remained unchanged in a frame fixed to A. In the second example all plates move in the frame fixed to the junction.

It is not easy to discover the general stability conditions for all possible junctions by the method used in constructing Fig. 2. Perhaps the simplest example of the general

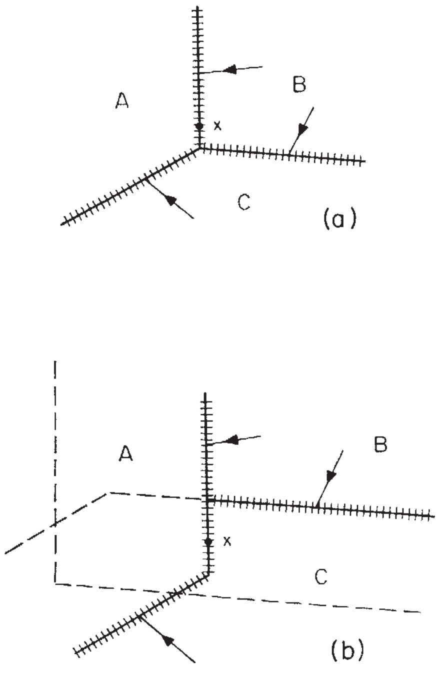

Fig. 2. The junction of three trenches. (a) shows the geometry before evolution, with the arrows as in Fig. 1. The arrows on B point in two directions because the relative motion between B and C is different from that between A and B. At some later time (b), the positions B and C would have reached if they had not been consumed are shown as dashed lines. The trench between B and C must move with C, and therefore moves away from the apex of A.

method is the triple junction between three ridges, which we shall call an *RRR* junction (Fig. 3). An example of such a junction is the meeting of the east Pacific rise and the Galapagos rift zone in the equatorial east Pacific[17,18]. The Great Magnetic Bight in the north Pacific was probably formed by another such junction which has now ceased to exist[19,20]. In this and all other examples the relative velocity vectors at the junction are required to satisfy[3] (Fig. 3):

$$ {}_A\mathbf{v}_B + {}_B\mathbf{v}_C + {}_C\mathbf{v}_A = 0 \qquad (1)$$

This equation must be satisfied if the plates are rigid.

In Fig. 3 the lengths *AB*, *BC* and *CA* are proportional to and parallel to the velocities ${}_A\mathbf{v}_B$, ${}_B\mathbf{v}_C$ and ${}_C\mathbf{v}_A$ respectively. The triangle is therefore in velocity space, and represents the condition imposed by equation 1. Because ridges spread symmetrically at right angles to their strike, a point on the axis of the ridge *AB* will move with a velocity${}_A\mathbf{v}_B$2 relative to *A*. This velocity corresponds to the mid point of *AB* in Fig. 3. Consider a reference frame moving with a velocity corresponding to some point on the perpendicular bisector *ab* of *AB*. *ab* is parallel to the ridge *AB*, so in this frame the ridge will move along itself and will have no velocity at right angles to *AB*. The same is true of the plate boundaries *BC* and *CA* when observed from reference frames whose velocities lie on *bc* and *ac* respectively. The perpendicular bisectors of the sides of any triangle meet at a point called the centroid, and this point *J* in velocity space gives the velocity with which the triple junction moves. It is therefore always

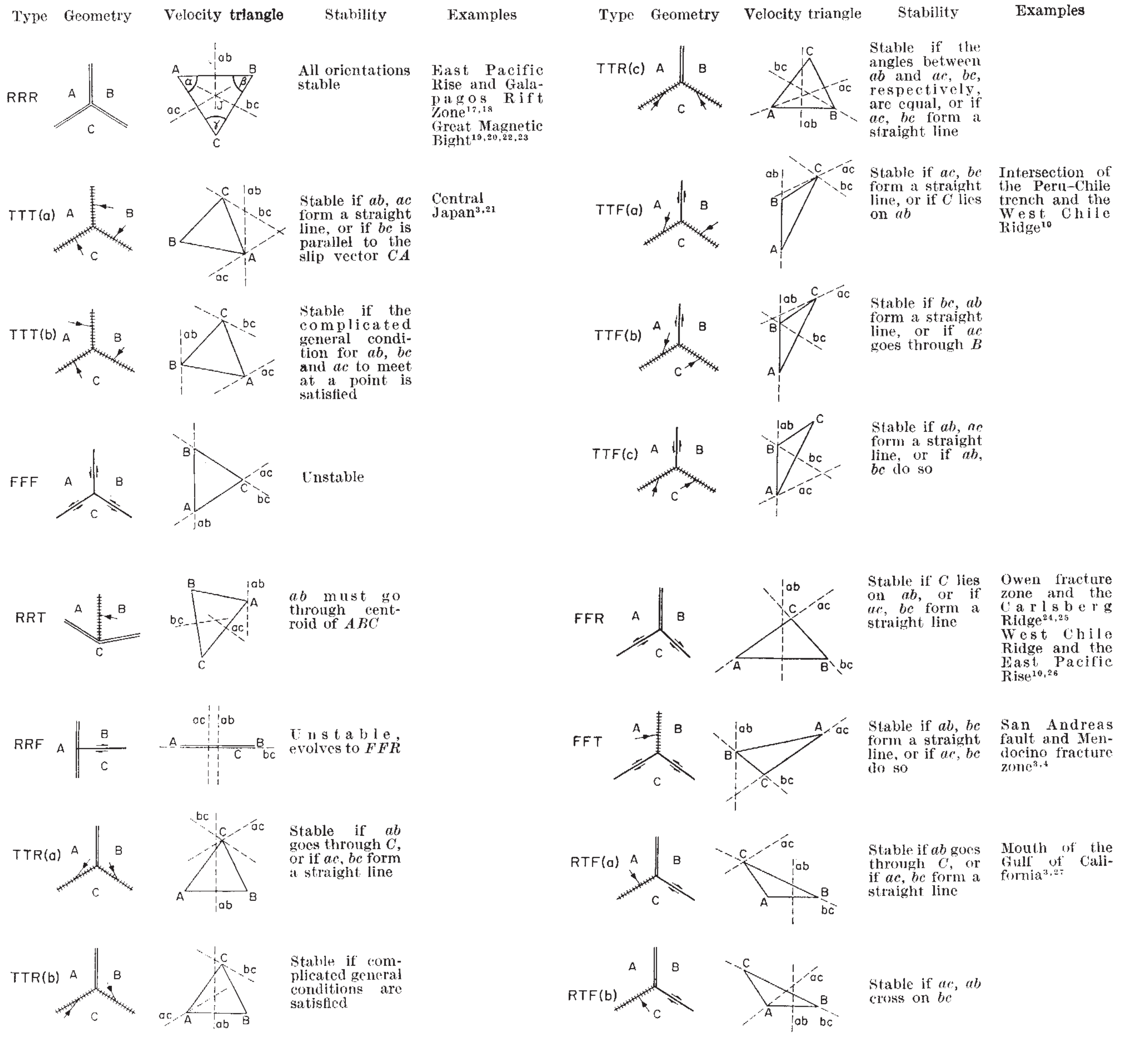

Fig. 3. The geometry and stability of all possible triple junctions. Representation of structures is the same as in Fig. 1. Dashed lines *ab*, *bc* and *ac* in the velocity triangles join points the vector velocities of which leave the geometry of *AB*, *BC* and *AC*, respectively, unchanged. The relevant junctions are stable only if *ab*, *bc* and *ac* meet at a point. This condition is always satisfied by *RRR*; in other cases the general velocity triangles are drawn to demonstrate instability. Several of the examples are speculative.

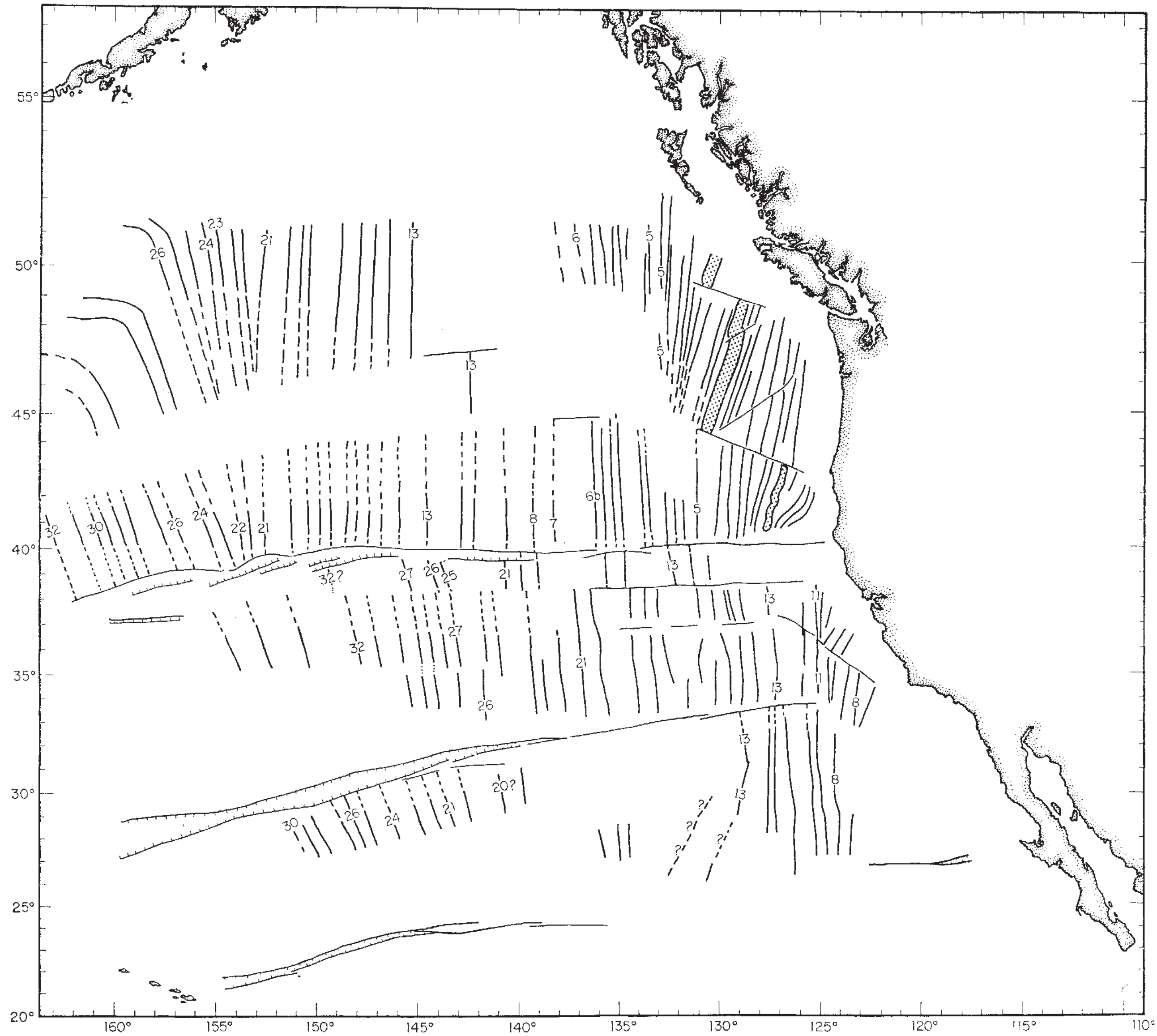

Fig. 4. Fracture zones and magnetic anomalies in the north-eastern Pacific (from Menard and Atwater[15]).

possible to choose a reference frame in which the triple junction does not change with time. From the velocity triangle the relative velocity **v** of all plates relative to the triple junction is:

$$\mathbf{v} = \frac{|{}_B\mathbf{v}_C|}{2\sin\alpha} = \frac{|{}_C\mathbf{v}_A|}{2\sin\beta} = \frac{|{}_A\mathbf{v}_B|}{2\sin\gamma} \qquad (2)$$

Also the angle between AB and AJ is 90-γ. Such a junction between three ridges is therefore stable for all ridge orientations and spreading rates. If the ridges spread symmetrically, but not at right angles to the relative slip vectors, the lines ab, bc and ac must still be drawn through the mid points of the sides, but not at right angles to the velocity vectors. Certain simple geometric conditions must then be satisfied if the triple junction is to be stable in these conditions.

A more complicated junction is that of three trenches, TTT(a) in Fig. 3, which has already been discussed. An example of such a junction occurs in the north-west Pacific[3,21], where the Japan trench branches to form the Ryukyu and Bonin arcs (Fig. 9). The arrows are on the plates being consumed and show the relative vector velocities between plates. The velocity triangle is formed as before, but points in velocity space corresponding to reference frames in which the position of the plate boundaries is fixed no longer lie on the perpendicular bisectors of the sides of the triangle. Consider, for example, the trench between plates A and B. Because A is not consumed, the trench does not move relative to A. Clearly this condition is also satisfied by any reference frame with a velocity parallel to the plate boundary AB. Such velocities correspond to points on ab, a line through A parallel to the trench AB. The lines bc and ac are constructed in the same way. Unlike the triple junction of three ridges, ab, ac and bc do not intersect at a point unless certain conditions are satisfied. The velocity triangle shows that if bc goes through A, and therefore the plate boundary BC is parallel to ${}_A\mathbf{v}_C$, the junction is stable and fixed to plate A. Another possible stable arrangement occurs if ab and ac are the same line. This requires the boundaries AB and AC to form one straight line. Thus a triple junction between three trenches can be stable. These stability conditions have already been obtained (Fig. 2), but it was difficult to prove that these were the only possible stable junctions by using the previous method. There is another possible junction between three trenches, TTT(b), which has a rather complicated general condition for stability.

The junction between three transform faults is unstable in all circumstances (Fig. 3) because ab, bc and ac can never meet at a point. Though an unstable junction can occur, it immediately changes into one or more stable junctions and is therefore not useful in understanding plate evolution.

A collection of all sixteen possible triple junctions (Fig. 3) shows that all except two are stable in certain conditions which can easily be obtained from the vector velocity diagrams. The most important of these stable junctions are those with two boundaries in a straight line, bounding a plate which is neither being generated nor consumed. Such junctions are easy to form, and do not depend for their stability on the exact values of the relative velocities. The only important exception to this rule is RRR.

There are at least four examples of triple junctions active at present in the north Pacific. Three of these were discussed by D. P. McK. and Parker[3] before the importance of stability was understood, and as a result two of the junctions they describe are unstable. The two junctions concerned are probably both stable at present. Three of the active junctions occur along the west coast of North America, and their evolution demonstrates how complicated the interaction of three plates can be even without any changes in their relative motion. Fig. 4 is taken from Menard and Atwater[15], and shows diagrammatically the magnetic lineations in the north-east Pacific. They point out that there are two striking changes in the trend of both transform faults and of magnetic lineations. The first is between anomalies 23 and 21 throughout the north-east Pacific north of the Pioneer fracture zone, and is best explained by a change in the motion direction of one of the plates. Most probably the plate between the Main Pacific plate and the American plate was the one involved. This plate is called the Farallon plate throughout the rest of this discussion, after the Farallon Islands off the coast of central California. The second change in trend occurs at anomaly 10 near San Francisco, but not until after anomaly 5 north of the Mendocino. It is thus not possible to produce this change by a change in the motion of any of the plates at a given time. Such apparent changes in spreading direction are, however, easily explained by the evolution of the triple junctions formed at the time of anomaly 10.

The main features of the north-eastern Pacific before the time anomaly 10 was formed have now largely vanished. Except near the Gorda and Juan da Fuca ridges, and south of Baja California, only one half of the anomaly pattern remains. Thus there must have been a trench between the ridge and the coast of North America which consumed the Farallon plate with its anomalies. This trench must have existed as a continuous feature up to about the time of anomaly 10, or the Middle Oligocene. Fig. 5a shows the arrangement of plates at about the time of anomaly 13. If we assume that all relative plate motions remain constant from the time of anomaly 13 onwards we can deduce the motion of all the junctions relative to any plate. In Fig. 5 all fracture zones except the Mendocino and the Murray have been omitted. The offsets in the ridge show that it will first meet the trench just south of the Mendocino fracture zone to form two triple junctions, FFT in the north and RTF(a) in the south (Fig. 5b). Fig. 5c shows that the first of these is stable if the transform fault between A and C and the trench between A and D lie in a straight line. The triple junction is then at rest relative to C, and therefore J moves north-westward relative to A, changing the trench into a transform fault. Similarly the second junction is stable if the trench and the transform fault are in a straight line (Fig. 5d). Clearly this junction can move

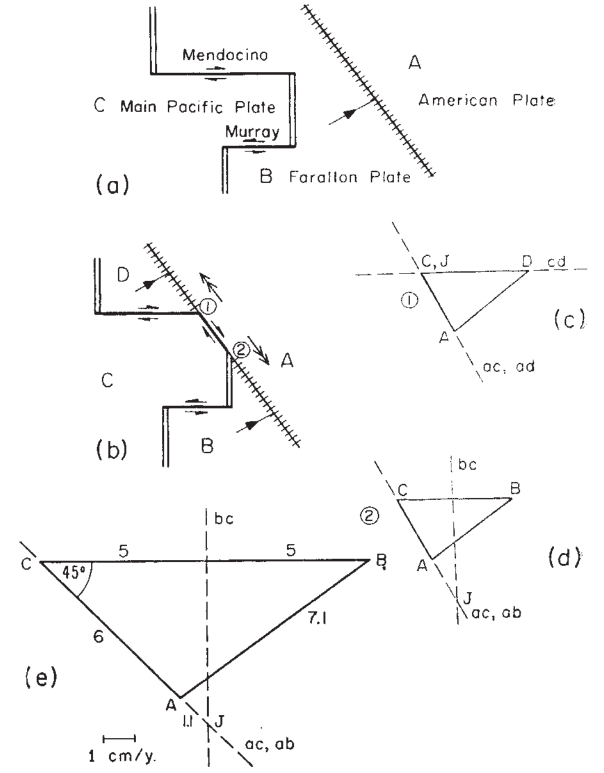

Fig. 5. (a) The geometry of the north-east Pacific at about the time of anomaly 13. All fracture zones except the Mendocino and the Murray have been omitted for simplicity. (b) Stable triple junctions at about the time of anomaly 9, formed when the east Pacific met the trench off western North America. The double headed arrows show the motion of the two junctions (1) and (2) relative to the American plate A. (c) is a sketch of the vector velocity diagram for junction (1) and shows it will move north-west with the Main Pacific plate. (d) is a similar diagram for (2). If the relative plate motions have not changed since at least the Middle Oligocene, the magnetic lineations and the present motion on the San Andreas may be used to draw the velocity diagrams to scale. (e) is such a drawing of (d), and shows that the triple junction J will slowly move to the south-east relative to A. The numbers are in cm/yr and the vector AB shows the direction and rate of consumption of the Farallon plate by the American.

north-west or south-east relative to A, depending on the magnitude and direction of the relative velocities. Unless bc lies to the east of A in Fig. 5d, however, the ridge axis will move away from the trench, and they could never have met. Thus J lies to the south-east of A, and the junction will move down the boundary of A. This southward migration stops when the junction RTF(a) reaches the Murray fault (Fig. 6a) where it must change to FFT and move rapidly north-westward relative to the American plate, for it must then be fixed to C (Fig. 6b). The stability condition is again that the trench and transform fault between A and C form a straight line. The north-west motion then regenerates the trench on the western margin. During this period (Fig. 6b) the trench along the west coast continues to consume the two remaining pieces of the Farallon plate except between the Mendocino and the Murray faults. Thus whether or not the oceanic transform faults possess continental extensions they can influence the tectonics of the continental margin. The geometry of the plate boundaries in Fig. 6b changes back to Fig. 5b when the ridge south of the Murray migrates east to meet the trench. The resulting triple junction RTF(a) then continues the earlier slow movement to the south-east relative to the American plate.

The stability of all the junctions on the west coast of North America depends on the trench which was originally on the west coast being parallel to the slip vector between the American and the Main Pacific plates. Fig. 3 of D. P. McK. and Parker[3] clearly shows that this condition would have been satisfied by a trench along the continental margin, and is still satisfied by the northern part of the Central American trench. This curious and important coincidence is not easily explained.

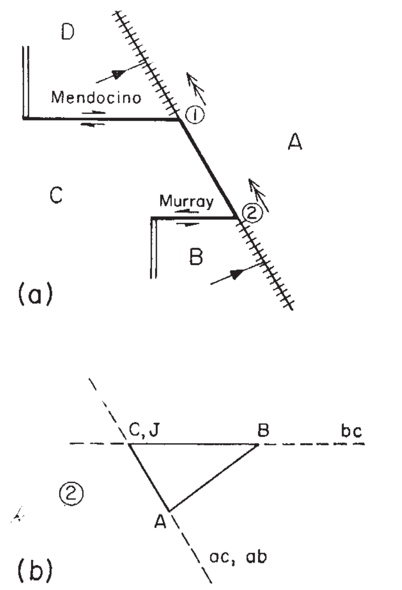

Fig. 6. When the southern junction (2) in Fig. 5*b* reaches the Murray, the right lateral offset of the ridge must change it from *RTF*(a) to *FFT*, and also cause the junction to move north-west, because it is then fixed to plate *C*. (*b*) gives the velocity triangle for junction (2) in (*a*).

The complex series of events described is the inescapable consequence of the motion of rigid plates whose relative velocity remains constant. The geological history of the west coast of America and of the surrounding sea floor since the Cretaceous is in general compatible with the evolution of the plates and triple junctions outlined here. The magnetic lineations off the west coast[15,22,27–31] show that the Farallon plate remained intact until the ridge first met the trench at the timeof anomaly 10 (Figs. 4 and 7) or in the Middle Oligocene[32,33]. As expected, the anomalies to the north and south show no change in spreading direction at this time. To the south the anomalies in contact with the continental margin become progressively younger to the present active ridge axis at the mouth of the Gulf of California, with probably a short interruption in the steady progression at the Murray fracture zone. If the motion of the Main Pacific and American plates has remained unchanged since at least the Oligocene, it is possible to determine the relative velocities of all three plates and their associated triple junctions. The relative velocity between the main Pacific plate and the Farallon may be obtained from magnetic lineations older than anomaly 10[15,32,33], and is 5·0 cm/yr half rate. The fracture zones show that the ridge was at right angles to the east–west relative motion, shown to scale as *BC* in Fig. 5*e*. The present motion between the Main Pacific and American plates is close to 6 cm/yr[4,7,15], with the slip vector parallel to the San Andreas. This vector is shown as *AC* in Fig. 5*e*. The motion of the Farallon plate towards the American plate is then found to be 7 cm/yr. The motion vector is almost at right angles to the trench *ab*, with a small left-handed component of 1 cm/yr. This consumption rate is similar to that of the eastern end of the Aleutian arc.

Fig. 5*e* also determines the relative motion of both triple junctions with respect to all plates. The southern junction (Fig. 5*d*) moves south-east with a velocity of 1·1 cm/yr relative to the American plate, whereas the northern junction moves north-west with a velocity of 6 cm/yr. The length of the strike slip fault between these junctions therefore increases at 7·1 cm/yr, and if the junctions first formed in the Oligocene 32 million years ago, they should now be 2,270 km apart. This estimate agrees remarkably well with the observed separation of about 2,300 km between the triple junctions at Cape Mendocino and at the mouth of the Gulf of California. This simple calculation is successful because the right handed offset on the Murray fracture zone is almost the same as the left-handed offset on the Molokai[31]. Thus the effective velocity of the southern junction has been constant since the time it was formed.

The success of this calculation supports the original assumption that the relative velocities of the major plates have remained unchanged during the Tertiary. It also suggests that the point at which the ridge first met the trench was at the southern end of Baja California, about 350 km north-west of where the southern triple junction is now. It is difficult to understand how the right lateral motion on the San Andreas and related faults can have begun on a large scale before the Oligocene[34], for the small strike slip motion on the trench was left lateral. This evolution of the west coast also suggests that a considerable part of the Franciscan may have been removed from Baja California, where it exists only as isolated outcrops, and added to that of the Coast Ranges.

These observations agree well with the evolutionary outline. In detail, however, the history is much more complicated, principally because the Farallon plate did not remain intact during the events described, nor did the resulting pieces continue to move in the same directions, for the Farallon plate was moving before the time of anomaly 10. One such break is apparent in Fig. 7, which shows the lineations off central California[29]. If the Murray was active only between ridge crests during the period shown by Fig. 5*b*, then the spreading rate to the

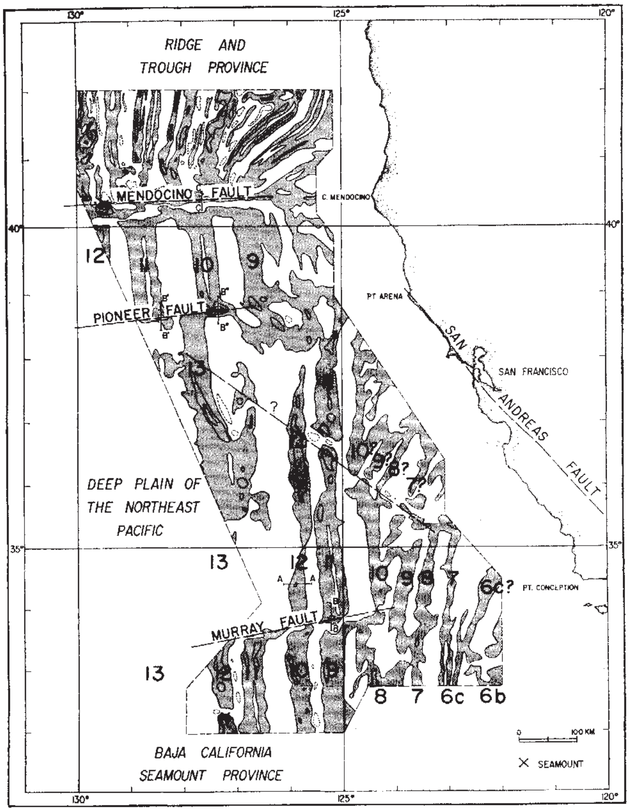

Fig. 7. Magnetic lineations off central California[29]. The identification of anomalies followed by a question mark is somewhat in doubt.

north must be the same as that to the south. The fracture zone must then offset each anomaly by the same distance. This is true for anomalies 10 to 12 inclusive, but not for those which are perhaps 8 and 9. Thus some fault to the east became active as a left lateral ridge trench transform fault (Fig. 8). This fault may well have been the eastward extension of the Murray, though it is not possible to prove this from the remaining magnetic anomalies. This activity east of the ridge started at the time of anomaly 10, or the same time as the ridge first met the trench south of the Pioneer. This behaviour is very similar to the present activity in the mouth of the Gulf of California, where the extension of the east Pacific rise is in the process of changing strike[27], and in so doing has broken a small plate containing Las Tres Marias islands from the Cocos plate to the south[11]. Because the spreading rate to the north of the Murray was less than that to the south, the offset decreased after anomaly 10 was formed, and may have vanished by the time the ridge to the south reached the trench. Thus the geometry in Fig. 6*a* may well never have existed in this area.

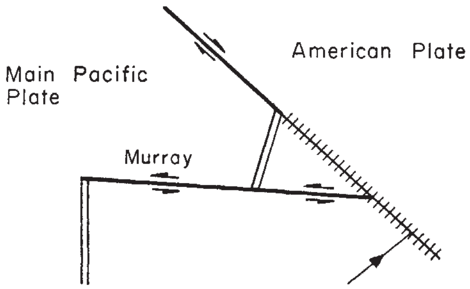

Fig. 8. The geometry of the plates at about the time of anomaly 8. The magnetic lineations in Fig. 7 show that the plate to the east of the ridge axis broke into at least two parts, and the simplest explanation is that the eastward continuation of the Murray fault became active.

The land geology is at least as complicated as that of the ocean floor, but is less complete because the stratigraphy and tectonics have to be painstakingly reconstructed from careful observations[3–36], and cannot be obtained simply by towing a magnetometer behind an aeroplane or ship. It is tempting to identify the transform fault between plates A and C in Figs. 5 and 6 with the San Andreas. There is, however, an important objection to such a choice. If, as seems likely from palaeomagnetic and other evidence, the motion of the American plate relative to the Main Pacific plate has remained approximately unchanged at 6 cm/yr since anomaly 10 time or for the last 32 million years[32,33], then the total displacement between the plates since their first contact must be about 2,000 km. The largest postulated displacement on the San Andreas since the Oligocene is about 350 km[34], and therefore the remainder must have been taken up on other faults. Some of these are offshore, and formed a series of transform faults joined by ridges south-west of San Francisco. The youngest of the anomalies produced by these ridges which is visible in Fig. 7 is probably between 6 and 7. Such movement can therefore account for 500 km and perhaps more, leaving about 1,200 km still unaccounted. Some of this remaining displacement may be on the Nacimiento, and some on offshore faults. It is not, however, possible to use some of this displacement to create the Central Valley by moving the coast ranges away from the Sierra Nevada. Though such movement after the Oligocene could account for a large part of the missing displacement, and is not in conflict with the seismic[37] and magnetic evidence[38,39] for an oceanic basement beneath the sediments, it is not consistent with the presence of large thicknesses of Cretaceous sediment found throughout the Valley[40]. Thus the evolution discussed here is no help in understanding how the Central Valley was formed, nor why it extends from the extension of the Murray to that of the Mendocino. It is particularly difficult to understand the relation of the Valley to the oceanic transform faults if the San Andreas in the coast ranges has a displacement of at least 300 km. Thus the evolution of the triple junctions in Figs. 5 and 6 provides a simplified but probably useful guide to the evolution of the ocean floor off California, but not as yet to that of the land. Perhaps the geology of Baja California will be more revealing.

A different type of triple junction evolution occurs in Japan where the Japan trench divides into the Ryukyu and Bonin arcs[3,21]. Fig. 9 is from Gutenberg and Richter[21] and demonstrates that the deep earthquakes do not follow this division but occur beneath the Bonin arc alone. Along this eastern arc the deep earthquakes occur considerably closer to the trench and island arc than they do farther north beneath the seas of Japan and Okhotsk[41]. This difference is even more marked if the recent more accurate locations of earthquakes are used[42]. These show that the Benioff zone beneath the Bonin arc is not plane but has a steeply inclined part at intermediate depths, with less steeply inclined parts above and below. Farther south beneath the Marianas islands the earthquake zone becomes vertical. In contrast to this remarkable geometry of the deep earthquake zone beneath the eastern branch, that of the western branch is planar and dips at 45°. This difference between the two zones is probably caused by the evolution of the triple junction in central Japan. If the Ryukyu arc were inactive and the Bonin arc were about 200 km east of its present position, the present position of the deep earthquakes would lie on a plane dipping at 45° into the mantle. The Philippine Sea would have been joined to the plate containing America and Kamchatka. Crustal consumption must then have started along the Ryukyu arc, perhaps about 3 million years ago, to form a TTT(a) junction off northern Japan. Such a junction must migrate southwards, carrying the Bonin arc westwards towards its deep earthquake zone.

Though both examples are from the north Pacific, there seems no reason to believe that other regions are essentially different, though they are less well studied. It is therefore expected that stable triple junctions and their evolution will provide an outline of the evolution of many areas, especially oceanic ones. Indeed, many of the examples suggested in Fig. 3 show the effects expected, though few of these have as yet been studied in detail.

Throughout our discussion, velocity, rather than angular velocity triangles, were used. This simplification is justified[3] because the behaviour of a triple junction depends only on the relative motion of the three plates at the point where they meet. A quite different cause of plate evolution does, however, depend on the relative motions being rotations. This type of evolution produces real changes in the relative motion of three plates at a triple junction, and depends on the observation that finite rotations, unlike infinitesimal ones, do not add vectorially. Fig. 10*a* shows such a junction between three plates A, B and C, and the three axes of relative rotations ${}_A\omega_B$, ${}_B\omega_C$ and ${}_C\omega_A$ which satisfy:

$$ {}_A\omega_B + {}_B\omega_C + {}_C\omega_A = 0 \qquad (3) $$

By definition the points a, b and c where these axes intersect the plates B and C are fixed with respect to A and B, B and C, and C and A respectively. If finite rotations of B and C relative to A take place about the axes ${}_A\omega_B$ and ${}_C\omega_A$ and at a rotation rate given by the values of the two vectors, the orientation and magnitude of ${}_B\omega_C$ will remain constant and fixed relative to A, ${}_A\omega_B$ and ${}_C\omega_A$. The original point at which ${}_B\omega_C$ cuts plate C, b, is not, however, fixed to A but to C, which rotates about ${}_C\omega_A$ relative to A. Thus the final position of b after finite rotations of B and C relative to A will not be at the intersection of ${}_B\omega_C$ with C (Fig. 10*b*). Thus it is not possible for all three plates to rotate through finite angles about

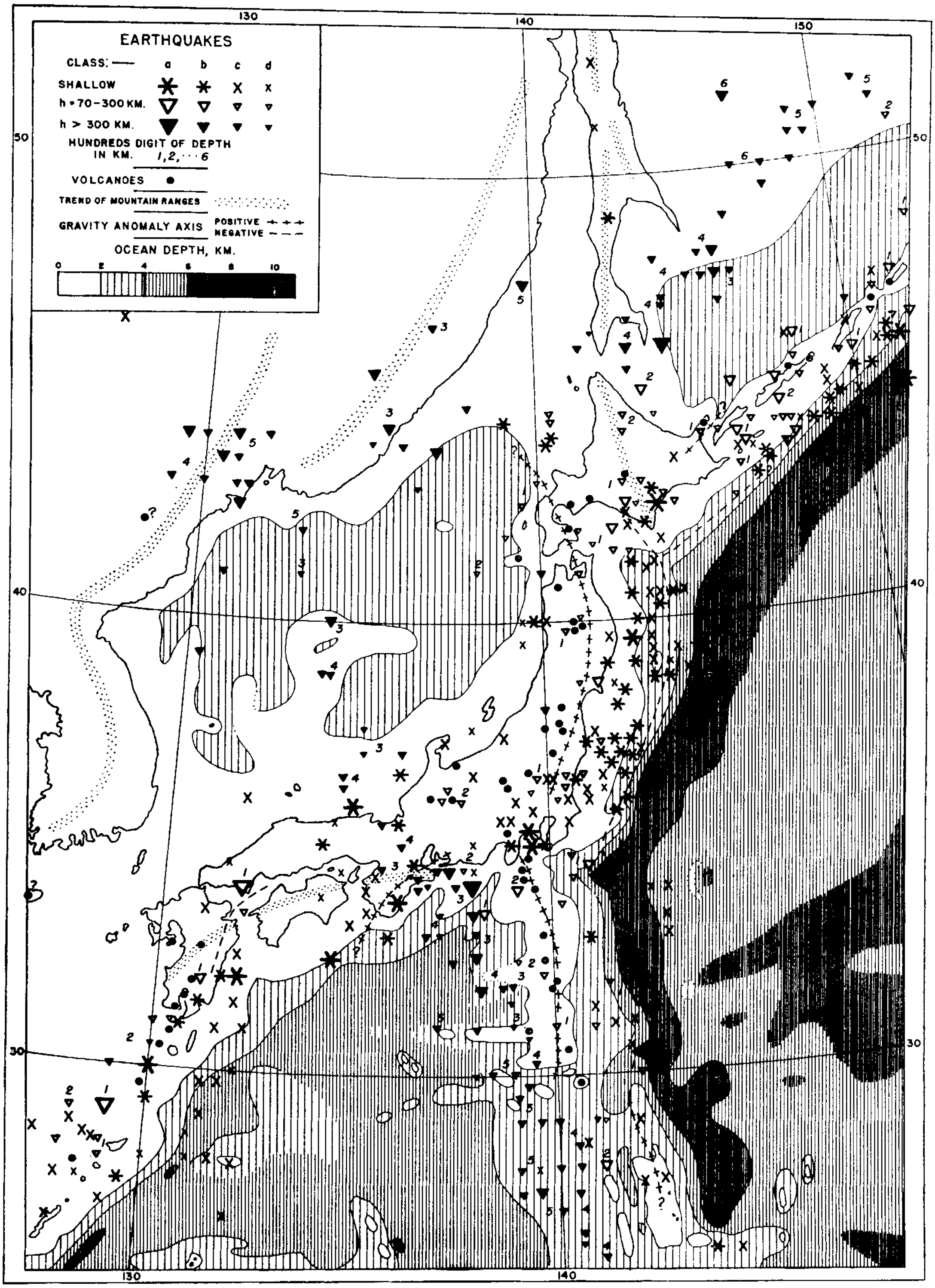

Fig. 9. The seismicity, vulcanism and water depth in the region of Japan[21]. The branching of all surface features in central Japan does not extend to the deep earthquakes, which follow the Bonin and not the Ryukyu arc. The horizontal separation between the deep earthquakes and the arc is less in the region of the Bonin islands than it is in that of the Kuriles.

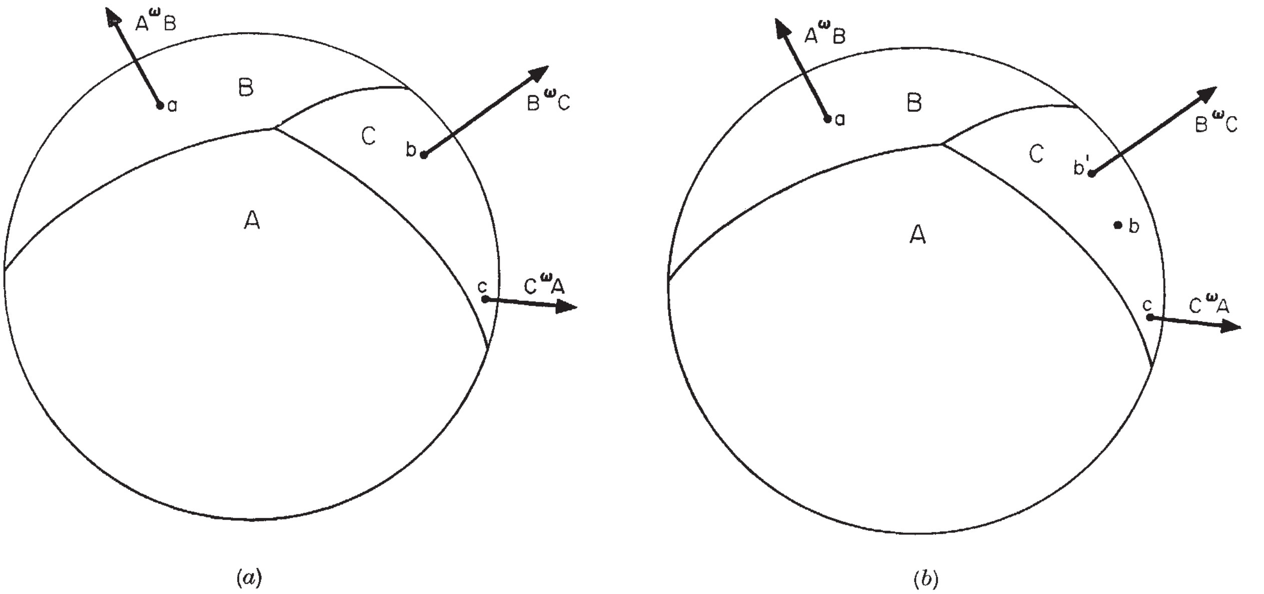

Fig. 10. (*a*) shows the angular velocity vectors of plates forming a triple junction. If $_A\omega_B$ and $_A\omega_C$ are taken to be fixed relative to *A* throughout the evolution, and their magnitudes also remain constant, then by (3) the direction and magnitude of $_B\omega_C$ are constant. The point *b* is fixed to *C* and is the point at which $_B\omega_C$ initially intersects *C*. As *B* and *C* rotate through finite angles with respect to *A* the axis of rotation $_B\omega_C$ moves with respect to both *B* and *C*, and does not continue to pass through the point *b* on *C*. (*b*) shows the geometry after finite rotations.

their instantaneous relative rotation axes. The only special case occurs if all ω vectors lie along the same axis, when finite rotations add as scalars and no changes need take place.

The geometry of plate boundaries suggests that there will be wide variations in their resistance to changes in spreading direction required by Fig. 10*b*. In general, ridges offset by both right and left handed transform faults can change their spreading direction only if one or other of the plates breaks. Such structures will therefore strongly oppose any changes in spreading direction, though not in spreading rate. Ridges with only left handed faults only oppose clockwise changes in the motion direction, because anticlockwise changes can change all transform faults into ridges. The opposite is true of right handed systems. Because the slip vector across trenches is rarely without a strike slip component, and because there seems to be no particular preferred direction of the slip vector relative to the strike of the trench, they probably offer little resistance to a change in the direction or magnitude of the slip vector. Thus the changes in relative motion caused by finite rotations may often be accommodated by the trenches and not by the ridges. There is no obvious method of separating the consequences of finite rotations from the other causes of velocity changes, so it is not known if it is this mechanism which produced the change in relative motion between the Main Pacific plate and the Farallon plate observed by Menard and Atwater[15].

These extensions of plate tectonics are geometric results, and are not concerned with the driving forces. The examples illustrate how a complex series of events can be produced by geometry alone, and also how sea floor spreading and plate tectonics may be used to provide a framework for the understanding of the tectonic evolution of continents and oceans.

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1 Hess, H. H., *Petrological Studies: A Volume in Honor of A. F. Buddington* (edit. by Engel, A. E. J., *et al.*), 590 (Geol. Soc. Amer., 1962).
2 Dietz, R. S., *Nature*, **190**, 854 (1961).
3 McKenzie, D. P., and Parker, R. L., *Nature*, **216**, 1276 (1967).
4 Morgan, W. J., *J. Geophys. Res.*, **73**, 1959 (1968).
5 Le Pichon, X., *J. Geophys. Res.*, **73**, 3661 (1968).
6 Isacks, B., Oliver, J., and Sykes L. R., *J. Geophys., Res.*, **73**, 5855 (1968).
7 Vine, F. J., *Science*, **154**, 1405 (1966).
8 Pitman, W. C., Herron, E. M., and Heirtzler, J. R., *J. Geophys. Res.*, **73**, 2069 (1968).
9 Wilson, J. T., *Nature*, **207**, 343 (1965).
10 Barazangi, M., and Dorman, J., *Bull. Seism. Soc. Amer.*, **59**, 369 (1969).
11 Sykes, L. R., *J. Geophys. Res.*, **72**, 2131 (1967).
12 Brune, J. N., *J. Geophys. Res.*, **73**, 777 (1968).
13 McKenzie, D. P., *Geophys. J.*, **18**, 1 (1969).
14 Hamilton, R. M., and Evison, F. F., *NZ J. Geol. Geophys.*, **10**, 1319 (1967).
15 Menard, H. W., and Atwater, T., *Nature*, **219**, 463 (1968).
16 Laughton, A. S., *Phil. Trans. Roy. Soc.*, *A*, **259**, 150 (1966).
17 Herron, E. M., and Heirtzler, J. R., *Science*, **158**, 775 (1968).
18 Raff, A. D., *J. Geophys. Res.*, **73**, 3699 (1968).
19 Pitman, W. C., and Hayes, D. E., *J. Geophys. Res.*, **73**, 6571 (1968).
20 Vine, F. J., and Hess, H. H., *The Sea* (edit. by Maxwell, A. E., *et al.*), 5 (Interscience, in the press).
21 Gutenberg, B., and Richter, C. F., *Seismicity of the Earth* (Princeton University Press, 1954).
22 Peter, G., *J. Geophys. Res.*, **71**, 5365 (1965).
23 Elvers, D. J., Mattewson, C. C., Kohler, R. E., and Moses, R. L., *Coast and Geodetic Survey Operational Data Report C, GSDR-1* (1967).
24 Matthews, D. H., *Phil. Trans. Roy. Soc.*, *A*, **259**, 172 (1966).
25 Sykes, L. R., *The History of the Earth's Crust* (edit. by Phinney, R. A.) (Princeton University Press, 1968).
26 Morgan, W. J., Vogt, P. R., and Falls, D. E., *Nature*, **222**, 137 (1969).
27 Larson, R. L., Menard, H. W., and Smith, S. M., *Science*, **161**, 781 (1968).
28 Vacquier, V., Raff, A. D., and Warren, R. E., *Bull. Geol. Soc. Amer.*, **72**, 1251 (1961).
29 Mason, R. G., and Raff, A. D., *Bull. Geol. Soc. Amer.*, **72**, 1259 (1961).
30 Raff, A. D., and Mason, R. G., *Bull. Geol. Soc. Amer.*, **72**, 1267 (1961).
31 Raff, A. D., *J. Geophys. Res.*, **71**, 2631 (1966).
32 Heirtzler, J. R., Dickson, G. O., Herron, E. M., Pitman, W. C., and Le Pichon, X., *J. Geophys. Res.*, **73**, 2119 (1968).
33 Maxwell, A. E., *Trans. Amer. Geophys. Union*, **50**, 113 (1969), abstract.
34 Hill, M. L., and Dibblee, T. W., *Bull. Geol. Soc. Amer.*, **64**, 443 (1953).
35 Crowell, J. C., *Geol. Soc. Amer.*, Spec. Pap., **71** (1962).
36 *Proc. Conf. on Geological Problems of San Andreas Fault System* (edit. by Dickinson, W. R., and Grantz, A.), **11** (Stanford Univ., 1968).
37 Bateman, P. C., and Eaton, J. P., *Science*, **158**, 1407 (1967).
38 Grantz, A., and Zietz, I., *US Geol. Survey Prof. Paper* 400-*B*, **158**, *B*342 (1960).
39 Griscom, A., *Geology of Northern California*, *Bull.*, **190**, 407 (Calif. Div. of Mines, 1966).
40 Hackel, O., *Geology of Northern California*, *Bull.*, **190**, 217 (Calif. Div. of Mines, 1966).
41 Uyeda, S., and Vacquier, V., in *The Crust and Upper Mantle of the Pacific Area*, Monog. 12, Amer. Geophys. Union (1968).
42 Katsumata, M., and Sykes, L. R., *Trans. Amer. Geophys. Union*, **50**, 235 (1969).