CHAPTER 9

Plates

9.1 The mechanical lithosphere

In Chapter 8 we considered convection in a fluid medium. However, the earth's mantle behaves as a fluid only in its interior, where the temperature is high. Near the surface, its viscosity is much higher, so that it is effectively rigid much of the time. This is illustrated schematically in Figure 9.1.

However, as we saw in Chapter 6, with sufficient stress the cooler mantle may yield. Close to the surface, this yielding takes the form of brittle fracture. At intermediate depths, the yielding may be more fluid-like but still result in narrow zones of deformation, which geologists call ductile shear zones. At the large scale in which we are interested here, these narrow shear zones still have the characteristics of fractures or faults, and so we may consider the lithosphere at the large scale to be a brittle solid to a first approximation. The usefulness of this approximation is illustrated, for example, by the three kinds of plate margin, which correspond to the three standard types of faults in structural geology: normal (spreading centre), reverse (subduction zone) and strike-slip (transform fault).

The implication of this 'brittle–ductile transition' is that our convecting medium changes from being effectively a viscous fluid at depth to being a brittle solid near the surface. The material of the mantle flows from one regime to the other, and so ultimately we must consider the mantle as a single medium that undergoes radical changes in properties as it flows around. We will approach this task in Chapters 10 and 11, and we will see that there are some important consequences of these changes of properties. First, however, there are some important aspects of each regime that can be understood separately. Thus in Chapter 8 we looked at convection in a

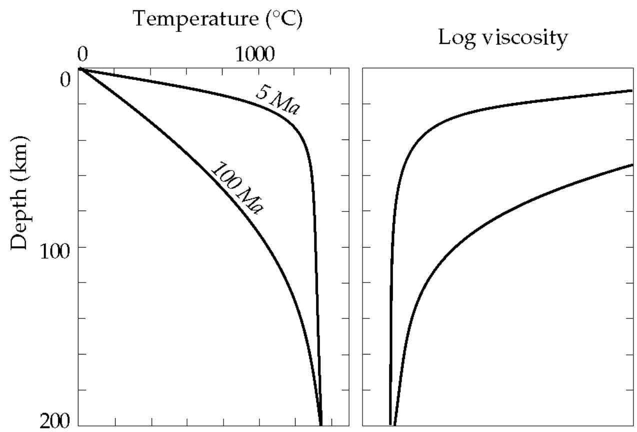

Figure 9.1. Sketch of two oceanic geotherms, ages 5 Ma and 100 Ma, and the corresponding viscosity profiles.

conventional fluid of constant viscosity. In this chapter, we look at some important specific behaviour of the lithosphere that reflects its character as a brittle solid.

We have seen already that it is important sometimes to consider the earth's surface without worrying, for the moment, about what is happening underneath. Thus Wilson's synthesis, in which he defined the plates, was done without reference to mantle convection (Section 3.4), and the description of plate motions in terms of velocity vectors and rotation vectors (Section 3.6.1) was presented in terms of the relative velocities of plates, without reference to any real or conceptual internal frame of reference.

There are two general aspects of the distinctive behaviour of the lithosphere that I want to highlight. One is that the plates, into which the lithosphere is broken, have a range of sizes and rather irregular shapes. These have been illustrated and summarised in Section 4.1. The other aspect is that the geometry of the plates changes in distinctive ways that are not like the ways fluid flow patterns change. The plates evolve steadily, following simple rules, and they may also change suddenly, if a plate breaks into two. These changes are the subject of this chapter.

What we look at in this chapter is the way plates move and change, but not the forces that cause the motions and changes. We are thus considering *kinematics*, the study of motions, as distinct from *dynamics*, the study of the way forces generate motions. Although the term dynamic is often used more loosely in popular parlance to refer to any moving or changing system, this usage is not technically correct. In Chapter 10 we will look at the way the mantle and the plates move in response to buoyancy forces, so there we will be considering dynamics. Similarly, in Chapter 11 we will look at plume dynamics.

I will use the term *plate margin*, rather than *plate boundary*, henceforth. It is useful in order to avoid confusion, since we have been considering internal boundaries in the mantle and thermal boundary layers in convection. Partly out of habit, partly for conciseness, I may use the term *ridge* interchangeably with *spreading centre*. Likewise I may interchange *trench* with *subduction zone*.

9.2 Describing plate motions

At first sight, it may seem that plates will not change much. However, it turns out that plates may grow, shrink, and even disappear without there being any major perturbations to the system, because of the different behaviour of different kinds of plate margin. It also turns out that the way the plates evolve in detail can be rather subtle. On the other hand, much of the time the plates follow a simple set of rules. It is thus possible to deduce fairly precisely how things ought to evolve, and to infer a lot about how the plates have evolved in the past. The rules are simple, but the results can be surprising, so deducing plate evolution sequences requires care in following the rules. This is aided by familiarity with a few ideas and examples, which are the subject of the next few sections.

The objective here is to understand the *kinds* of behaviour that plates exhibit, rather than to present a comprehensive reconstruction of how the plates have evolved. There are many papers on the latter topic. There are also now some lengthier treatments of plate kinematics, in both planar and spherical geometry [1, 2]. More specifically, we look here at the way the plates change their sizes and shapes even when their velocities are approximately constant and no new plate boundaries are forming by the breakup of old plates.

We do not consider in the same detail how new plate margins form, nor what might cause plate velocities to change. These are important questions, but they are not very well understood. This may be surprising, but an important reason is that these processes are not very well constrained by observations. Some important aspects can still be understood in spite of our ignorance of these processes.

The ways that certain parts of the plate system have evolved will be used later to illustrate the kinds of evolution that can be deduced from the rules of plate motion. First, those rules and some of their consequences will be presented.

9.3 Rules of plate motion on a plane

Most of the ideas I want to convey here can be illustrated in planar geometry, rather than spherical geometry. Planar geometry is much more familiar to most people, and it is easier to draw. Later I will briefly outline how plate motions work on a sphere, emphasising mainly the points that are relevant to mantle convection. Others have described the details of spherical plate kinematics [1, 2].

9.3.1 Three margins

Even when plate velocities are constant and no new plate margins are forming, the sizes and shapes of plates can change. The motions of plate margins, and the consequent evolution of plates, can be deduced from remarkably few rules. These are that the plates are rigid, and that plate margins behave as follows.

1. Spreading is symmetric at spreading centres. Equal amounts of new material attach to each of the plates that meet at a spreading centre.
2. Subduction is completely asymmetric. Material is removed from only one of the two plates that meet at a trench.
3. The relative motion of plates that meet at a transform fault is parallel to the transform fault.

The symmetry of spreading centres is an empirical rule based on the observed symmetry of magnetic stripes (Figure 3.5). It presumably comes about as follows. Suppose new oceanic crust is formed by the injection of a vertical dike of new magma (Figure 9.2). This will be hotter than its solidified surroundings, and will lose heat through its sides. If, some time later, horizontal tension has accumulated normal to the dike it will be pulled apart and new magma may intrude. If the dike has cooled symmetrically to the sides, it will be hottest and weakest at its centre. Therefore it will

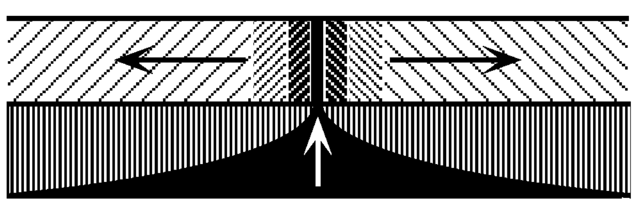

Figure 9.2. Sketch cross-section of a midocean ridge spreading centre showing the symmetric addition of crust (diagonal patterns) to each plate. Compare with the map view of Figure 3.4.

split down the centre and equal parts of it will become attached to the two plates that are pulling apart at the spreading centre.

Not all spreading is symmetric. There are some segments of spreading centres that spread asymmetrically, at least for a time, an example of which occurs on the Australian–Antarctic ridge [3]. There is evidence also that spreading centres may behave asymmetrically on short time scales. A reasonable guideline is that most spreading centres behave symmetrically most of the time at the scale resolved by the magnetic stripes. Another common feature of spreading centres is that they are oriented perpendicular to the direction of spreading. However they do sometimes deviate from this, for example south of Iceland. It is not necessary to state it as a basic rule here.

Asymmetry of subduction implies that the trench (i.e. the surface trace of the subduction zone fault) moves with the overriding (non-subducting) plate, since none of the overriding plate is removed. This rule also is to some degree empirical, and it may not always be strictly true. It is possible that some of the overriding plate is removed and carried down by the subducting plate, or that material is scraped off the subducting plate and attached to the overriding plate. This commonly happens with sediments scraped off the subducting plate. However, the resulting accretionary wedge of sediment is usually a superficial feature. Asymmetric subduction is certainly a good approximation.

9.3.2 Relative velocity vectors

Figure 9.3 depicts four different spreading centres. They are shown with different velocity vectors, but they differ only in the way the velocities are measured, each being measured from a different reference. In Figure 9.3a, the velocity of plate B is measured relative to plate A, as though you were sitting on plate A watching plate B move away from you. The others are, respectively, relative to the spreading centre (9.3b), relative to plate B (9.3c), and relative to a

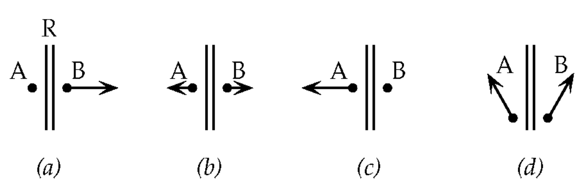

Figure 9.3. Different cases of two plates spreading from a ridge in which velocities are measured from different references. The plates have the same relative velocities in all four cases.

point moving 'south' along the ridge (9.3d) (taking north to be towards the top of the diagrams, here and subsequently).

The velocity of plate B *relative* to plate A is the velocity B would appear to have if you were moving with plate A. It is given by the vector velocity of B minus the vector velocity of A. This quantity is the same in all four cases. This is made more explicit in Figure 9.4a, which shows the velocities from Figure 9.3 plotted in terms of their components north (v_N) and east (v_E). In each case the *relative* velocity vector, represented by the line joining A and B in the velocity plot, is the same. The only difference between the four cases is the position of the line AB relative to the origin, which is determined by the frame of reference we happen to have chosen.

Since the origin is arbitrary, we can leave it out, and plot just the relative velocities of the plates. This is done in Figure 9.4b, and the result is called the *relative velocity diagram* for all of the cases shown in Figure 9.3. Included in Figure 9.4b is a point R. This represents the relative velocity of the ridge. Symmetry of spreading implies that the velocities of the two plates relative to the ridge are equal and opposite. In other words, the ridge velocity point is midway between the plate velocity points, and the ridge velocity is the vector *average* of the velocities of the plates that meet at the ridge.

Since the ridge is actually a line (presumed straight here), only ridge velocities normal to itself make sense. For an infinitely long ridge, an arbitrary velocity parallel to itself could be added without making any difference. In reality ridges often have distinguishing features along them, such as a transform offset, which removes this ambiguity. However, for limited periods and lengths, this ambiguity in ridge velocity needs to be borne in mind, as you will see later. In that case, the R point in the velocity diagram could lie anywhere

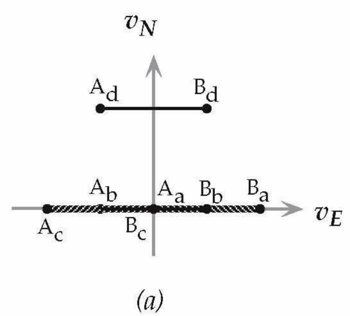

Figure 9.4. (a) Plots of the velocities of the plates for each case in Figure 9.3. (b) The same velocities referred internally to each other, rather than to an external origin.

along the dashed line, which is drawn through R and parallel to the ridge direction (usually, but not necessarily, perpendicular to the spreading direction).

Examples of trenches and their corresponding velocity diagrams are shown in Figure 9.5. The standard map symbol for a reverse fault is used to denote a trench, the 'teeth' being on the side of the overriding plate. Trenches are usually not straight, either being island arcs or taking the shape of a continental margin. The trenches in Figure 9.5 are drawn as though they are island arcs, with the appropriate sense of curvature.

Although plate B is located to the east of plate A, its velocity point is to the west of A's point in the velocity diagram, because it is moving west relative to A. According to rule 2, above, the trench moves with the overriding plate, so the trench velocity can also be represented on the velocity diagram. However, it is different in the two cases shown in Figure 9.5: it moves with plate A in case (a), and with plate B in case (b).

These simple ideas can be extended to include more than two plates, and velocities in any direction in the plane. You will see that the velocity diagram, which may look trivially simple so far, is a powerful way to keep track of plate evolutions.

9.3.3 Plate margin migration

Even with constant plate velocities, plate configurations can change. This is because only in special cases will ridges and trenches be stationary relative to each other. The reason is that spreading is symmetric and subduction is asymmetric. This means that inter-

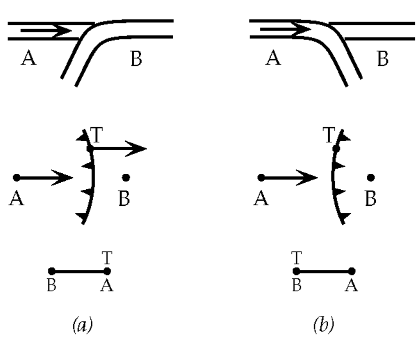

Figure 9.5. Relative velocities at a trench. The two possible trench polarities are shown (a, b), depending on which plate is being consumed. In each case, the top panel shows a cross-section, the middle panel shows a map view, and the bottom panel shows the velocity diagram.

vening plates will usually grow and shrink, and shrinking plates can disappear.

This can be illustrated most simply with three plates whose velocities have no northerly component. Figure 9.6 shows several situations in which plates have the same instantaneous (snapshot) configuration, but different velocities. The different velocities give rise to different evolution. In all cases the velocities are shown relative to plate C (and the trench). A velocity diagram is included with each case. Comparing the first three, you can see that in case (a) the ridge is moving west relative to C and so plate B is growing, in case (b) the ridge is stationary and the size of plate B is not changing, whereas in case (c) the ridge is moving east, towards the trench, and plate B is shrinking. In each case the plates are moving in the same *directions*, all that is different is the *magnitudes* of the velocities. In fact if you study the velocity diagrams you can see that the difference can just as well be regarded as a difference in the velocity of plate C relative to the others.

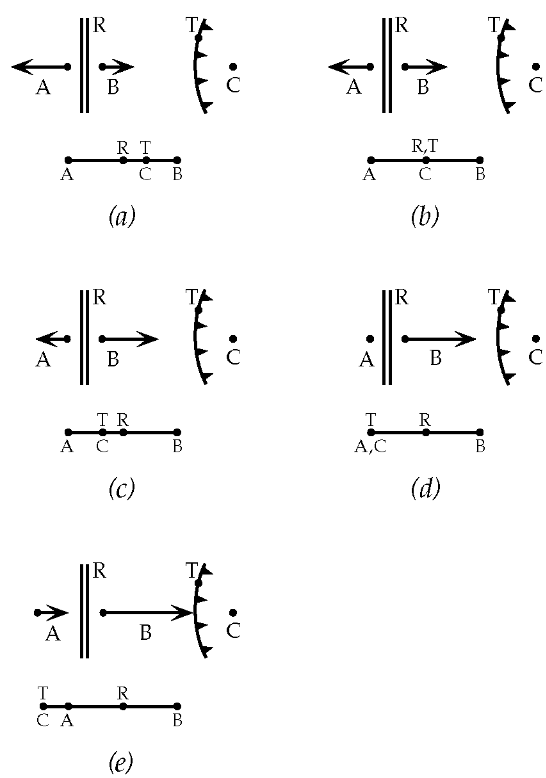

Figure 9.6. Different relative motions of ridges and trenches.

Now compare cases (c–e). In each of these cases, plate B is shrinking. The differences are in the direction of plate A relative to C. The difference does not become important until plate B shrinks to zero. At that point, plates A and C come into contact, forming a new plate margin between them. The nature of the new margin and the subsequent evolution of the system then depends on the relative velocities of A and C. In case (c), plate A is moving away from C, in which case the new margin between them will be a ridge, and this ridge will move west, so plate C will begin to grow. In case (d), plate A is stationary relative to C, so they will form a single plate when they come into contact. In case (e), plate A is moving towards C, which means the new margin between them will be a trench. The subsequent evolution will then depend on the polarity of the new trench. If it is the same as before, then A will subduct under C, following plate B into the mantle.

Examples of several of these situations can be inferred from the record of the seafloor magnetic stripes. The Phoenix plate used to subduct under Antarctica, until it disappeared and the Pacific and Antarctic plates came into contact. Now the Pacific–Antarctic ridge migrates slowly away from Antarctica, as predicted in case (c). Case (d) resembles the former situation off western North America, where the former Farallon plate has disappeared, except that the new margin, the San Andreas fault, between the Pacific and North American plates, has a strike-slip component because of the relative northward motion of the Pacific plate. Case (e) is similar to the North Pacific, where the Kula plate used to subduct under the Aleutian Islands, but now the Pacific plate subducts after it. More examples like these will be presented later.

9.3.4 Plate evolution sequences

Although you can deduce from the velocity diagrams in Figure 9.6 that the ridge in cases (c–e) will migrate towards the trench, it is not obvious at first sight exactly how this will proceed. It is useful to draw a *sequence* of sketches in order to clarify this. A simple sequence showing the development of a spreading ridge was shown in Figure 3.4. Another sequence, that illustrates the way in which case (d) of Figure 9.6 develops, is shown in Figure 9.7.

The approach is as follows. To generate the next diagram in a sequence, draw each plate with its *old margins* in their *new positions* relative to the other plates. Thus the old margin *a* does not move, because A is not moving. The old margin *b* moves to the east. The trench does not move. This will generate gaps or overlaps with neighbouring plates. A gap should be filled by drawing a ridge in

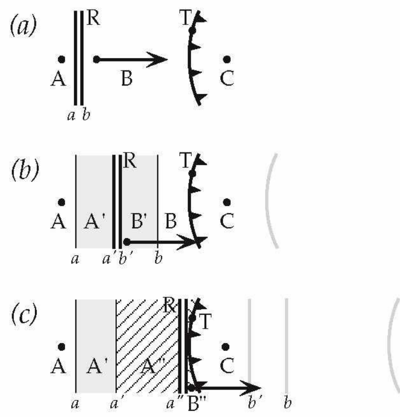

Figure 9.7. A plate evolution sequence showing the development with time of case (d) of Figure 9.6. The grey lines are former features on plate B that have been overridden by plate C.

the middle (if the spreading is symmetric). Each side of the new ridge (a' and b') represents the new margin of the plate that adjoins it. Shade the space between this plate's new margin and its old margin: this is new crust added to this plate (A$'$ and B$'$). Overlap should be eliminated by removing the overlapping area from one or other of the overlapping plates, depending on the polarity of the trench at which they meet (B is subducting under C, so part of B is removed). This procedure defines the new positions of the plate margins, according to the rules of how plate margins evolve.

In the last frame, plate B has almost disappeared. As it disappears, plate A comes in contact with plate C. Since, in this example, plate A is stationary relative to plate C, the new margin will be inactive. Of course this is a very special case: in the real world you would expect plates A and C to have some relative motion, and to form the appropriate kind of new margin between them.

This sequence assumes that there is no change in the velocity of B as it disappears. This may not happen in reality, but the point here is to illustrate the kinds of changes that can occur even without any change in plate velocities. Also it is best not to think of the ridge as being subducted. Plate B is subducted (removed), but the consequence of plate A contacting plate C is that the two old margins (ridge and trench) *coalesce to form a new margin*. Again it is better to focus on the surface features, rather than on what might be happening under the surface.

Another plate evolution sequence, in Figure 9.8, illustrates how a ridge with a transform fault offset evolves. This example is like part of the central Mid-Atlantic Ridge illustrated in Figure 3.6.

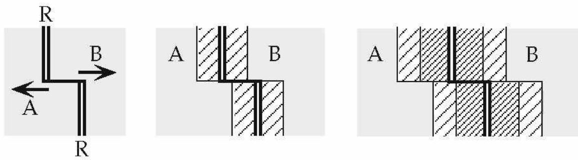

Figure 9.8. Sequence showing the evolution of a ridge with a transform fault offsetting it.

Transform fault margins translate parallel to themselves. The parts of the fault that connect ridge crest segments are shown here as heavy solid lines, indicating that they are active faults. The parts that are beyond ridge crests are shown as light lines, denoting that they are extinct faults across which there is no longer any relative motion. If the changes in shading corresponded to magnetic field reversals, then the pattern generated would represent magnetic anomaly stripes. This example shows how a transform offset of a ridge results in the magnetic anomaly pattern also being offset.

9.3.5 Triple junctions

Figure 9.9 depicts a sequence involving three plates separated by ridges. Points where three plates, and three plate margins, meet are called triple junctions. In this case the benefits of the procedure for constructing sequences just described, and of velocity diagrams, are more evident. A new feature occurs in this example, in the vicinity of the triple junction: after the old margins of B and C are displaced to their new positions, the new ridge segments need to be longer in order that they all meet again. Comparing (a) and (b), there is a triangular area (*abc*) around the triple junction that is the same

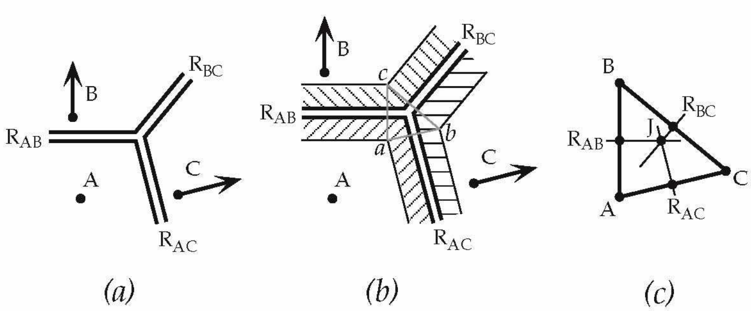

Figure 9.9. (a) and (b) Evolution of a ridge–ridge–ridge (RRR) triple junction. (c) Velocity diagram showing the three plate velocities, the three ridge velocities and the triple junction velocity (J). The ridges must lengthen into the triangle (*abc*) in (b).

shape as the velocity triangle (c), and the ridges must be extended into this region. On the velocity triangle (c), the ridge velocities are included, as light lines parallel to the corresponding ridge. They meet at a point that defines the velocity of the triple junction (J). Since these lines bisect the sides of the triangle (for symmetric spreading) the triple junction point is the *circumcentre* of the triangle (so-called because it is the centre of a circle that passes through the vertices of the triangle, that is it circumscribes the triangle). It is observed that junctions of three ridges really do work this way.

Important features can be read off the velocity diagram. For example, the triple junction point J is to the right of the line AB, which corresponds to the fact that the triple junction is moving east relative to A and B, and the ridge R_{AB} is getting longer. Since B is moving north relative to A and C is moving ENE, the relative motion of B and C is determined by vector addition. The ridge segment R_{BC} is perpendicular to this velocity vector.

If the new, shaded material on plate A is interpreted as a magnetic anomaly, you can see that it changes direction near the triple junction. 'Bent' magnetic stripes like this are observed in the Pacific, and can be seen in Figure 9.10, near the Aleutian Islands in the north-west part of the map. They are inferred to have been formed near a triple junction, but this implies that there were two additional plates that are no longer present. The eastern one, analogous to plate C in Figure 9.9, is called the Farallon plate and the northern one is called the Kula plate. A reconstructed evolutionary sequence of the plates in the north-east Pacific is shown in Figure 9.11. The inferred triple junction between the Pacific, Farallon and Kula plates can be seen at the 80 Ma, 65 Ma and 56 Ma stages.

Other types of triple junction are possible. Figure 9.12 shows a ridge–transform system that has migrated into a trench, in the manner of Figure 9.7, and created two triple junctions. At the northern triple junction, J_N, two transform faults and a trench meet, whereas at the other (J_S) a ridge, a trench and a transform meet. It is useful to denote the type of triple junction by the types of plate margin involved. Denoting a ridge by R, a trench by T and a transform fault by F, J_N can be denoted an FFT triple junction, whereas J_S is RFT. The triple junction of Figure 9.9 is RRR.

The example in Figure 9.12 is comparable to the evolution of the plates along the western margin of North America. Comparing with Figure 9.11A, we can see that plate A is analogous to the Pacific plate and plate D is analogous to the North American plate. Plate B is analogous to the small Juan de Fuca plate off Oregon and Washington states, and plate C is analogous to the Cocos plate off Central America. The transform fault contact

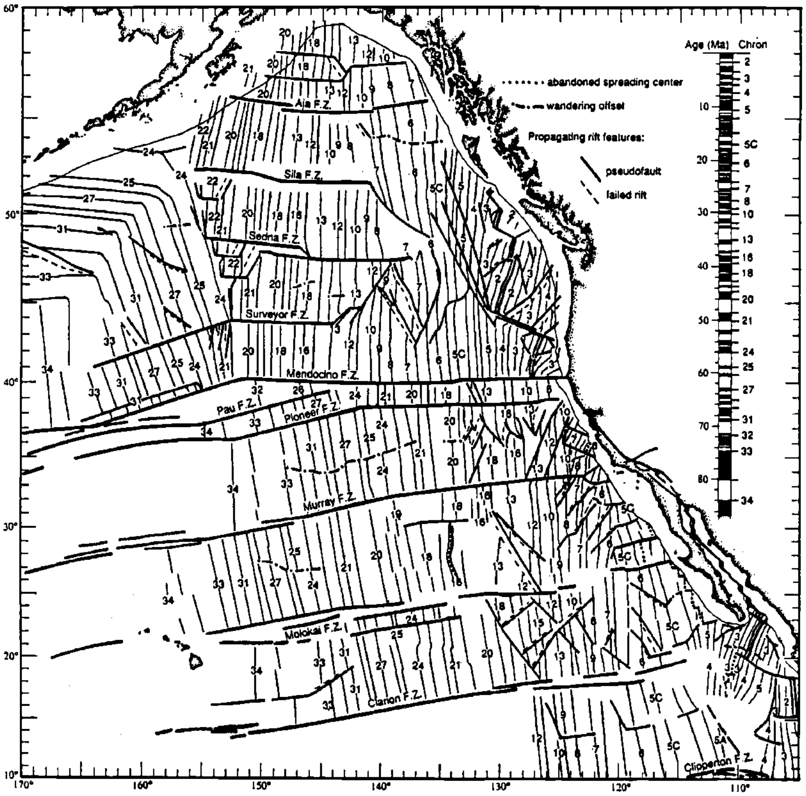

Figure 9.10. Magnetic anomalies that have been mapped in the north-east Pacific. The magnetic anomalies are the predominantly north–south lines, labelled with an identifying sequence number (which is not their age). This rather complex map also shows fracture zones and other features that interrupt the anomaly patterns. From Atwater and Severinghaus [4].

between A and D is analogous to the San Andreas fault system in California. The Juan de Fuca plate and the Cocos plate are fragments of the large Farallon plate (Figure 9.11) that used to exist between the Pacific and North American plates. The fragmentation of the Farallon plate can be seen in Figure 9.11 at the 56 Ma, 37 Ma and present stages.

It is possible to imagine all combinations of ridge, trench and transform fault meeting at a triple junction, but it turns out that some combinations can only be instantaneous juxtapositions, and they will immediately evolve into a different configuration. An example of such an ‘unstable’ triple junction is shown in Figure 9.13a. Because each part of the trench moves with a different plate, they are soon separated, as is illustrated in Figure 9.13b. There is then still a triple junction, and it is still of the TTF type, but its

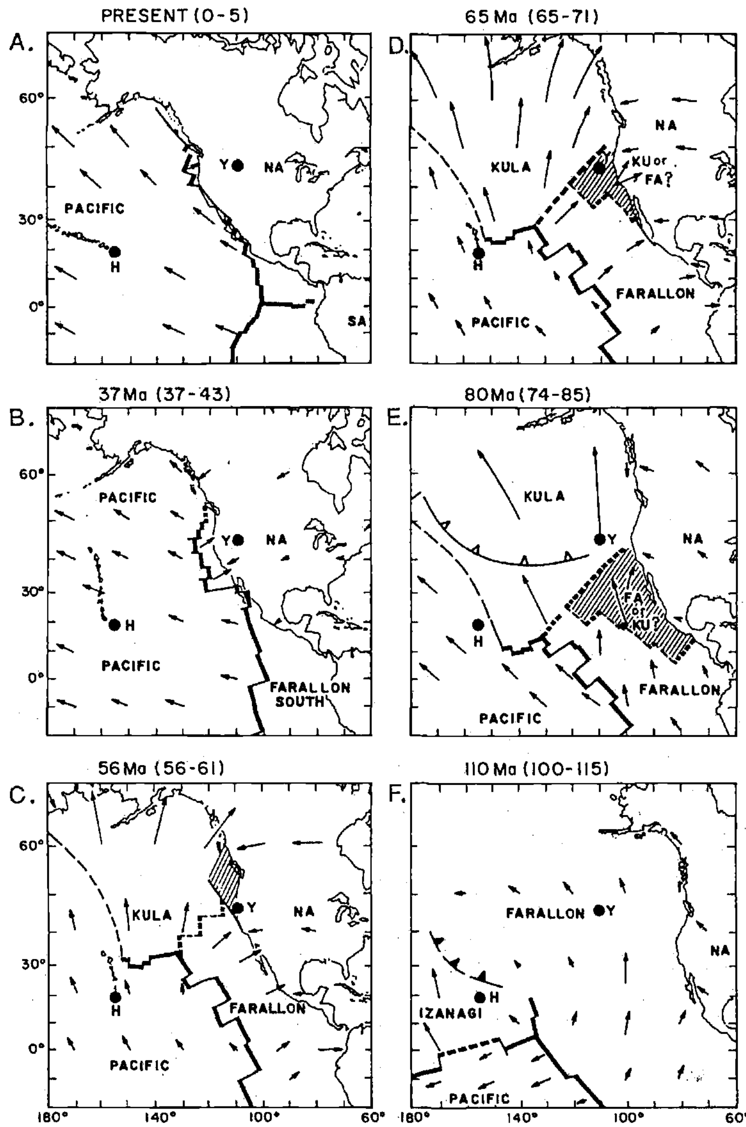

Figure 9.11. Reconstructed evolutionary sequence of plates in the north-east Pacific. From Atwater [5].

arms are now reoriented into a configuration that is 'stable', that is it can persist for a finite time. This example is taken from Central America, where the Managua fault, separating the Caribbean and North American plates, cuts through Nicaragua and joins the Central America trench.

The motions of the triple junctions in Figures 9.12 and 9.13 can also be represented in a velocity diagram using the concepts already

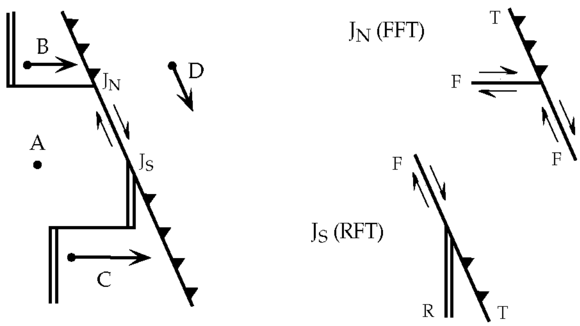

Figure 9.12. Triple junctions, J_N and J_S, created when a ridge–transform system is overridden by a trench.

outlined. However, you will have to add transform faults to your velocity diagram repertoire and bear in mind that subduction is often oblique. Subduction and transform margins can be represented on velocity diagrams by lines that are parallel to the corresponding margin, as we have already seen for ridges (Figure 9.9). A good exercise is to construct a velocity diagram including all the plates, margins and triple junctions of Figure 9.12.

9.4 Rules on a sphere

So far we have considered only plate motions on a plane, but of course the earth is not flat. The concepts we have developed so far all transfer to a spherical surface, but there are some modifications and additions for the case of a sphere. We will only note some of the important points here. A comprehensive treatment of plate tectonics on a sphere is given by Cox and Hart [1].

Euler's theorem states that any displacement of a spherical cap on a sphere can be represented as a single rotation about an axis through the centre of the sphere. Since the displacement can be taken to be relative to another spherical cap, it applies also to

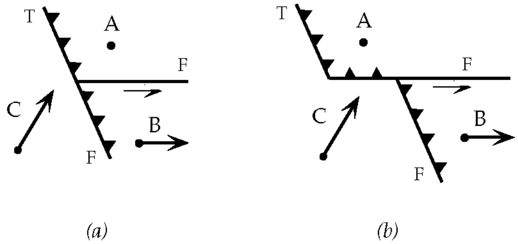

Figure 9.13. An example of an unstable triple junction (a), that immediately evolves into a different configuration (b).

the relative motions of plates. The intersection of the axis of rotation with the sphere is called the pole of (relative) rotation, or, following Menard [6], the Euler pole. The ambiguity of having two poles can be eliminated by choosing the pole for which the rotation is right-handed. The axis of rotation and the rate of rotation can be combined to define an angular velocity vector that describes the instantaneous relative motion of two plates.

There is a complication in spherical geometry that does not occur in planar geometry. Whereas infinitesimal rotation vectors add and commute, finite rotations do not. This can be seen by rotating a point from the north pole to 0 °E on the equator, followed by a rotation from 0 °E to 90 °E on the equator. Reversing the order of the two rotations does not yield the same result. Likewise taking the sum of the two rotation vectors and applying the resulting rotation does not accomplish the same result. For this reason only infinitesimal or small rotations can be treated by normal vector algebra.

A consequence of Euler's theorem is that transform faults should follow small circles centred on the Euler pole of the plates that meet at the fault. A planar version of this relationship is shown in Figure 9.14 (rotations are of course also possible in planar geometry, we just hadn't considered any until now). The fracture zones formed by transform faults will also follow small circles for as long as the Euler angular velocity vector of the two plates is constant. A consequence is that the normals to fracture zones and transform faults intersect at the Euler pole (Figure 9.14). This principle was used by Morgan [7] to locate relative rotation poles of pairs of plates.

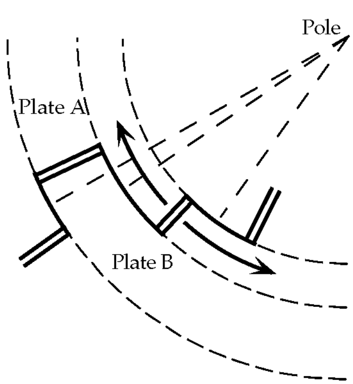

Figure 9.14. Relative rotation between two plates in the case of planar geometry. The transform faults and fracture zones form circles centred on the pole of rotation. On a sphere they form small circles.

On a sphere, the local spreading or convergence rate varies with position along plate margins, and there may even be a change in the type of margin. In Figure 9.14, the spreading rate will increase with distance from the pole. An example of this is that the spreading rate of the Mid-Atlantic Ridge is largest near the (geographic) equator and decreases towards the North America–Europe rotation pole, which is located in the Arctic. An example of a change in margin type is that the motion between the Pacific and Australian plates changes from nearly normal subduction at Tonga, north of New Zealand, to nearly strike-slip along the Macquarie Ridge, south of New Zealand, which is close to the Euler pole.

9.5 The power of the rules of plate motion

The rules of plate motion have proven to be a powerful tool for deciphering the history of the plates. We saw in Chapter 3 how the great Pacific fracture zones were extremely puzzling until it was recognised that they were formed at the Pacific–Farallon ridge, which no longer exists in this region (Figure 9.11). The 'great magnetic bight', where the magnetic stripes turn from northerly to westerly (Figure 9.10) was also puzzling. Once the unique properties of plate kinematics were discovered, it was possible to use these puzzling features to make powerful inferences, such as the former existence of two large plates in the Pacific basin (the Farallon and Kula plates).

An early and striking example of this power came from the Indian Ocean, where the sequence of events has been rather complex. The outlines of the main phases of seafloor spreading were correctly inferred by McKenzie and Sclater in 1971 [8] on the basis of a data set that was remarkably sparse for such a huge area. Given that there were four continents involved, and several distinct phases of seafloor spreading, this remains one of the more remarkable demonstrations of the power of the rules of plate motion.

Another example comes from the Pacific. In the course of teaching about this subject, I noticed that the magnetic stripes near the great magnetic bight form a peculiar 'buttress' shape. Part of it is outlined by anomaly 33 in Figure 9.10, and the shape is also evident in Figure 9.11 (stages 80 Ma, 65 Ma, 56 Ma). This shape will not extrapolate back in time without seeming to reach an impossible configuration, in which a small piece of the Pacific plate would have had to emerge separately and then merge with the main plate at its north-east corner. (This part of the plate evolution is not recorded because of a magnetic 'quiet zone', due to the cessation of magnetic reversals for a time in the late Cretaceous.) Graduate student Mark Woods pursued the idea and developed the case that the Kula plate had actually formed by breaking off the Pacific plate, in the late Cretaceous, along the Chinook fracture zone [9]. A direct implication was that a series of older Mesozoic magnetic stripes in the north-west Pacific, which had previously been attributed to Pacific–Kula separation, must have involved another plate, since the Kula plate did not then exist. This made it much easier to understand the relationship between the Mesozoic and Tertiary magnetic stripes. We named the inferred older plate Izanagi (Figure 9.11, 110 Ma stage), after one of the gods of Japanese mythology responsible for the creation of the Japanese islands. Thus the inference of a former large plate in the western Pacific resulted from noticing a small inconsistency implied by the rules of plate motion.

9.6 Sudden changes in the plate system

Plates change with time, even when no new plate margins form. There are actually three kinds of change recorded by seafloor magnetic stripes: steady growth or shrinkage of plates, changes in plate velocity, and the formation of new plate margins by plate breakup. The first kind of change is a consequence of the difference in behaviour between spreading margins and converging margins, which we have explored in some detail in this chapter. Thus plates may grow and shrink, and some plates may disappear, through the normal evolution of their margins.

A dramatic change in plate velocity occurred about 43 Ma ago when the velocity of the Pacific plate in the vicinity of Hawaii changed from north-north-west to west-north-west. This change is recorded by the 'bend' of the Hawaiian–Emperor chain of seamounts that marks the trace of the Hawaii volcanic hotspot on the Pacific plate (Figure 4.3). A number of less dramatic changes in the relative motion of the Pacific and Farallon plates is recorded by magnetic stripes on the Pacific plate (Figure 9.10). Some of these are associated with the shrinking and fragmentation of the Farallon plate.

The breakup of Pangea involved the formation of new spreading centres, and these are well recorded by magnetic anomalies in the Atlantic, Indian and Southern Oceans. Sometimes a new spreading centre has formed near an existing one, and the existing one has ceased. This has been called a 'ridge jump'. Several ridge jumps were associated with a change in the Pacific–Nazca relative motion. There was a ridge jump from one side of Greenland to the other at the time of eruption of the North Atlantic Tertiary flood basalts about 60 Ma ago.

Examples of the formation of new subduction zones are harder to find, because much of the evidence is subsequently destroyed. It is conjectured that the Mariana subduction zone began at an old fracture zone on the Pacific plate, possibly at the time of the change in Pacific motion 43 Ma ago. This relatively recent origin might help to explain the existence of sub-parallel subduction zones on either side of the Philippine plate.

Indirect evidence for episodes of subduction is recorded, in principle, in the mountain belts of island arcs and continental margins associated with subduction zones. Because the geology so recorded is complex, it is difficult to resolve detail. However it is clear, for example, that the western margin of Canada changed from being passive (like the present eastern margin) to having active subduction in the late Precambrian.

The disappearance of a number of plates from the Pacific basin can be inferred from the magnetic stripe record. The Farallon plate has not really disappeared, it has fragmented as it shrunk, into the Nazca, Cocos and Juan de Fuca plates. In the north Pacific, the Kula plate is reliably inferred to have been subducted into the Aleutian trench. The Phoenix plate (or most of it) disappeared under Antarctica. Exercise 3 illustrates a simplified version of these events. The Izanagi plate (or plates) has disappeared under Japan, as was related in Section 9.5.

9.7 Implications for mantle convection

The most important implication of plate kinematics for mantle convection is that the locations of upwellings and downwellings must be influenced, if not controlled, by the (brittle) mechanical properties of the lithosphere, rather than the (viscous) properties of the deeper mantle. This is because, by conservation of mass, there must be upwellings under spreading ridges and downwellings under subduction zones. This statement is true independently of what forces are driving the system. It is a deduction from the surface kinematics and conservation of mass. This important point will be taken up in Chapter 10.

Another implication arises from the time dependence of the configuration of plates. If plates and mantle convection are intimately related, as we will see in Chapter 10, then we should expect the pattern of mantle convection also to be unsteady. The time dependence of the plates is of a peculiar sort, being quite different from the unsteadiness of a strongly heated convecting fluid of the more familiar kind. In normal fluid convection, the flow structure can change rather randomly, and may reach a state of 'deterministic chaos'. The plate system, on the other hand, tends to evolve steadily for substantial periods, but then to suddenly shift into a different pattern of motions if a new plate boundary forms. Thus mantle convection must be consistent with the facts that plates have a range of sizes and odd, angular shapes, that plates grow and shrink, that some plates disappear, that others break up, and that plate velocities may change suddenly. Such changes are evident in Figure 9.15, which shows a selection of reconstructed plate configurations over the past 120 Ma.

The time dependence of the plates has important implications for many aspects of the interpretation of geophysical evidence, as well as for the way chemical heterogeneities will be stirred in the mantle (Chapter 13). Thus, for example, the deep expression of past subduction, as expressed in the gravity field, may not coincide with the present location of subduction zones.

The effects of spherical geometry on plate kinematics must be borne in mind, especially in relation to larger plates. This means, for example, that near a pole of rotation the plate may be rotating about a vertical axis relative to the mantle under it, and it would not be accurate to think of the mantle motion in terms of simple roll-cells of convection. In a spherical shell, the flow may connect globally in a complex way. Thus the 'return flow' from subduction under the north-west Pacific back to the East Pacific Rise may pass

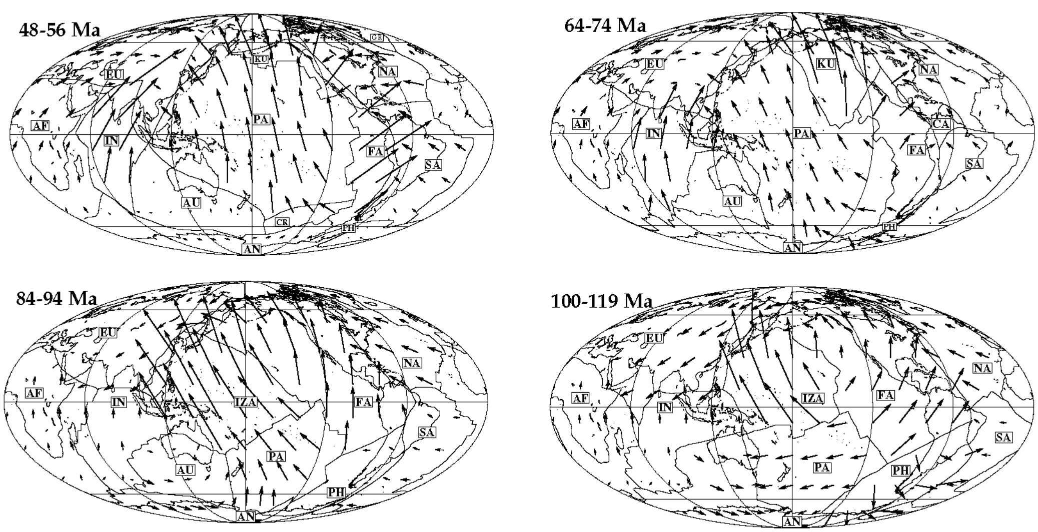

Figure 9.15. Reconstructions of plate configurations and velocities for several time intervals over the past 120 Ma. From Lithgow-Bertelloni and Richards [10]. Copyright by the American Geophysical Union.

under North America, approximating a great circle path [11], so the flow under North America may have a southerly component that would not be inferred from the local part of the plate system.

9.8 References

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9.9 Exercises

1. Sketch an evolution sequence, in the manner of Figure 9.7, for cases (a), (c) and (e) of Figure 9.6. If the nature of a plate margin changes, continue the sequence for one stage after the change in order to show the character of the subsequent evolution.

2. (a) Construct a velocity diagram for Figure 9.12. Include the velocities of all plates, plate margins and triple

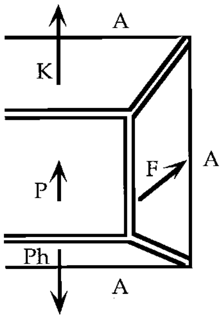

Figure 9.16 Plate configuration for Exercise 3.

junctions. (b) Sketch stages in the evolution of these plates until a steady situation is reached.

3. (a) Construct a velocity diagram for the situation in Figure 9.16. Velocities are shown relative to plate A, which surrounds the others on three sides. This is a simplification of the situation in the Pacific basin during the early Tertiary. (b) On the basis of the velocity diagram, predict the fates of plates K, F and Ph and any consequent changes in the nature of their margins with plate A. (c) Sketch an evolution sequence up to the stage where there are only two plates. (d) What would be the ultimate outcome if there are no changes in plate velocities?