CHAPTER 7

Tectonics and Volcanic and Igneous Plumbing Systems

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7.1 INTRODUCTION

7.1.1 What is the Role of Plate Tectonics in Volcanic and Igneous Plumbing Systems?

Plate tectonics and mantle convection set the scene for magmatism, and magma is an essential product of plate tectonics. Magma ultimately produces the lithospheric portion of plates. The different tectonic environments creating magmatism are illustrated in Fig. 7.1.

Magma is produced principally at divergent plate boundaries by spreading at rifts and mid-ocean ridges (about 90% of all magmatic activity is at mid-ocean ridges). New oceanic lithosphere is generated by magma accumulation and eruption in a continually growing and expanding plumbing system.

Continental rifts can also produce magma and eventually evolve into full oceanic spreading systems. Many of these rifts start as passive rifts, with no initial asthenospheric convection. These produce no magma until stretching thins the lithosphere sufficiently for the

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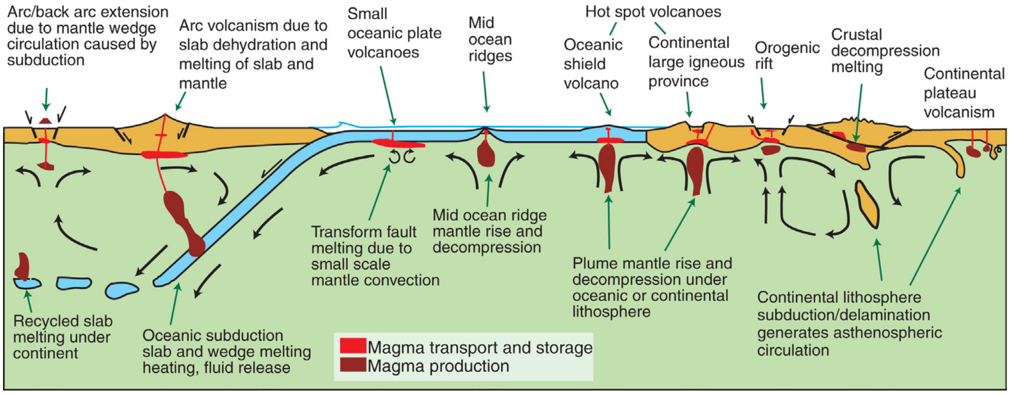

Figure 7.1 ***Plate tectonics and magma production.*** Conceptual figure showing the Earth's plate tectonic system, with the principal magma generation, transport and storage systems.

asthenosphere to melt through decompression. Active rifts, which are associated with early asthenospheric convection, begin with large-scale volcanism and uplift followed by rifting.

Hotspots are zones of rising asthenospheric convection or circulation and/or zones where the mantle is especially prone to melting (Foulger, 2010). At hotspots asthenospheric or lithospheric melts are produced through excess heat and create a variety of volcanic fields ranging from the continental flood basalt provinces (Colobia River, USA), huge oceanic islands (Hawai'i) and large volcanic fields (El Pinacate, Mexico) to small, disperse monogenetic fields (southeast Australia).

At convergent plate boundaries, subduction of oceanic lithosphere causes slab dehydration, volatile release and melting of the overlying mantle. This process has worked to create continental crust since at least 2.4 billion years ago.

In orogenic belts, melting of the crust and mantle lithosphere occurs by heating (from basaltic magma underplating), decompression (by removal of load through erosion or rifting/crustal stretching) or from the addition of volatiles that lower the melting point (solidus).

Subduction of continental material does not cause the same scale of melting as oceanic subduction; instead, the subducted continental material is assimilated and may be recycled at a later date. The mantle circulation perturbed by the subduction may also lead to the asthenosphere rising and decompressing, thus generating additional melt.

Once magma is produced, it collects and moves through the lithosphere in bodies that make up an igneous plumbing system (see, e.g. Chapter 2). Depending on the relevant tectonic environment, the configuration of these plumbing systems varies widely. We will consider magma plumbing at mid-ocean ridges, continental rifts, hotspots, oceanic subduction zones (both oceanic and ocean–continental), continental convergence and transform zones.

We will then take a closer look at very shallow plumbing systems, where topographic stresses and sedimentary/volcanic lithology and rheology are important. This includes superficial structures, which only become significant at very shallow levels. Finally, we will consider the possibility of a unified system for tectonics and igneous plumbing systems.

7.2 HOW IS MAGMA TRANSPORTED AND STORED IN DIVERGENT GEODYNAMIC SETTINGS?

7.2.1 Volcanic and Igneous Plumbing Systems at Mid-Ocean Ridges

Mid-ocean ridges are the longest, largest and most voluminous magmatic environment on Earth. Ridges are the site of new lithospheric and crustal production that may be subsequently subducted into the mantle and recycled, or involved in magma-producing dehydration reactions that slowly build up continental crust (Fig. 7.2).

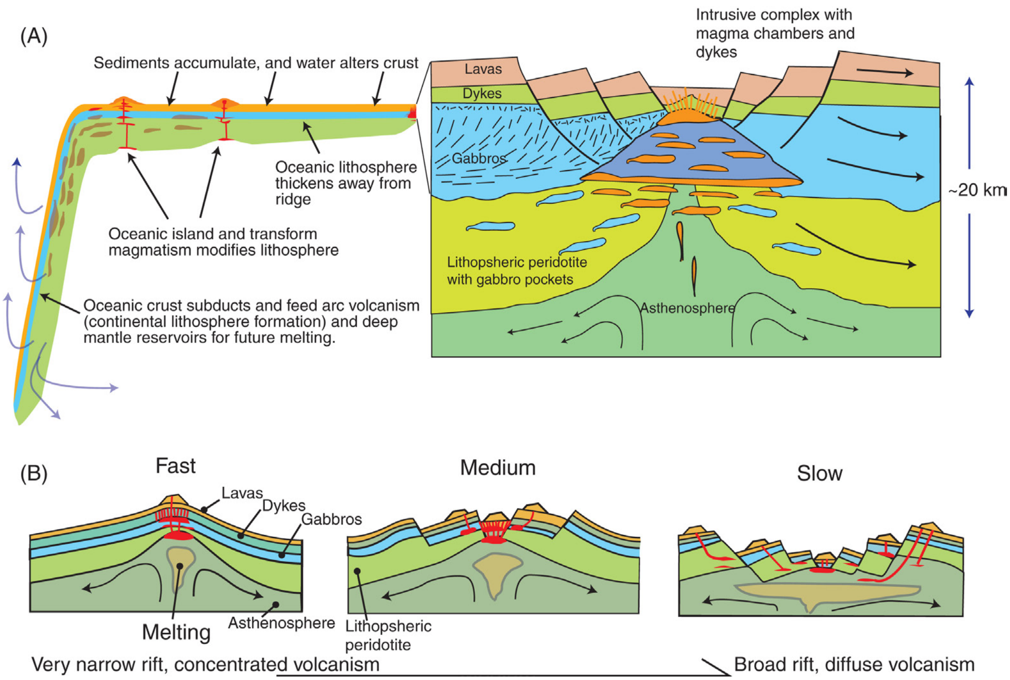

Figure 7.2 ***The mid-ocean ridge plumbing system.*** **(A)** The structure of the oceanic crust resulting from the development of magma chambers, dykes and lavas, as well as their subsequent deformation and transport away from the ridge centre. Effectively, the whole oceanic crust is made up of plumbing system components. The new crust travels away from the rift zone to eventually subduct and later form arc magmas. Oceanic sediment collects on the crust, and hydrothermal alteration (creating serpentinites), oceanic island and transform volcanism modify the crust on its journey. (B) Magma-dominant (fast) ridges construct crust made only of plumbing system components (dykes, sills and their eruptive products), magma-poor (slow) ridges stretch by faulting and exhume lithosphere and asthenosphere. The crust in such situations is a mix of magmatic addition and stretched mantle. Volcanism at fast ridges is concentrated at the axis, while at slow ridges it can be broadly distributed and intrusions may follow other pathways to erupt at the rift shoulders.

The mid-ocean ridge system is made up of diverging lithosphere over rising asthenosphere (Fig. 7.2A). The latter decompresses and melts with volumes related to its ascension rate. At fast spreading ridges, such as the East Pacific Rise, the rapid spreading rate (up to 20 cm/year) produces large amounts of magma as decompression is fast in relation to cooling, whereas at slow spreading ridges, magma production is very low as cooling dominates over decompression.

In ocean-ridge plumbing systems, this means that at fast spreading ridges, magma is the dominant material added to make new crust (typical ophiolite sequence), whereas at slow spreading ridges the asthenosphere may rise to the surface without any magmatic crust forming (serpentinitic crust; Fig. 7.2C). One consequence of this is that at fast spreading ridges, the crustal structure is controlled by magma and volcanics, whereas at very slow spreading ridges, faulting and stretching dominate, allowing exhumation of the asthenosphere. The oceanic crust at slow spreading ridges is thus thinner than fast ones and includes exhumed mantle. The thickness relation between the fast and slow ridges can be seen on Moho depth maps. Departures from this pattern happen where other influences, such as mantle plumes, add additional magmatic input. For example, in Iceland, the magmatic production is high compared to the spreading rate, leading to unusually thick crust (see maps in Artemieva et al., 2017).

The magma plumbing system at a mid-ocean ridge starts with an area of partial melt generation and migration within the rising asthenosphere. When enough magma is collected, it can move upwards as a body, through buoyancy (see Chapter 2). Magma may continue to rise as a dyke and either erupt or cool in the crust, or it may feed into a magma chamber. A conceptual magmatic system is show in Fig. 7.2, which shows that often the whole oceanic crust is made up of magma plumbing elements, topped by lavas and sediments. The thickness and the extent of the oceanic crust relate to the melt flux and the spreading rate, such that at slow spreading ridges some crust will be composed of serpentinised mantle, whereas at fast ridges (or ones with excess melting, such as Iceland), the crust would be exclusively built out of plumbing elements.

Along a mid-ocean ridge, magma collects into discrete centres, each of which concentrates magma and distributes it outwards via a plumbing system of dykes and sills (Fig. 7.2B). The Axial seamount on the Juan de Fuca Ridge is a good example of this (Sigmundsson, 2016) (see also Chapter 11).

Consequently, the intrusive complex can be considered to extend from the axial magma chamber throughout the entire plate, making up the largest intrusive systems on Earth (Fig. 7.2B).

Two types of field sites provide evidence of mid-ocean ridge plumbing. The older parts of Iceland represent exposed sections of magmatic systems, where analogues to mid-ocean ridges can be seen. These have central intrusive systems with cone-sheet intrusions and dyke swarms (see Chapter 4). There are generally many more dykes below 2 km depth than above (80% are below this level). In rifting episodes, such as at Krafla volcano in the 1970s and 1980s (Einarsson and Brandsdóttir, 1980), the majority of dykes identified in seismic data did not reach the surface. While exposures such as those in the east and west of Iceland provide a view into the upper few kilometres of the oceanic crust, deeper levels remain unexposed. However, in ophiolites (obducted oceanic crust), entire sections from the mantle upwards can be seen. In these ophiolites, a complex plutonic sequence of coarse gabbros that transition up into sills and dykes, and finally into lavas (Moores, 2003) is exposed, representing typical fast spreading mid-ocean ridge segments.

The mid-ocean ridge system is driven by several forces, in particular, from asthenospheric flow as the subducting oceanic lithosphere sinks. Known as slab pull, this force is thought to be the main driving force for ocean spreading. The expansion from intruded dykes, and the gravitational force from the topography and magmatism and the slope of the crust–mantle boundary also contribute. All the forces acting from around a mid-ocean ridge can be grouped together and termed 'ridge push', with restrictive forces being the rheology of the lithosphere/asthenosphere, friction and inertia.

7.2.2 How Do Continental Rift Volcanic and Igneous Plumbing Systems Work?

Mid-ocean ridges are born either directly within the oceanic crust as plate motions shift or by the splitting apart of continental crust. In both cases, initial stretching creates a rift that develops into a full oceanic basin with new crust formed by extension. In the case of a continental rift, the process is a long drawn-out evolution that thins the continental lithosphere and slowly leads to the development of oceanic crust.

The continental rift plumbing system differs from the mid-ocean ridge, as continental crust is present as a medium into which the magmas are intruded, rather than magmas forming their own crust (Fig. 7.3).

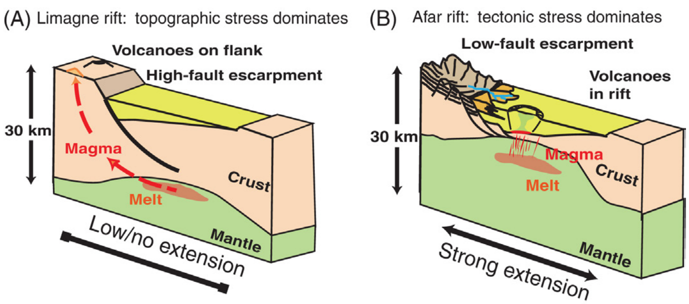

Figure 7.3 ***Two examples of continental rift plumbing systems.*** (A) The example of a deep rift with low tectonic stress (equivalent to a slow spreading ridge). Here volcanism starts only after large degrees of extension and is concentrated on the rift margin as the rift deepens. (B) The example of a mature rift with higher tectonic stress, where extension and magmatism are concentrated in the centre of the rift. Here the stretching is mostly accommodated by dyking and superficial faulting, although sills may also have a major role in weakening and stretching the lithosphere. A sedimentary basin within the rift also provides local lithological control on the type of plumbing.

Nevertheless, the main driving forces and conditions are similar. The continental crust varies more in terms of density and rheology, and its greater thickness means that magma has more volume into which to intrude. The corresponding intrusive systems thus also exhibit more variety. Magma can reside in the crust and assimilate it and also tends to form large central magmatic complexes in which magmas can collect and evolve. These are characteristic of well-developed rifts such as in East Africa (e.g. Nongorogoro) or the Rio Grande (e.g. Valles Caldera, the Socorro magma body).

Rifts have distinct contexts and evolutionary sequences that correlate with different magmatic plumbing styles. Two main evolutionary pathways are possible for rifts:

1.1.1 Passive Rifts

One such pathway is passive, where divergence occurs without initial asthenospheric convection or circulation. Such rifts exhibit no magmatism until the lithosphere is thinned enough to allow decompression melting. Once this occurs, then small-degree melts feed small-scale systems, which are typically monogenetic fields.

Such passive rifts may have small-scale volcanic and igneous plumbing systems, with isolated dykes and sills, the location of which are strongly controlled by local lithology and structure. The strong linkage between tectonics and volcanic grouping and alignment has been explored by Le Corvec et al. (2013), who studied many monogenetic fields and found that most have alignments controlled by local structures. They also noted that as fields became more concentrated (with closer volcanoes), then this association became more evident. The most concentrated volcanic fields were also the most compositionally varied, relating to the progressive development of crustal magma storage, and magma intruded closer in time and space (Fig. 7.3).

As such, passive rifts are not associated with large magmatic systems, and if divergence continues, they can become non-magmatic continental margins and slower oceanic spreading ridges, where the asthenosphere has risen to the surface.

Passive rifts begin with no volcanism and gradually develop limited intra-rift plumbing that may extend out over a broad area, not just within the rift. Passive rifts are often continuously infilled with sediments. This results in subdued topography, however thinning of the lithosphere and externally driven asthenospheric flow can cause uplift; in this case, increased magmatism may accompany regional uplift. Uplift causes the rift sediments to be eroded, allowing topographic stresses to concentrate magmatic activity towards the rift margins (Fig. 7.3A).

1.1.2 Active Rifts

The other path is that of active rifting, where additional asthenospheric uplift provides greater initial melt volume. Uplift tends to occur early in active rifts, and is accompanied by voluminous magmatic activity. Large igneous provinces such as flood basalts can also be produced at this stage. Active rifting can be associated with large-scale magmatic under-plating and in later stages, crustal melting and silicic magmatism, producing large caldera systems such as Yellowstone Caldera. Where this occurs, it is progressively concentrated on the developing rift margin.

Shallow sedimentary basins in active rifts contain large sills interpreted as shallow plumbing systems, such as in the Ethiopian or Antarctic rifts, or in East Greenland (see Chapter 5, Fig. 7.1). Deeper plumbing is not well represented in the surface record, so can only be indirectly imaged. Overall, large lower crustal–mantle lithospheric sill reservoirs are probable, as suggested by gravity anomalies and isostatic uplift.

Central volcanoes and magmatic systems can be associated with the later evolved stage, such as the Messum Centre in Namibia (Korn and Martin, 1955; Jerram et al., 1999), or the North Atlantic Palaeocene igneous province. In East Africa, the later stage of flood basalt eruption is exposed in centres, such as Ras-Dashan in Ethiopia (Williams, 2016).

As the rift further develops into a basin, rift shoulder magmatic systems develop (such as Mt Kenya, Kenya; and Kilimanjaro, Tanzania). The setting of these on the rift shoulder may be linked to magma migration up faults, direct ascent from the edge of rifts or even by the control of magma pathways by a balance of topographic and tectonic stresses (Maccaferri et al., 2014).

As the rift develops, strain and stress are concentrated in the thinning lithosphere, and magmatism becomes more and more concentrated within the rift with first a generation of central volcanoes (often with large calderas and silicic volcanism), then progressively more fissural activity on basaltic systems, with smaller magma storage centres. This can trend towards mid-ocean ridge style elongated magma systems, as seen in northern Ethiopia (Erta Ale) and Iceland. Finally, this type of rift can develop into full mid-ocean ridge conditions as the continental crust is fully replaced. Corti (2013) provides a good description of this process for the East African Rift.

Active rifts form when abundant melting occurs either independently, or caused by the divergence over an area of especially fertile mantle (Foulger, 2010). This classically occurs associated with continental hotspots, or mantle plumes, where rising asthenosphere can melt even before rifting begins. The Ethiopian trap series and the Afar traps are examples of this.

Back arc, or arc rifts, and mountain belt-related rifts can also be associated with abundant magmatic activity. In a continental collision foreland setting, the Auvergne and Eiffel provinces in the European Cenozoic rift system are examples. The Nicaraguan and El Salvador Depression in Central America are examples of arc extension, and the Payun province in Argentina is an example where abundant magmatism is associated with back-arc rifting.

7.3 IN MANTLE PLUMES HOW IS MAGMA STORED AND TRANSPORTED?

Mantle plumes are rising areas of buoyant asthenosphere. There is a certain amount of controversy surrounding their origin and real nature. For example, Foulger (2010) argued that the model of plumes originating at the core–mantle boundary does not fit with much geological data and rather proposed a more diverse range of mantle convection, circulation and differential melting capacity can better explain what we see. However, for the purposes of this chapter, this argument can be bypassed to focus on the consequences of mantle melting caused by asthenosphere circulation of any type. Whatever their origin and exact nature, mantle plumes produce large volumes of magma over a point or area, which may or may not remain stable with respect to overlying plate motions (Fig. 7.4).

In the case of intraplate oceanic settings, classic sites are found in Hawaii, Galapagos, La Reunion, the Canary Islands and the Azores. In each of these cases, there are major differences in the style of volcanism and structure of the islands. All of these relate to underlying plumbing systems and in part to tectonic settings, although the main features of all types are regrouped in Fig. 7.4A.

In the case of the Azores, they coincide with strike-slip faulting at the European-African plate boundary, which leads to highly elongated edifices and rift zones. In the case of the Canary Islands, the setting is a continental margin without any distinct structural influence. Hawaii and La Reunion are located on fast moving oceanic plates, which has led to a periodic shift in magmatism from one edifice to the next, forming long island chains. In these sites, there may be a periodic magmatic evolution from voluminous basaltic shield building to subsequent more evolved alkaline magmatism.

In all cases, the volcanoes are very large (up to 12 km tall and 100 km wide), so large plumbing systems build up within them. Thus, the tectonics of the volcanic edifice has a major control on its internal plumbing system. Conversely, the plumbing will also have an effect on the volcano's tectonics and a very active role in shaping the volcano (e.g. Borgia, 1994; Klügel et al., 2015; Delcamp et al., 2012).

Sills can be favoured when the sagging of an edifice creates a horizontal maximum compression and layered crust is present. The sills can lead to relative uplift that reverses the sagging process. Uplifted submarine rocks or even emerged oceanic crust (e.g. Klügel et al., 2015) shows that at many sites, intrusions have caused uplift. Uplift can lead to higher slopes and to higher rates of sliding on the laterally spreading upper edifice.

For example, rifts such as those found in Hawaii, the Canaries and La Reunion may be correlated with gravity spreading, where a basal unit, like pelagic clay, allows outwards sliding that negates the effect of flexure (e.g. Nakamura, 1977; Borgia et al, 2000; see also Chapter 4). Flexure or 'sagging' tends to squeeze the volcano, creating compression, while spreading leads to extension—the balance is vital in determining the type of plumbing system within the volcano.

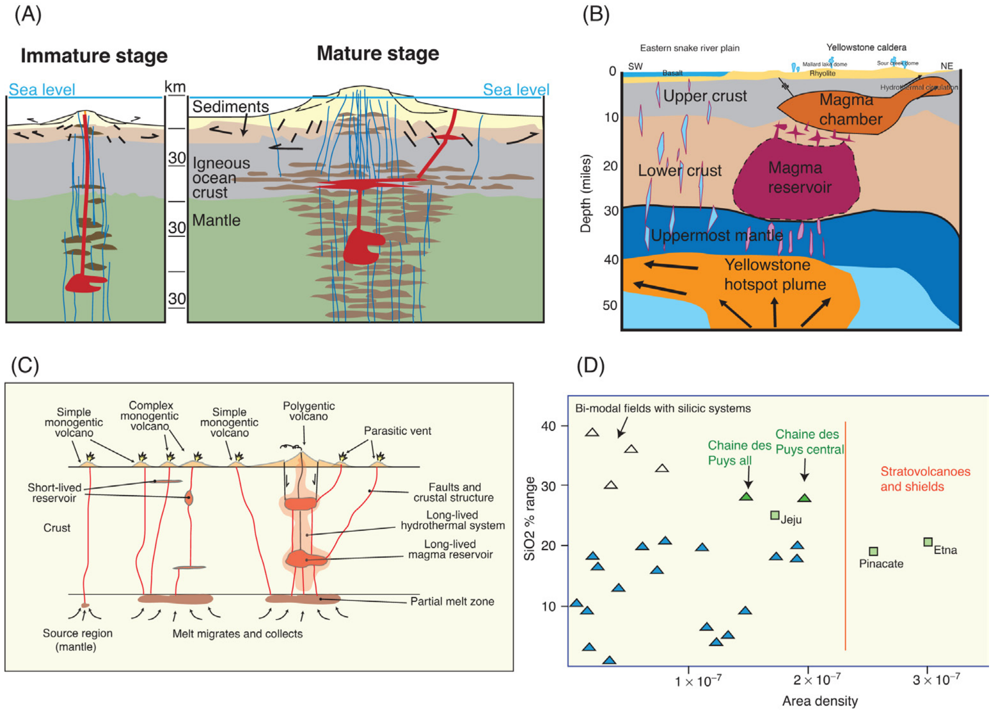

Figure 7.4 ***Mantle plume/melting anomaly plumbing.*** (A) A diagrammatic sketch of oceanic hotspot plumbing from Klügel et al. (2015) showing the evolution of a young to old oceanic hotspot-related plumbing system. (B) A diagrammatic sketch of a continental hotspot plumbing system: the Yellowstone Caldera system (Smith et al., 2009). (C) Diagram of a smaller scale intraplate monogenetic volcanic system with the evolution of plumbing from monogenetic to polygenetic. (D) Graph of volcano spacing in monogenetic volcanic systems vs silica range, showing that widely spaced systems are generally basaltic (no chance to evolve), while more concentrated fields have a wider range of silica concentrations (magmas can collect and evolve in proto-polygenetic systems). Outlying fields are also highly disperse fields with high silica ranges (related to major silicic caldera systems, Los Humeros, Yellowstone), and highly concentrated fields with low silica range (related to polygenetic volcanic systems with multiple vents such as El Pinecate and Jeju)

The Galapagos Islands have a silicic basal sediment layer, which does not deform as easily as the clay layer below Hawai'i. Because of this, McGovern et al. (2014) suggested that the large calderas and radial dyke swarms of these islands were caused by a lack of spreading and preponderance of sagging. The Galapagos islands may also have larger intra-volcano magma plumbing systems and fewer deep sills, such that sagging is predominantly linked to uplift from underplating.

In continental areas, hotspots can lead either to large-scale basaltic magmatism (e.g. Columbia River, Siberian Traps) or large-scale under-plating of magma and crustal melting, such as at Yellowstone (Fig. 7.4B). In these areas, large basaltic ocean shield-type volcanoes can exist (Jeju, South Korea is an example, El Pinacate, Mexico another).

Many monogenetic fields around the world have been tentatively associated with weaker plumes, however more and more of these are also being interpreted as resulting from other processes, such as lithospheric delamination or asthenospheric flow under the edges of the continental lithosphere.

There is a clear progression from small volumes of mantle being associated with small and sparse volcanism, to more concentrated volcanism and then polygenetic volcanoes, flood basalts and large caldera systems (Fig. 7.4C and D).

7.4 HOW IS MAGMA TRANSPORTED AND STORED IN CONVERGENT GEODYNAMIC SETTINGS?

7.4.1 Oceanic Subduction Zones and Volcanic and Igneous Plumbing Systems

Magma production at oceanic or oceanic/continental convergent plate boundaries is linked to dehydration of the subducting slab and melting of the overlying asthenosphere. The asthenospheric flow caused by slab descent and may also cause decompression melting especially in the back-arc (Sternai et al., 2014). The location and volume of melt depends on the tectonic context. Where the slab is steeply dipping, magma is produced in a narrow zone and leads to a narrow arc of concentrated volcanoes (e.g. Central America). In shallower subduction, melting occurs over a much broader area and leads to a broad arc (e.g. Mexican volcanic belt). When subduction changes from shallow to steep, the 'slab rollback' can create major extension in the arc and back-arc, and the inflowing mantle will generate additional volcanism. The opposite, when a slab changes from steep to shallow, occurs when a hotter or thicker oceanic crust is subducted. An example of this is southern Central America, where the Cocos Ridge is subducted below Costa Rica and Panama. Here, the arc volcanoes are very large, and broad and associated with contraction, while in neighbouring Nicaragua, the steep slab is related to a very narrow arc, of smaller volcanoes.

Under the arc, magma tends to gather near the Moho, where in oceanic environments it can create gabbroic chambers that then feed upper plumbing systems (Fig 7.5). In continental zones, such underplating may be accompanied with crustal melting and the creation of partial melt zones, such as in the Andes (Schilling et al., 1997). The underplating can then generate uplift and produce high topography, such as in the Puna and Altiplano. This uplift is caused either by the support of the underplated magma or by its high-grade metamorphism. This process causes a density increase and then the sinking of the underplated material by delamination, which allows new asthenosphere to flow in. The uplift of the Sierra Nevada has previously been explained in this way (Saleeby et al., 2004).

Magma in the lithosphere can provide low resistance layers that can concentrate deformation (Fig. 7.5). Such intrusion-related strain localisation can also happen at the

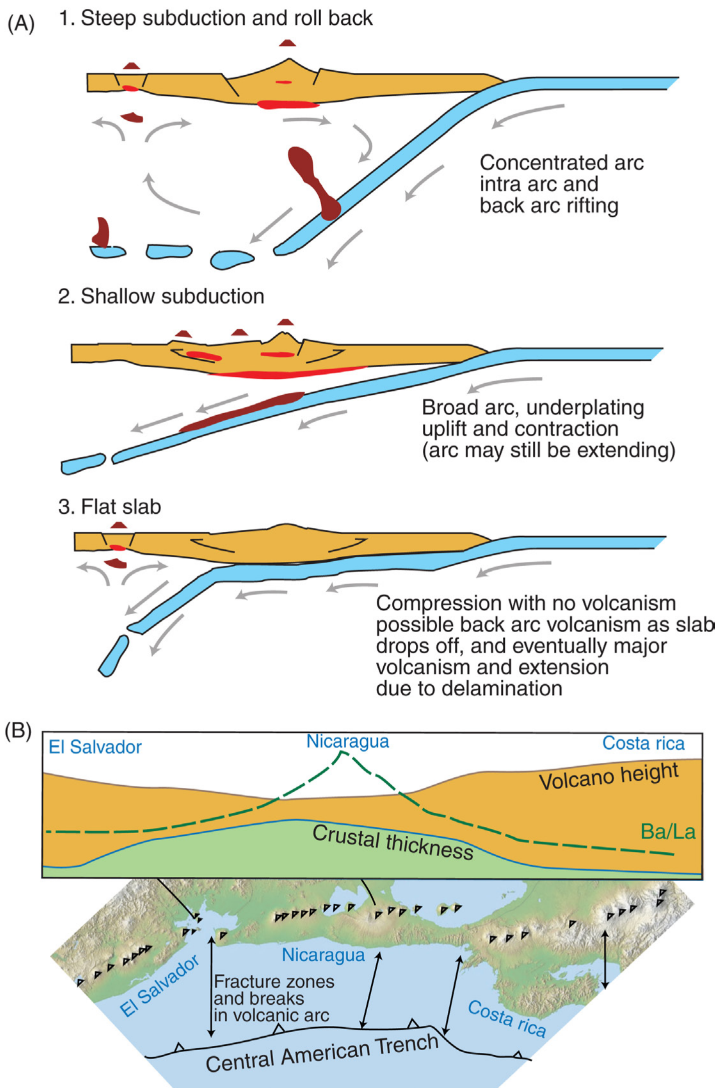

Figure 7.5 ***Convergent oceanic plumbing: the oceanic subduction plumbing system.*** (A) Cartoon showing the different plumbing systems that develop in steep subduction, shallow subduction and flat subduction. Note that a change from shallow to flat subduction can create major extension in the arc, and high rates of magmatism as the mantle flows in behind the retreating slab. Flat subduction has no associated volcanism, except potentially in the far back arc. A very shallow slab can eventually founder and delaminate, as may have occurred under the Colorado plateau. (B) Example of Central America (El Salvador to Costa Rica) with the segmented subduction of the Cocos plate, leading to changes in plumbing style and along arc volcanism. Crustal depth, volcano height and Ba/La values (a proxy for the amount of subducted sediment) are shown, which indicate how crustal structure and the amount of subducted sediment also correlates with changes in plumbing (Carr et al., 2003).

scale of individual volcanoes, for example, at Tromen, Argentina, where thrusting is concentrated at the base of the edifice (Galland et al., 2007).

Subduction zones are often segmented and the associated magmatic systems follow this trend. This is particularly clear in Central America (Fig. 7.5), where subduction segment boundaries are either zones of no volcanism (Nicaragua/Costa Rica boundary) or voluminous activity, such as between Nicaragua and El Salvador, or in central Nicaragua at Masaya (van Wyk de Vries et al., 2001; Carr et al., 1982). Transverse fault zones that cut arcs provide pathways for magma plumbing. In such zones, the magmas tend to have shallower fractionation trends and the volcanoes tend to be monogenetic. Where polygenetic they are formed of multiple vents, indicating that the plumbing is built out of many separate pathways, which may merge (van Wyk de Vries, 1993).

In oblique subduction, the transverse component of movement is taken up along the volcanic arc. This is most clearly illustrated in Sumatra along the great Sumatra fault, but is also seen in northern Central America with the Montagua fault or in Celebes (van Wyk de Vries and Merle, 1996). In these areas, there is a chicken and egg situation where magma in the lithosphere may reduce its effective strength and thus concentrate faulting along the arc, but also the fault concentrates magma into the zone of deformation. Pull-apart basins can be produced around intrusive centres, and the resulting extension may further concentrate magma (Girard and van Wyk de Vries, 2004). The largest calderas, such as Toba, Raung, Tondano, Amatitlan and Masaya, all lie within such strike-slip pull apart basins (see also Chapter 10).

7.4.2 Convergent Continental Margins: Migmatite and Granite Plumbing

Magmatism in convergent continental settings is typically less voluminous than any other setting, especially in relation to erupted volumes. Magmas can be produced in such settings via heating and decompression of crustal rocks during burial, respectively and exhumation. However, they can also be a consequence of continental subduction and delamination. This causes asthenosphere circulation to bring hot mantle material to lower depths, where it can melt or cause delamination away from the main orogenic belt. It can also generate lithospheric stretching and rifting (Fig. 7.6). In the latter case, within mountain plateaus such as Tibet, this forms monogenetic fields generally associated with strike-slip fault zones relating to tectonic escape.

Crustal rock that is heated undergoes metamorphism, dehydration and melting of more mobile minerals. This forms migmatites that separate melt from residue. The melt can be transported out of the zone, collect and form granitic magmas (see also Chapter 2). In the Andes, underplating from subduction-derived magmas has led to a partially melted lower crust (Schilling et al., 1997), and in the Himalayas, around 21–24 Ma years ago, a partially melted layer (migmatite) formed due to decompression melting. The collected melt from this event generated a chain of granites throughout the Himalayas including the Mansalu granite (Fig. 7.6). The accumulation large volumes of melt in the crust allows enhanced strain and lateral flow of the lower crust (Hall and Kisters, 2016).

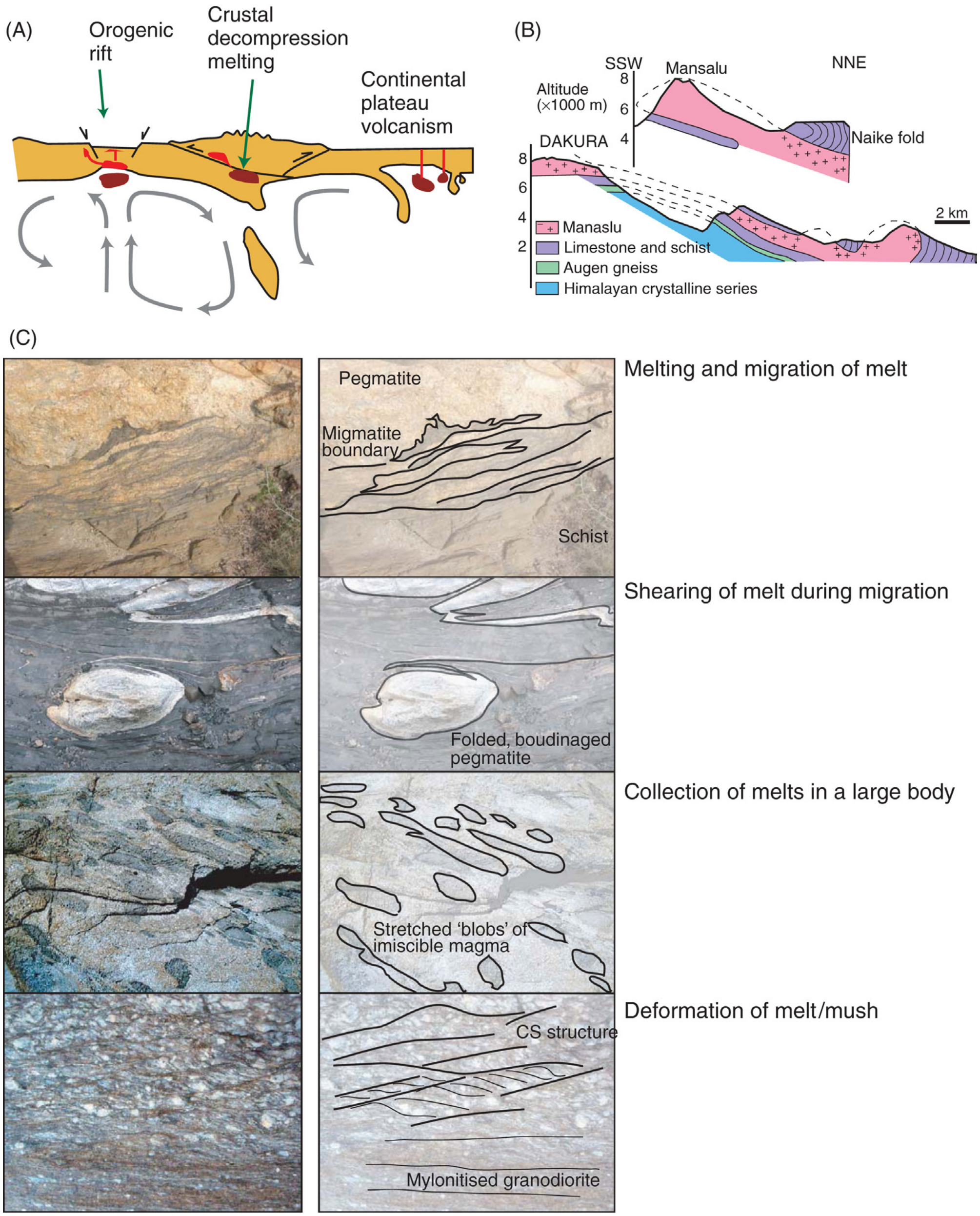

Figure 7.6 ***Convergent continental magmatic plumbing systems.*** (A) Diagrammatic sketch to show the geodynamic context of crustal melting in a continental collision, and other types of continental magma production. Crustal thickening followed by exhumation causes heating (possibly with fluids introduced) and then decompression to lead to partial melting of sedimentary rocks ('S-type' granites). These form migmatites that collect magma into ever larger bodies. Such low-viscosity zones are also zones of preferential deformation. (B) Cross-section of the Mansalu granite (Guillot et al., 1993) showing its intrusion into Himalayan orogenic sequences. (C) Images from the Cap de Creus and Roses area, Catalonia, Spain, showing the progression of migmatisation, pegmatite formation, the deformation of these in melt coeval shear zones, then the collection of liquid in the Roses granite (magma mingling and mixing), and the deformation of this partially melted mush, as deformation continued during ongoing deformation and cooling.

A good example of migmatisation and magmatic collection is found in the Cap de Creus area of Catalonia (Carreras et al., 2004) (Fig. 7.6C). Here, migmatitic melts are collected under high-pressure (sillimanite grade) conditions into pegmatite veins. The nearby Rosas Granite provides the example of a larger body composed of assembled pulses of magma. There is a very clear relationship in both cases with the tectonic strain, with early pegmatites being cut by shear zones, while later ones follow shear zones and balloon (expand) in them, but are not deformed. The pegmatites contain evidence of numerous pulses, with garnet, tourmaline and muscovite being the main accessory minerals in a quartz and feldspar groundmass.

The Rosas Granite is made up of many injections that mixed, associated with the progressive development of conjugate shear zones around the elongation axis of enclaves. Thus, deformation in both liquid and plastic states follows the same strain axes along which the pluton cooled. The mass is cut by small conjugate normal faults that also follow the same axis of compression as the ductile rocks, thus showing that the same tectonic stresses operated throughout the formation and cooling of the intrusion.

7.5 HOW DO VOLCANIC AND IGNEOUS PLUMBING SYSTEMS INTERACT WITH FAULTS, CRUSTAL RHEOLOGY AND TOPOGRAPHY?

7.5.1 The Influence of Faults on Magma Storage and Transport

Shear faults, of any type, do not tend to concentrate magma along the fault zones, as most magma tends to be transported in tensional cracks, which are not parallel to shear zones. However, magmas can also intrude by shearing the rock. Especially in the case of more viscous magmas or low-strength rocks, the creation of intrusion-related shear zones does occur (see Chapter 4). In all fault types, releasing bends, where space is opened between fault segments, can collect magma. This has already been noted in arc settings for the correlation between pull-apart structures and large magmatic systems.

Rift faulting. In rift systems, dykes are often found to open grabens above them and be associated with ground fracturing (Fig. 7.7A). Conversely, faults may be deflected around or towards magmatic systems by the topographic load of a volcano, or by the presence of a magma body (e.g. van Wyk de Vries and Merle, 1996). Volcanoes and calderas are often elongate along or oblique to rifting directions. In the case of rift-aligned calderas, such as Erta Ale (Fig. 7.7A), the strong control of rifting is clear. In many East African Silicic volcanic systems (Fig. 7.7), the caldera may either be produced by overlapping collapses, by sill intrusion oblique to the rift or by inheritance of older structures.

Detachment faults. A particular type of normal fault, detachments faults are low-angle (<20°) extensional faults. They typically form when a basin is asymmetrically extended and the asthenosphere can flow into the thinned lithosphere. A combination of decompression melting and shear melting lubricates the fault sustaining rapid motion and

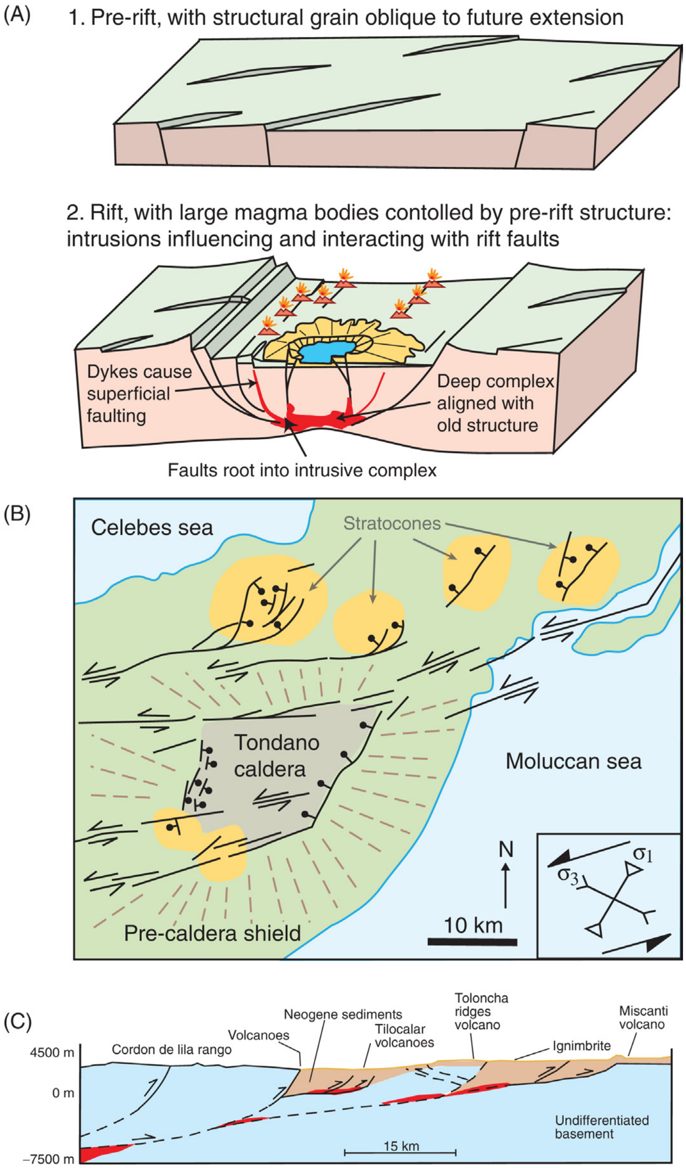

Figure 7.7 ***Magma plumbing with different tectonic regimes.*** (A) Calderas in the East African Rift are partly controlled by pre-existing deep structure (sketch modified from Robertson et al., 2016). Note that ancient structures may influence the location and shape of magma bodies, but the bodies will also affect the geometry of modern structures. (B) Magma in strike-slip zones collects in pull apart structures that can be initially generated by the load of the volcano, and the magma acting as a low-rheology zone. Example from the Sulawesi (van Wyk de Vries and Merle, 1998). (C) In compressional settings, the magma may follow thrust faults and form ramp structures. Example from the N Chilean Andes (Atacama) (Gonzales et al., 2009).

creating numerous *syn*-kinematic granite sheet intrusions (e.g. Passchier et al., 2005). This results in a portion of middle-lower crust plumbing being exposed at the surface as a core complex.

Strike-slip fault. These zones accommodate magma in pull apart structures. This is well displayed by the classic connection between granite plutons and strike-slip faults in Brittany, France, but is also seen at the surface in modern sites, such as Sumatra, Sulawesi and Central America (Fig. 7.7B). So, while transverse movement does not necessarily generate magma, it can be important for collecting and distributing it (Spacapan et al., 2016). Also, shear deformation engendered by strike-slip movement in zones of partial melt may provide a means of concentrating magma and extracting it, so transverse zones do have a role in magma generation, transport and storage.

Thrust faults. In compressional faults, magma may form sills in compressive zones and then be exploited as a flat in thrust sequences. The example of the Atacama compressional area is shown in Fig. 7.7C. The magma can intrude along the thrust plane, or the thrust can localise along the sill. Magma may then migrate up the thrust and collect in fault bend folds or thrust anticlines, where it can erupt through the crest of the fold (Gonzales et al., 2009).

7.5.2 The Influence of Shallow Crustal Stresses and Lithology on Magma Plumbing

When magma is close to the surface of the Earth, uplift is a means of creating space, such that shallow plumbing systems are strongly controlled by the way they uplift the surface (Fig. 7.8). This is seen in the formation of forced folds in the host rock (e.g. Magee et al., 2017; see also Chapters 5 and 6) and was one of the first aspects of volcanism noted by early geologists (e.g. von Buch's Craters of elevation theory: van Wyk de Vries et al., 2014).

Magma-related uplift creates a range of tectonic structures, some of which have already been described for oceanic island hot spot plumbing. In such environments, the huge volcanoes and large magma volumes produce marked uplift effects (Fig. 7.5).

The full range of structures related to intrusive uplift includes extensional fracturing and faulting over dykes and sills (Fig. 7.8), tilting of strata, marginal thrusting and strike-slip faulting. The uplift also permits lateral movement, and large sections of crust can slide away and be transported due to this process. Examples of this are the Mull volcano (Scotland), the south-west side of Etna (Italy) but such deformation can happen at all scales, and is a frequent element in monogenetic volcanoes.

Movement can also be rapid at larger scales, such as the huge heart mountain slide in Utah, USA (Mitchell et al., 2015). Such rapid displacements are found at all scales, and magma intrusion is one of the main causes of landslides on volcanoes (e.g. Bezymyanny, Mt Saint Helens; see Chapter 9).

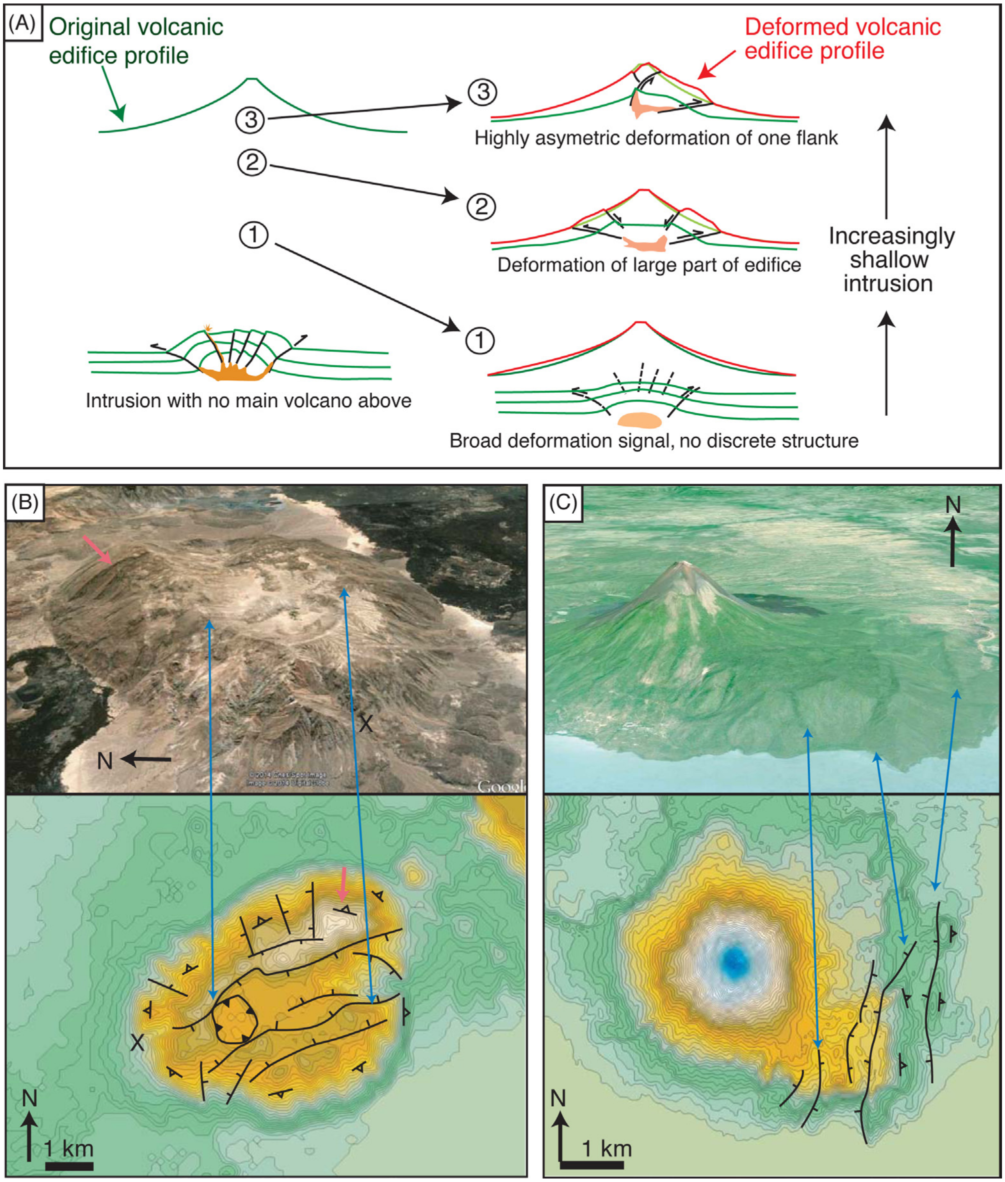

Figure 7.8 ***Shallow magma tectonics.*** (A) Sketch of the different types of tectonic uplift associated with magma intrusion, from underplating to very shallow, within edifice intrusions and intrusions with no edifice. (B) The example of Alid volcano, Eritrea, where a forced fold of 400 m height has formed due to an intrusion into proteozoic metasediments and rift sediments. Note the basaltic eruptions from the base of the dome, which has only erupted trachyte from small summit craters (Duffield et al., 1997). Blue arrows join faults in image and topographic map,' *(pink arrows mark)* the same spot in both. (C) The example of Momotombo, Nicaragua, where the east side of the volcano is uplifted by 300 m. This uplift may have occurred before the present cone had grown up, as the most recent lava flow around the faults. Blue arrows join faults in image and map.

7.5.3 The Influence of Topography on Shallow Magma Storage and Transport

Topography and gravity play important roles in creating stresses that guide magmas through the crust. They make the link between large-scale plate tectonic stresses (gravity controlled) and the local environment.

It has long been known that dyke intrusion is controlled at shallow levels by topography (e.g. experiments on rift zone formation in Hawai'i by Fiske and Jackson (1972). Observations on Etna show that dykes and eruptions often follow the margins of a valley (Valle del Bove) (Murray, 1988), thus being influenced by the topography. A similar conclusion has been reached at Stromboli (Walter and Troll, 2003; Acocella and Tibaldi, 2005) and at Calderas (Corbi et al., 2015). As described by (Maccaferri et al., 2014) and Maccaferri et al. (2015), eruptions favourably occur on the footwall, when magma is intruded near faulted rift escarpments. This illustrates the play between topographic and tectonic stresses especially well (Fig. 7.9).

Extension produced by gravity sliding or spreading also opens up pathways for magma to rise in; in contrast, flexure and sagging can compress the edifice and result in reduced magma output. These gravity tectonic processes have a major control on the evolution of magmatic plumbing. For example, at Concepcion, Nicaragua, early volcano growth resulted in a volcanic edifice that sagged into the lake basin, causing compression. The originally primitive basalts erupted were replaced by increasingly evolved rocks, and the compression eventually blocked magma ascent (Borgia and van Wyk de Vries, 2003).

Once the volcano began spreading, a rift developed and the trapped, highly evolved magma was erupted. The volcano has gone through cycles of stability and spreading and erupted a broad range of compositions reflecting the newly developed open system. The cyclic nature of the compositional variations and the stop–start nature of deformation (Saballos et al., 2014) indicate a strong interdependency between magma intrusion, gravity and regional tectonics.

In glaciated regions, ice volume can also be an important control on the volume of magma produced, erupted and stored within the plumbing system. Rapid removal of ice masses hundred to thousands of metres thick can both stimulate decompression melting at depth and allow shallow magma chambers to erupt their contents (Hardarson and Fitton, 1991; Jull and McKenzie, 1996; Slater et al., 1998). Thus, not only are volcanic and igneous plumbing systems strongly related to tectonics, they are also indirectly linked to climatic variations.

7.6 THE TECTONIC AND MAGMATIC SYSTEM

Magma plumbing systems have been shown to be an integral part of plate tectonics, and the interaction with structure occurs at all scales, from the global to the microscale. The processes that operate in each case are similar, as they all involve host-rock rheology,

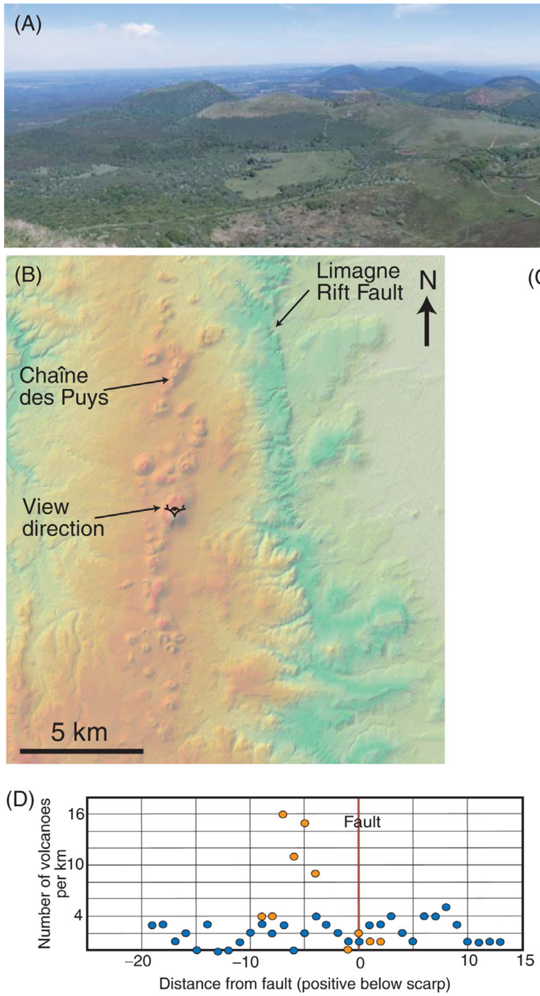

Figure 7.9 (A) Photograph of the aligned Chaîne des Puys and Limagne fault (arrows indicates fault), taken from the Puy de Dome. (B) Topographic shaded relief image of the Limagne fault and Chaîne des Puys, showing the position of the volcanoes behind the fault escarpment (eye shows view point). (C) Data from scoria cones and fault scarps in Ethiopia (Maccaferi et al., 2015), showing the tendency for volcanoes to erupt on the upper shoulder (footwall side) of the fault. (D) Distribution of volcanoes in the Limagne Rift pre- (*blue*) and post-deepening (*yellow*), showing the concentration of volcanism on the top of the escarpment.

magma rheology, density, heat, gravity and other tectonic forces. Thus, a generalised system can be built up for idealised relations between magmatic and tectonic systems. This is intended to help keep track of the importance of any individual part, irrespective of scale, on the entire system (Fig. 7.10).

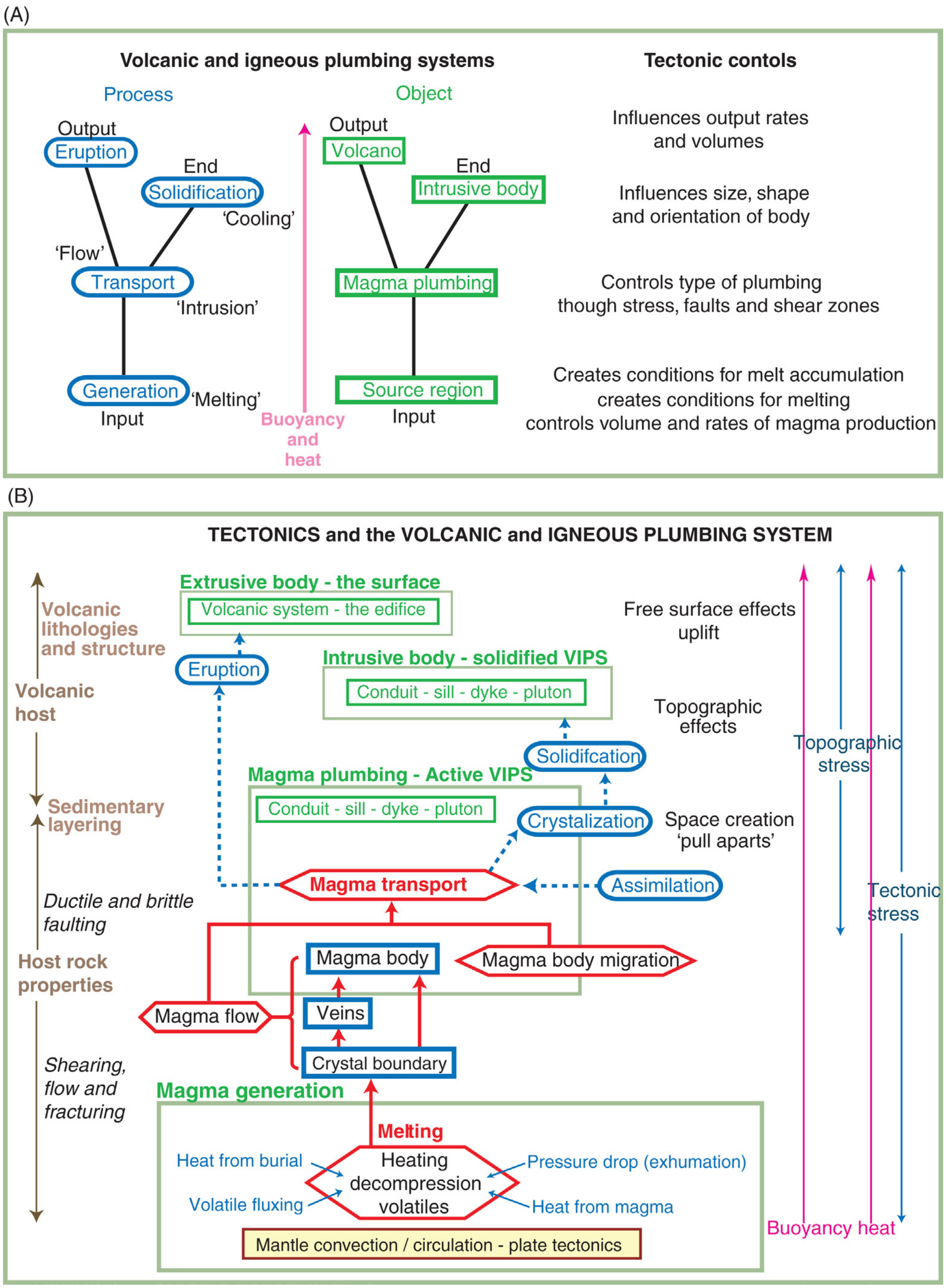

Figure 7.10 ***System diagram for the links between tectonics and volcanic and igneous plumbing systems.*** (A) A simplified system showing the main features of magma production (melting), magma collection and transport, magma migration (note flow within an intrusion is not the same as an intrusion migrating) and then magma evolution in different tectonic and lithospheric environments. (B) More full systems diagram, showing some of the many interactions within the tectonic and magmatic plumbing system.

CONCLUSIONS

Magmatic plumbing systems can be seen as a part of the plate tectonic system, where products from melting in the mantle and crust are redistributed according to temperature and density contrasts, which continuously feed back into the rest of the tectonic system.

This relation can be exemplified at the largest scale with an oceanic plate, which is almost exclusively formed of magma plumbing emplaced at the ridge. The increased load, due to the build-up of mass at the ridge, and magma pressure, associated with other large-scale forces pushes the plate away. At the other end, subducting oceanic lithosphere dehydrates and causes melting, interacting with the overlying asthenosphere and producing new magma to form an arc plumbing system. The dense slab pulls down the oceanic lithosphere (slab pull) and eventually mixes back into the rest of the mantle, to later be taken up by new ridges and hot spots.

The upper magmatic plumbing systems evolve under the joint influence of local tectonic forces, faults, topography and lithological contrasts. It influences the surface through eruptions, but also the creation of topography (bulging/sagging) and by triggering landslides and seismic events. Old extinct volcanoes, where plumbing may be exposed at the surface, provide visible evidence of these processes and valuable opportunities for public outreach.

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