Chapter 13: Maps of Intrusive Igneous Structures

IGNEOUS INTRUSIONS may have a large variety of shapes and sizes. They occur principally at plate boundaries and follow fracture zones or force aside the country rock in diffuse shearing. Eventually, igneous intrusions may crop out at the ground surface after removal of the overlying rock units by erosion. This chapter illustrates some of the principal features seen on geological maps of igneous terrains. The tectonic setting and various processes involved in the generation and emplacement of igneous intrusions are, also, briefly explained.

Contents: The geological setting of igneous rocks is outlined in section 13-1. Their various shapes are illustrated in section 13-2. Zoned plutons, nested plutons, and mantled gneiss-domes are addressed in sections 13-3 and 13-4.

13-1 Geological setting of igneous rocks

Igneous rocks originate from magma, produced by partial melting at depth. Most of the partial melting sites occur beneath modern, evolving plate boundaries and are associated with anomalies of pressure, temperature, and water-content in the crust and mantle. The solidifying melt is emplaced within the crust either along fracture zones or by forcing aside the country rock in diffuse shearing. Magmatism is particularly abundant in mature rift zones, along active continental margins, and at subduction island arcs. Each of these magmatic sites is briefly outlined in turn below.

Continental and oceanic rift zones

The extensional thinning and incipient failure of continental crust by rifting are commonly accompanied by the intrusion of large tabular or sheet-like bodies into fractures. These bodies, termed igneous dikes, are predominantly of basic, rather than acidic, composition. The Great Dyke of Zimbabwe, Africa, has long been considered the world's largest single dike feature. This gabbroic body is about 480 kilometers long with an average width of six kilometers (Fig. 13-1a). However, detailed field investigations have revealed that the Great Dyke is comprised of horizontal cumulus layers (Fig. 13-1b), intruded into the Archean greenstone-granodiorite terrane of the Zimbabwe craton about 2.5 billion years ago. The horizontal gabbro sheets were fed by steep dikes, much thinner than the six-kilometer-width seen on Figure 13-1a. The walls of the Great Dyke are merely faulted contacts of a central graben, formed posterior to the emplacement of the gabbro. The Zimbabwe craton, also, hosts the nested *plutons*, discussed in section 13-4.

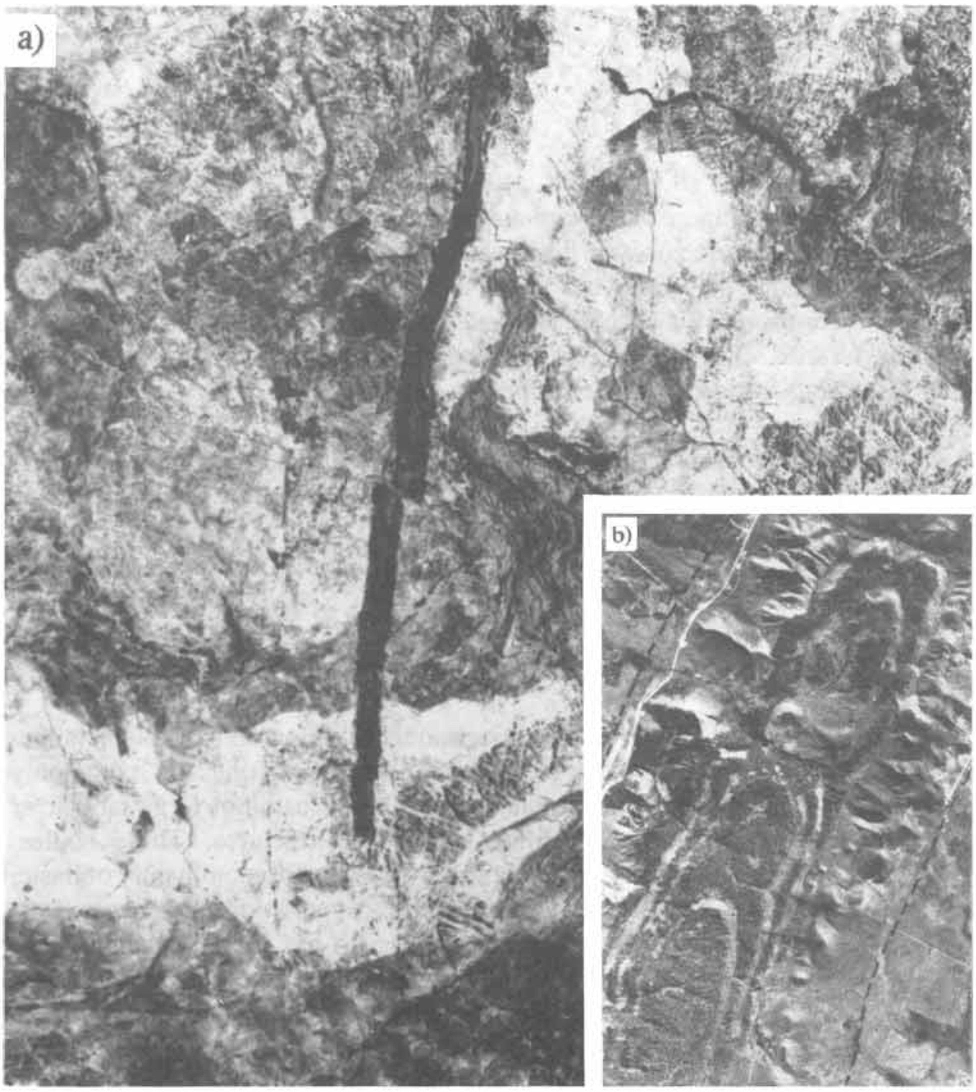
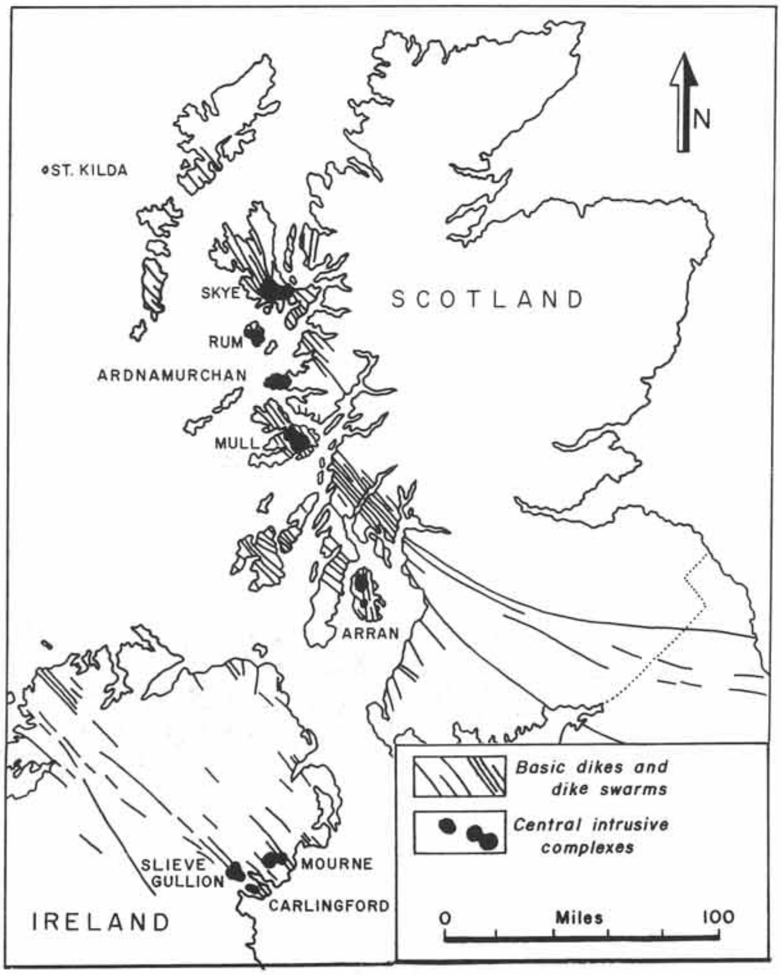


Figure 13-1: *a) Landsat image of six-kilometer-wide graben, containing the Great Dyke, Zimbabwe. b) Aerial photo, revealing erosion-pattern of horizontal cumulus layers now trapped in the central graben.*

Indeed, rather than emplacing a huge volume of igneous rock into one single fissure, *swarms* of subparallel, smaller dikes are more common in many parts of the world with formerly rifted, continental crust. The early Tertiary basic dike swarm of the British Isles is a good example of failed rifting (Fig. 13-2). The rifting ceased in an early stage, but, if the rifting continues, the continental crust may fail altogether and separate to give way to newly formed oceanic crust (Fig. 13-3). The ocean floor is composed of gabbro intrusions, overlain by basalt flows.

Much of the ocean floor's internal structure remains inaccessible, because the oceanic lithosphere is normally subducted back into the mantle when colliding with another plate. But, occasionally, segments of the subducting oceanic plate may be flexured or may become less dense so that they are *obducted* or thrust onto the continental margin. Consequently, the structure and composition of the oceanic crust, generalized in Figure 13-3, can be studied in detail in such obducted *ophiolites*, which crop out along many major collision sutures (e.g., in Oman). It is important to remember, however, that the oceanic crust preserved in ophiolite complexes was ini-

Figure 13-2: *NW-SE trending Tertiary basic dike swarm and central intrusive complexes of the British Isles and northern Ireland (Skye, Rum, Ardnamurchan, Mull, Arran, Mourne, Slieve, Gullion, and Carlingford).*



tially formed by rifting and spreading, rather than by the shortening involved in its emplacement onto the continental crust.

Iceland, perhaps, is one of the most unique locations for unravelling the internal structure and active growth of oceanic crust. It is located on the mid-Atlantic spreading ridge and is entirely made of modern oceanic crust. Figure 13-4 illustrates fresh 1988 lava and normal faults in the central rift zone near the Krafla field of Iceland. The time-averaged spreading rate across the rift zone is about five centimeters per year.

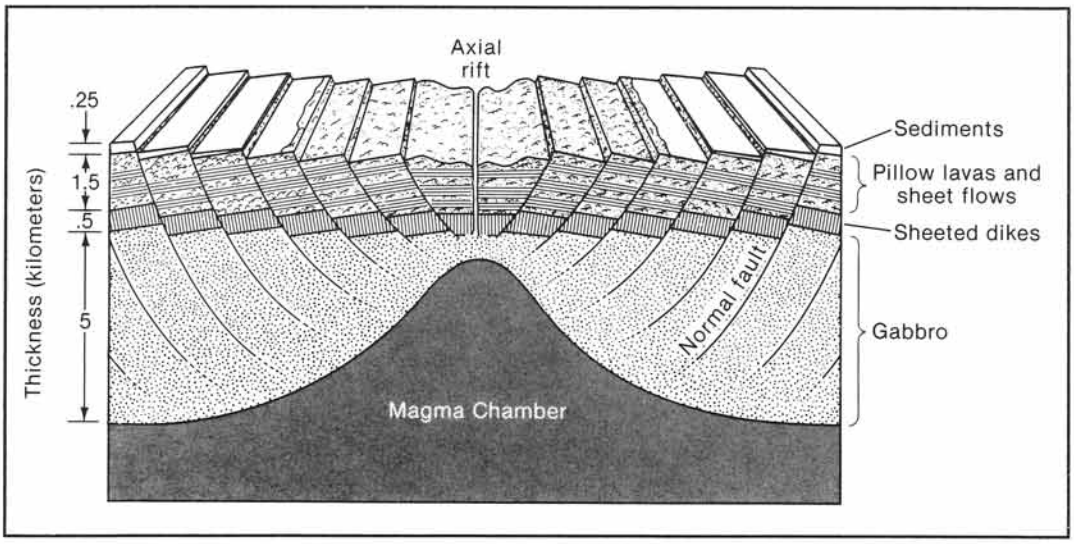


Figure 13-3: *Idealized cross-section of oceanic crust near a mid-oceanic spreading ridge.*

Continental collision zones

The convergence of tectonic plates and the associated subduction causes *partial melting* in the interaction zone between them. It is, therefore, common to find huge acidic or granitic intrusions stoped inside the mountain ranges formed at collision zones (Fig. 13-5a). Some of the plutons rise so close to the ground surface that they may feed large, volcanic *eruption centers*. In the core of eroded mountain ranges, these plutons form batholith complexes that may become exposed at the surface after erosion. A batholith is a large, generally discordant, plutonic mass that has more than one hundred square kilometers of surface exposure and no known floor. Individual plutons within the floor of batholiths often dominate the landscape as barren monoliths, protruding from the ground surface after removal of the surrounding rock units in which they were initially emplaced (Fig. 13-6). Batholiths are found in the core of all major fold belts. They may form at active collision zones of oceanic-continental lithosphere. They are, also, found in the thrust belts of mountain ranges, formed when two continents ultimately collide after subduction of the intermediary oceanic lithosphere that drove them together. "Batholith" literally means "rock that came from the deep." The various emplacement mechanisms of batholiths are the subject of continual investigations and are beyond the scope of the present book.

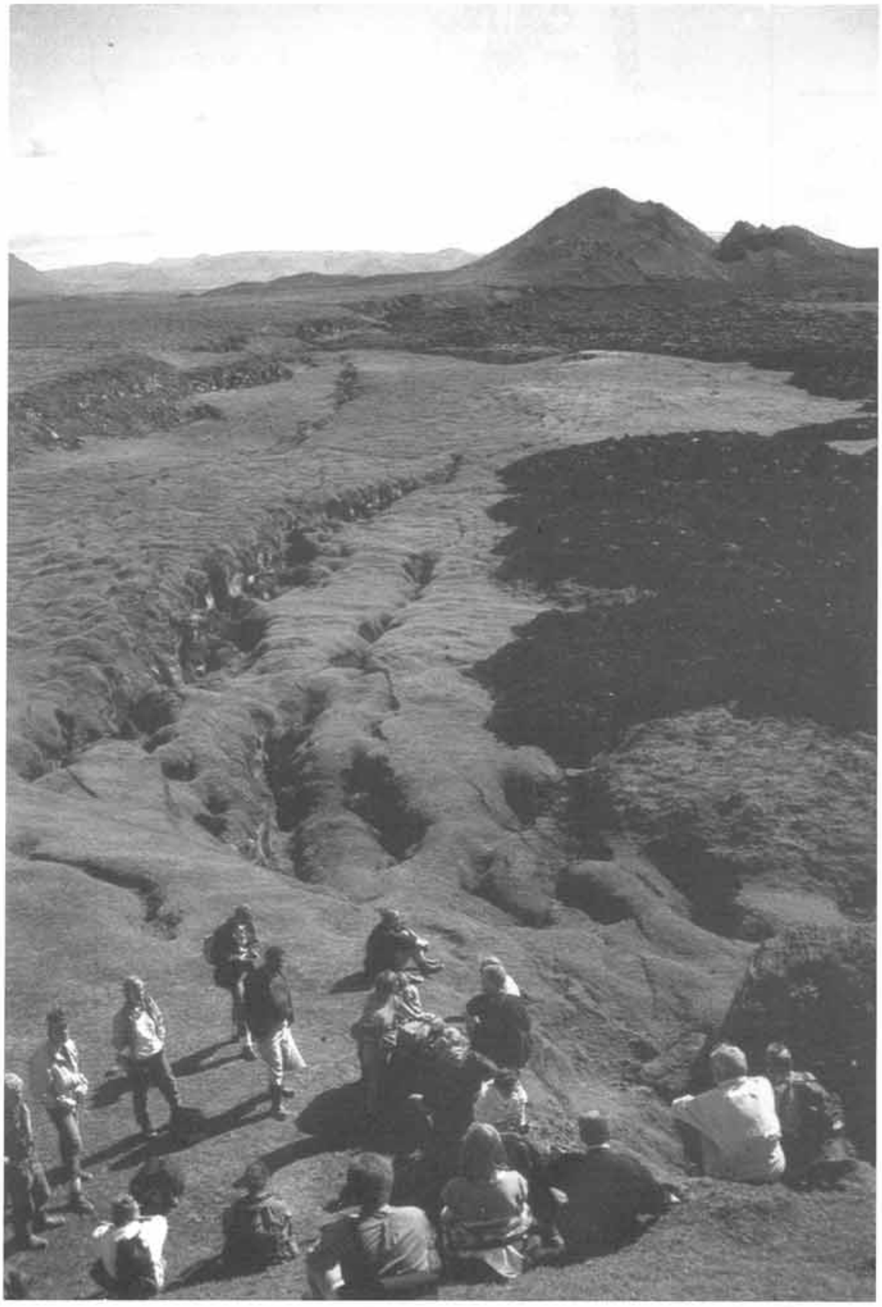


Figure 13-4: *Central rift zone near the Krafla field, Iceland. Looking due south, the North American plate, right, meets the Eurasian plate in the left of the image.*

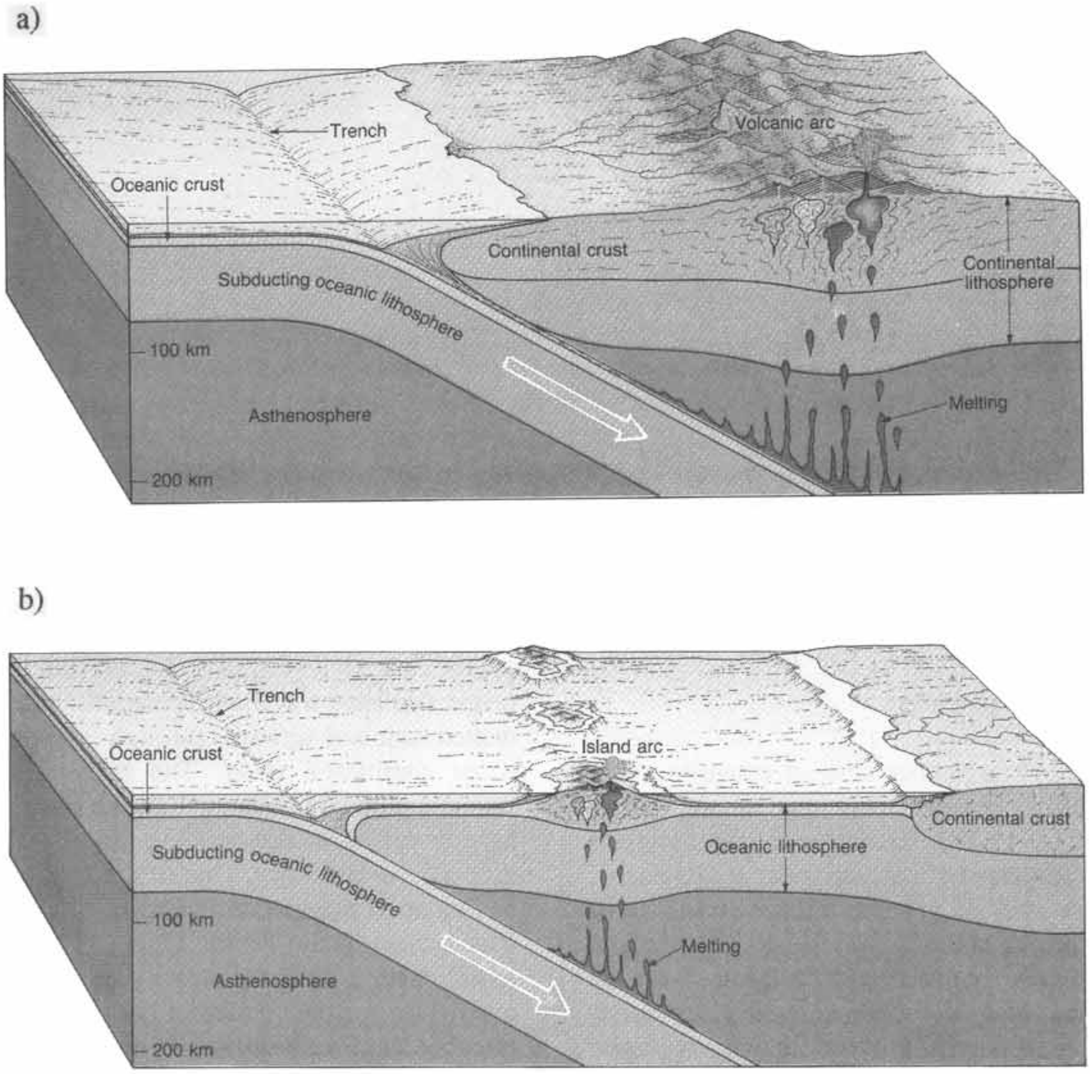


Figure 13-5: *a) Emplacement of plutons in proto-orogen on active continental margin. b) Formation of volcanic island arc in the overriding plate of an active oceanic-oceanic plate collision.*

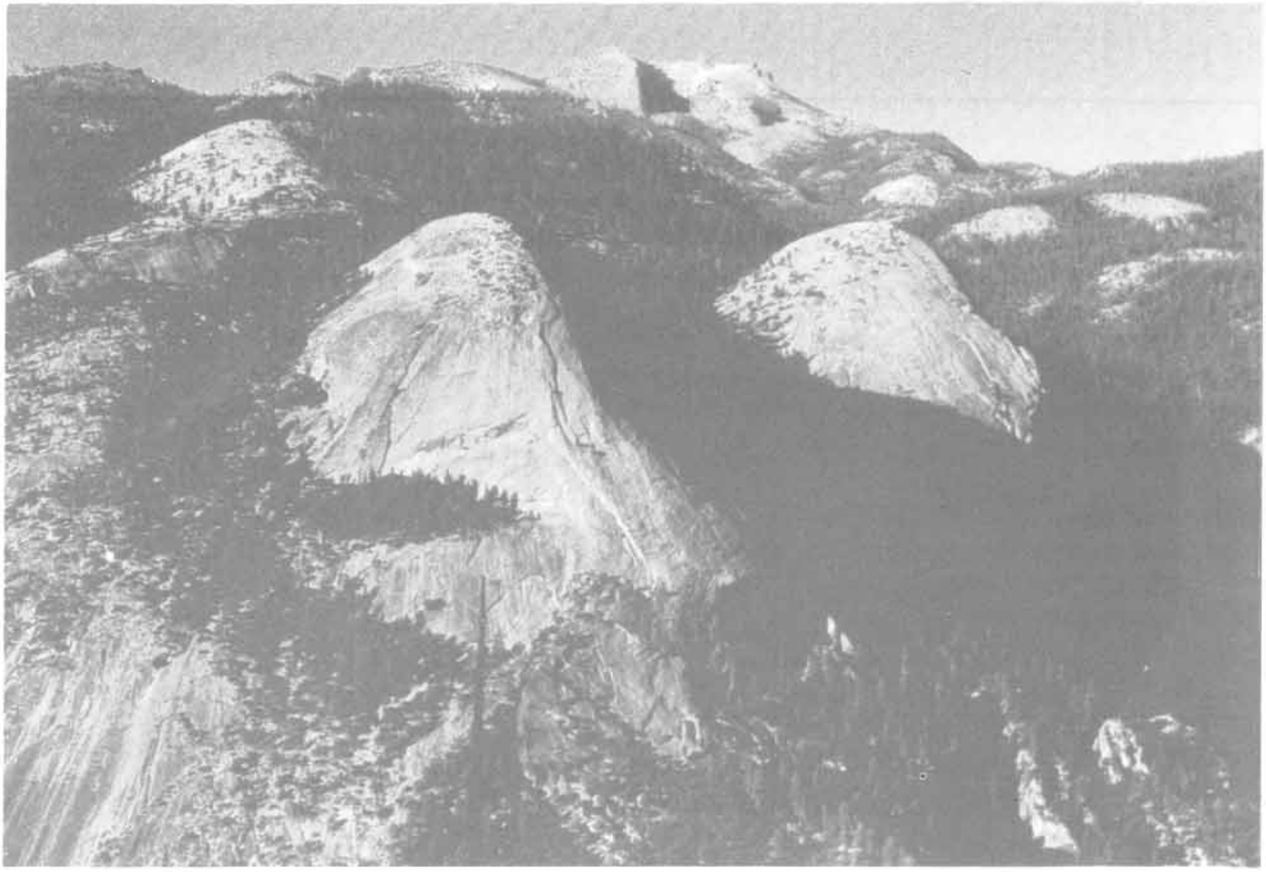


Figure 13-6: Exhumed plutons of the Sierra Nevada batholith, Yosemite National Park, California.

Subduction island arcs

Island arcs are other sites of extensive magmatic activity, formed where two oceanic plates collide (Fig. 13-5b). Examples are the Aleutians and the Indonesian and Japanese archipelagos, which are sites of granitic intrusions associated with extensive andesitic volcanism. Such island arcs naturally connect with volcanic belts on continental margins, because volcanoes form, also, where a continent overrides oceanic plates. For example, Mount Katmai is an active volcano on the continental margin of the Alaskan Peninsula that lines up with similar volcanoes on the oceanic island arc of the Aleutians (see next chapter, section 14-7).

Another type of magmatic emplacement occurs above *hot-spots*. These are parcels of deep mantle origin that have travelled through the mantle and melted their way upwards through existing oceanic or continental crust. The buoyant hot-spot material probably escapes from the unstable D''-layer (pronounce "dee-double-prime layer") at the core-mantle boundary. One of the best examples of hot-spot magmatism created the Hawaiian island chain in the Pacific Ocean. This volcanic island chain is nowhere near a plate boundary. It grew from episodic pulses of hot mantle magma, piercing from the mantle into the northwestward moving Pacific plate (Fig. 13-7).

☐Exercise 13-1: Consider regions of modern magmatic activity close to your region, and discuss their specific types of tectonic settings.

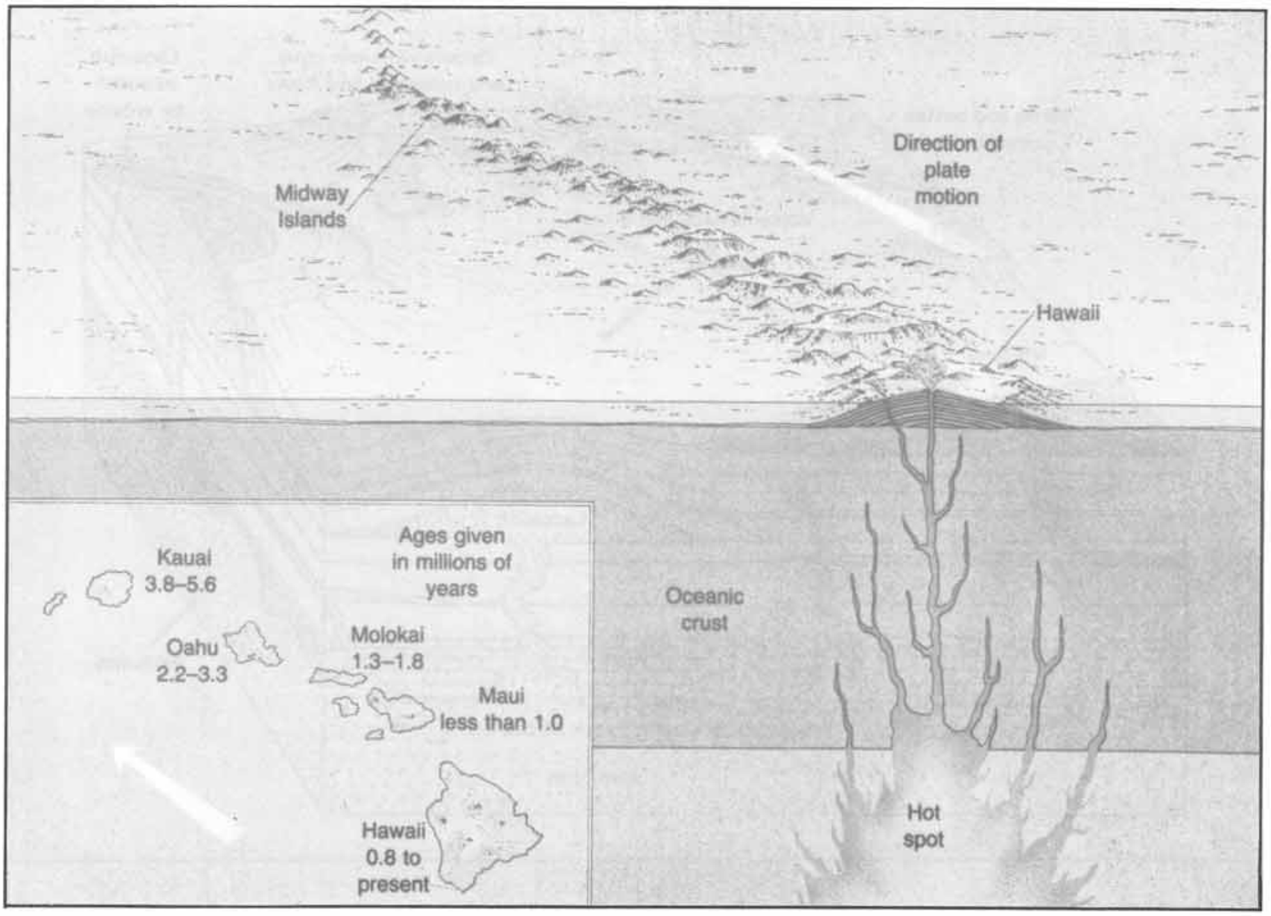


Figure 13-7: *The volcanic island chain, stretching from the Aleutian trench towards Hawaii, is emplaced by magmatic pulses of a stationary hot-spot, which is overridden by the northwest-moving Pacific plate.*

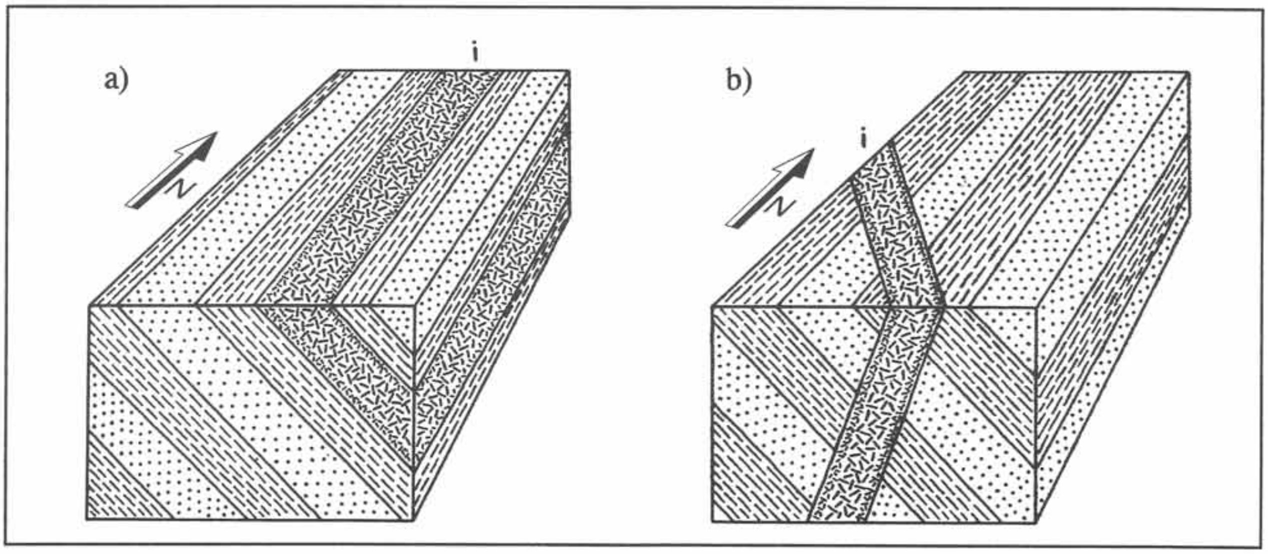


Figure 13-8: *Igneous dikes (i) intruded: a) concordantly, and b) discordantly, with respect to the layering of the host rock.*

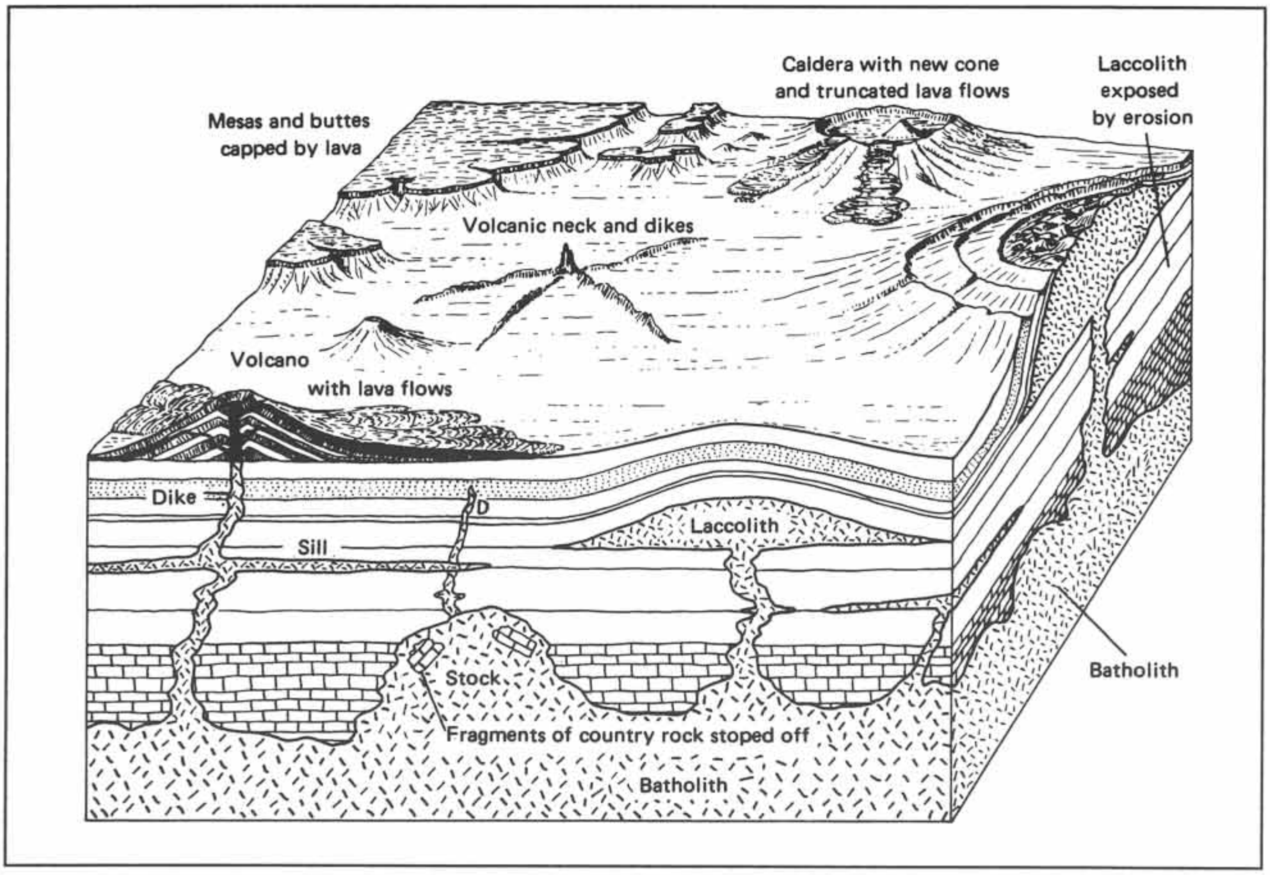
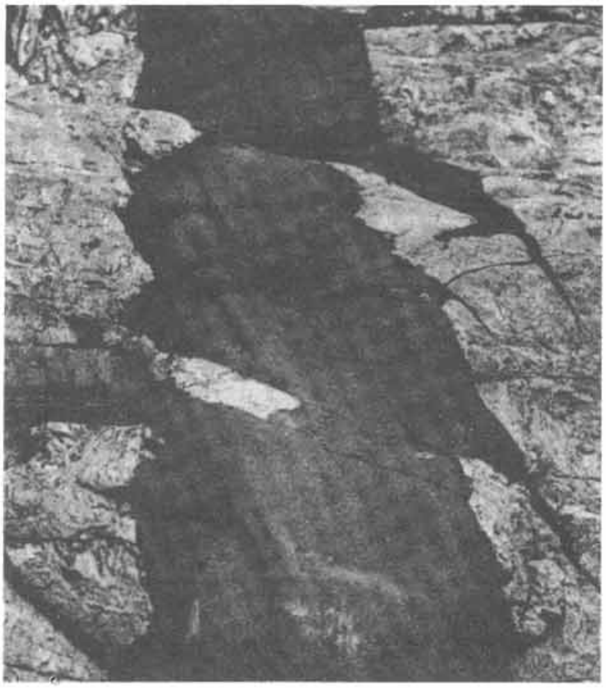


Figure 13-9: The geometry of a magmatic complex, including: stock, dike, sill, and laccolith in the subsurface, and lava flows, neck, and caldera at the surface.



13-2 Shape of igneous intrusions

Magmatic intrusions may cut across the lithological contact between pre-existing rock structures or may force their way parallel to pre-existing surfaces. Intrusions that cut across such contacts are termed *discordant*; those injected along existing contacts are termed *concordant* (Fig. 13-8). Figure 13-9 is a block diagram of a hypothetical region with a subhorizontal sedimentary sequence, intruded from below by a massive *magma chamber*, occupying a large volume in the subsurface. It fingers upward into smaller protru-

Figure 13-10: Two-foot-wide diabase dike with apophyses intruded into host rock of rhyolitic tuffs, Rye, New Hampshire.

Figure 13-11a: *Gabbroic sill in subhorizontally-foliated Proterozoic rocks of Bank Island, Northwest Territories, Canada. The sill steps discordantly across the layering in the central part of the picture.*

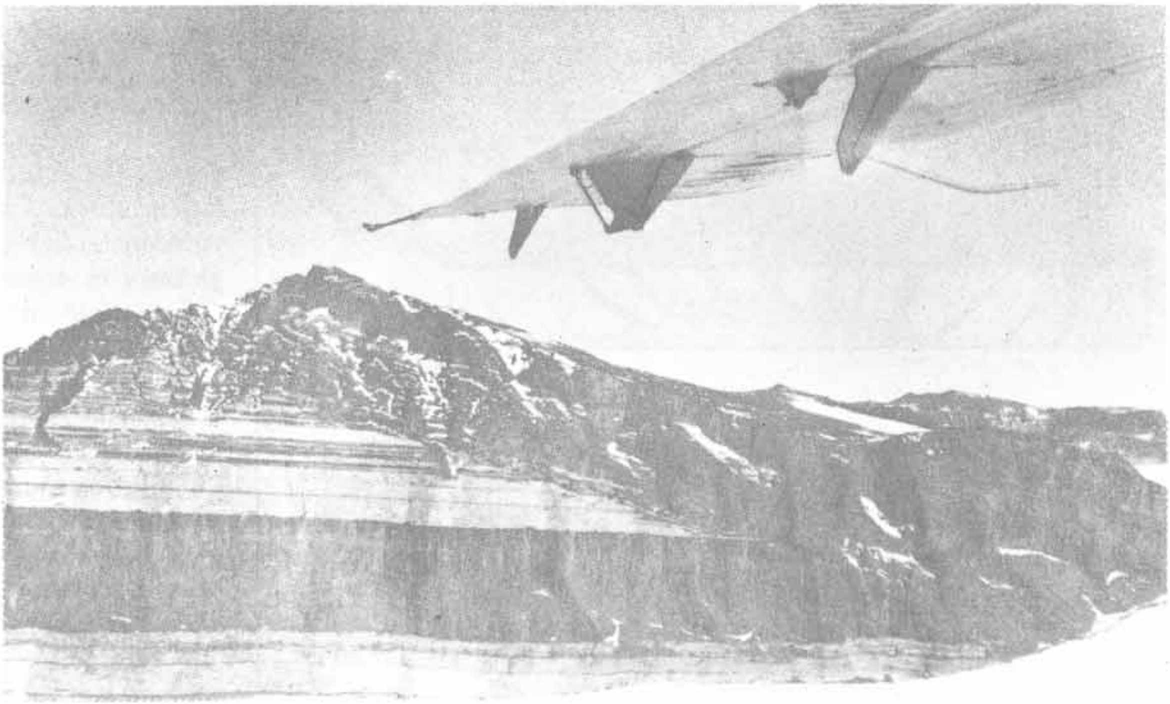


Figure 13-11b: *White-toned Carboniferous sandstones intruded by a concordant diabase sill. Both are truncated by a discordant diabase sheet, sloping to the right of the picture, Victoria Land, Antarctica.*

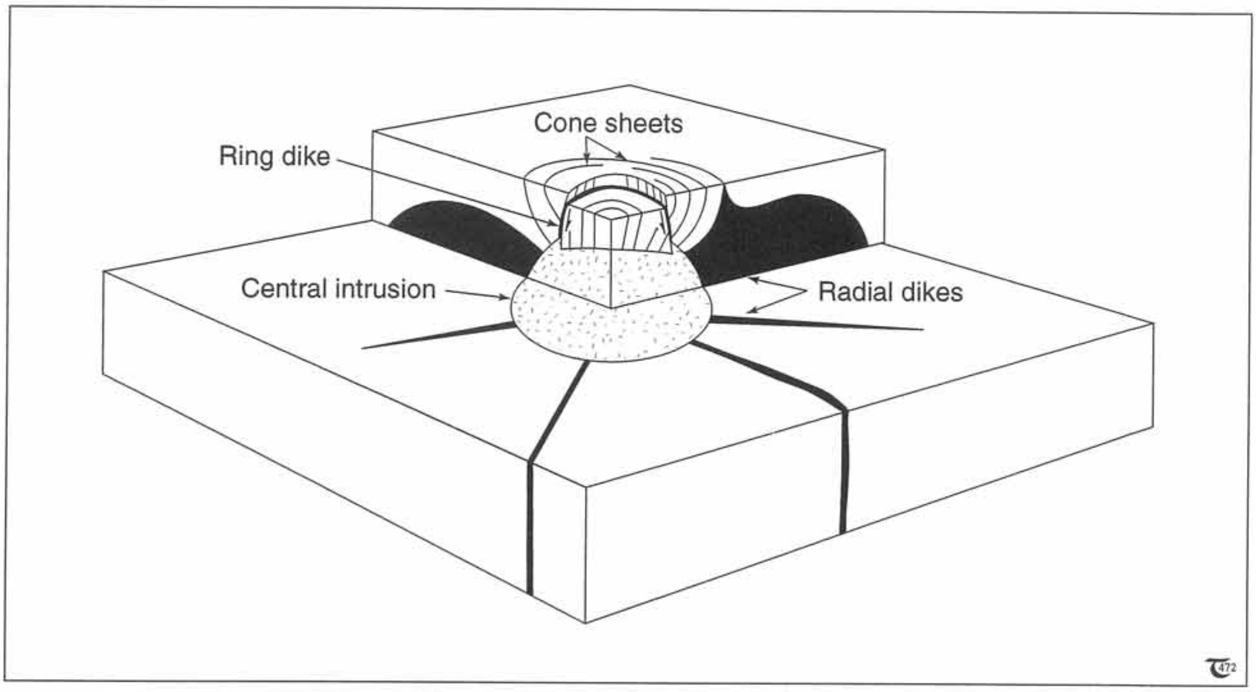


Figure 13-12: *Subsurface structure of a central subvolcanic complex. Shown are radial dikes, ring dikes, and cone sheets around the central magma chamber beneath the volcanic complex.*

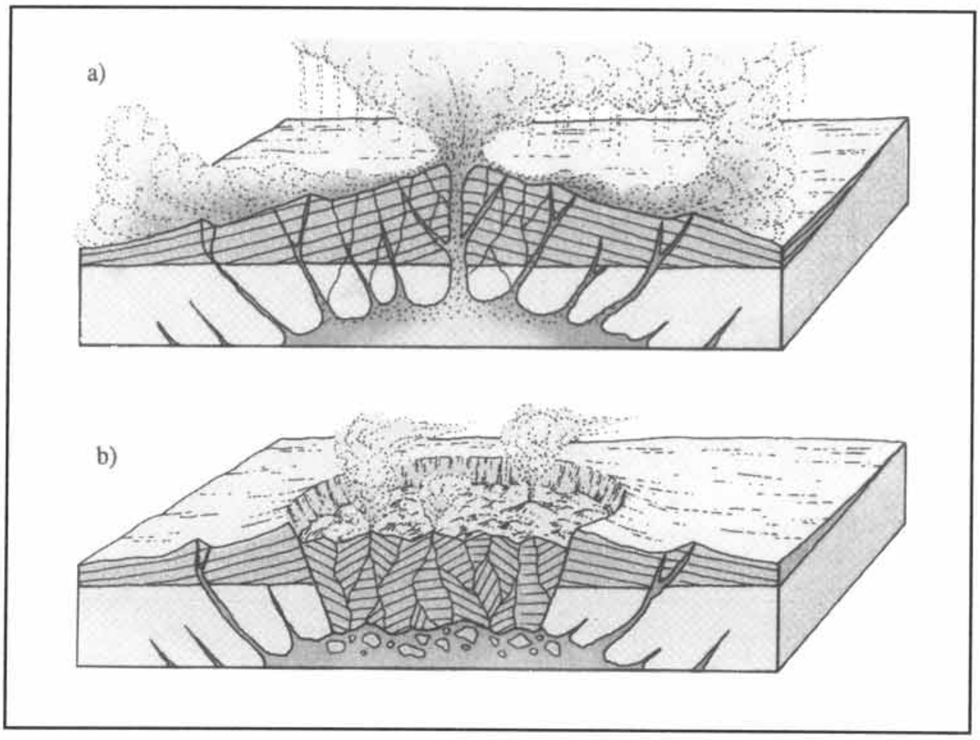


Figure 13-13: *Formation of a caldera. a) Build-up of a central volcano. b) Subsidence of the caldera floor, following a cone-sheet surface.*

sions, termed *stocks*. The stocks themselves feed narrower systems of magmatic injections, including *dikes*, *sills*, *laccoliths*, *necks*, and *volcanic cones* (see glossary in *Appendix C* for definitions).

Figure 13-10 shows a diabase dike, a discordant body, here about sixty centimeters wide, intruded into metamorphic rhyolite tuffs. Sills and laccoliths classify as concordant bodies, because they always closely follow the sedimentary bedding

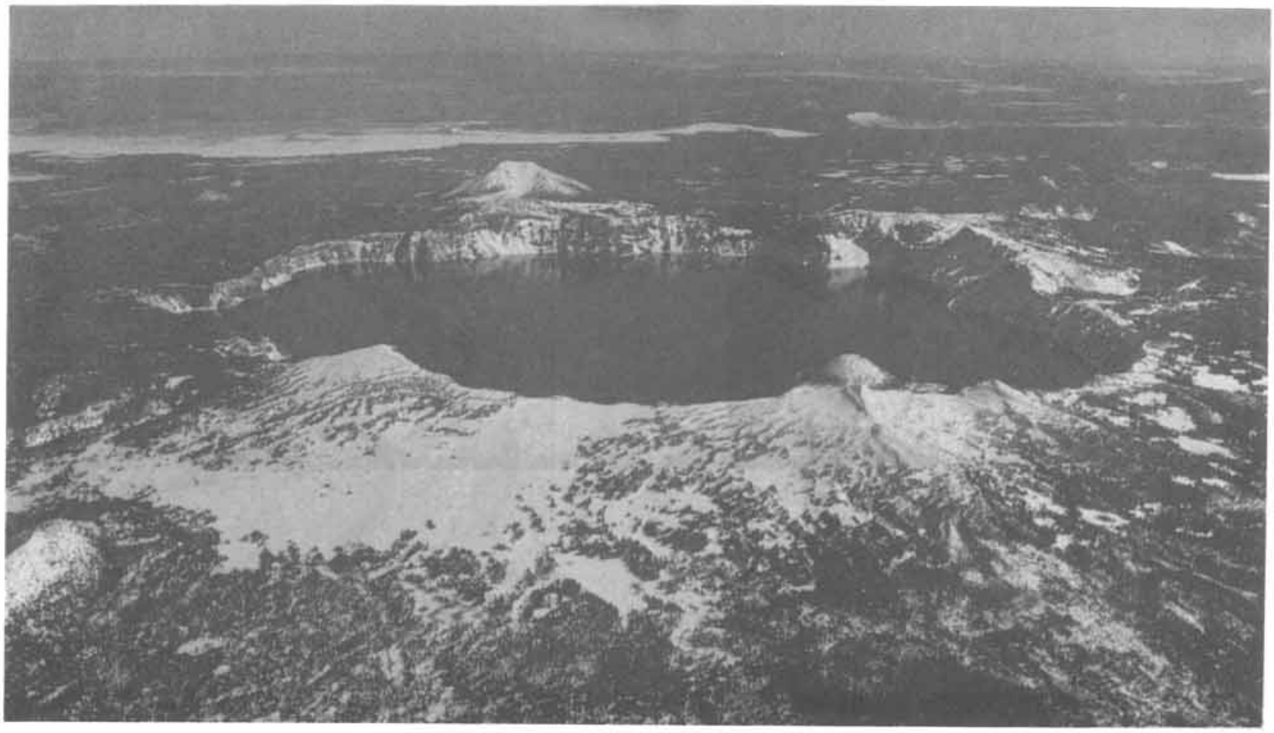


Figure 13-14: *Water-filled caldera of Crater Lake, ten kilometers across, with Wizard Island near the crater rim in the foreground, Oregon.*

or tectonic schistosity of the host rock. Sills and laccoliths are both tabular igneous bodies, that are commonly subhorizontal. The size of sills may range from several centimeters up to several hundred meters (Fig. 13-11a). Sills are more or less planparallel. Laccoliths differ from sills in that they cause updoming of the overlying strata (Fig. 13-9). The general term *igneous sheets* refers to tabular bodies, including both sills and dikes (Fig. 13-11b).

Figure 13-12 shows the generalized subsurface structure, as occurring beneath many major volcanoes. The so-called *subvolcanic complex* includes *radial dikes*, sub-circular *cone sheets*, and full circular *ring dikes* immediately above the central stock. The high pressure of the magma chamber and some thermal expansion elevate a central region, bounded by ring dikes. Alternatively, decompressed magma chambers may sometimes cause *cauldron subsidence*, a collapse of the central overburden into the underlying magma chamber, following the ring dikes as a surface of potential failure (Fig. 13-13). The resulting surface depression, termed a *caldera*, may be up to ten kilometers in diameter. Crater Lake, Oregon - which reaches that dimension - was formed 7000 years ago by the collapse of a former volcano, Mount Mazama. Subsequently, a smaller eruption from the caldera floor created a cinder cone, which emerges above the water surface - Wizard Island (Fig. 13-14). Other examples of calderas are outlined in the final section of chapter fourteen.

Plutons in map view may enclose isolated exposures of *cupolas* and *roof pendants* (Fig. 3-16). Cupolas are upward extensions of an igneous intrusion into its roof. Roof pendants are downward extensions of country rock into an igneous intrusion.

☐Exercise 13-2: The maps of Figures 13-15a and b outline in black the ring dikes, hosted in an igneous complex. Draw simple cross-sections M-N and O-P to illustrate the appearance of the ring dike at depth. Assume the ground surface has been leveled by erosion.

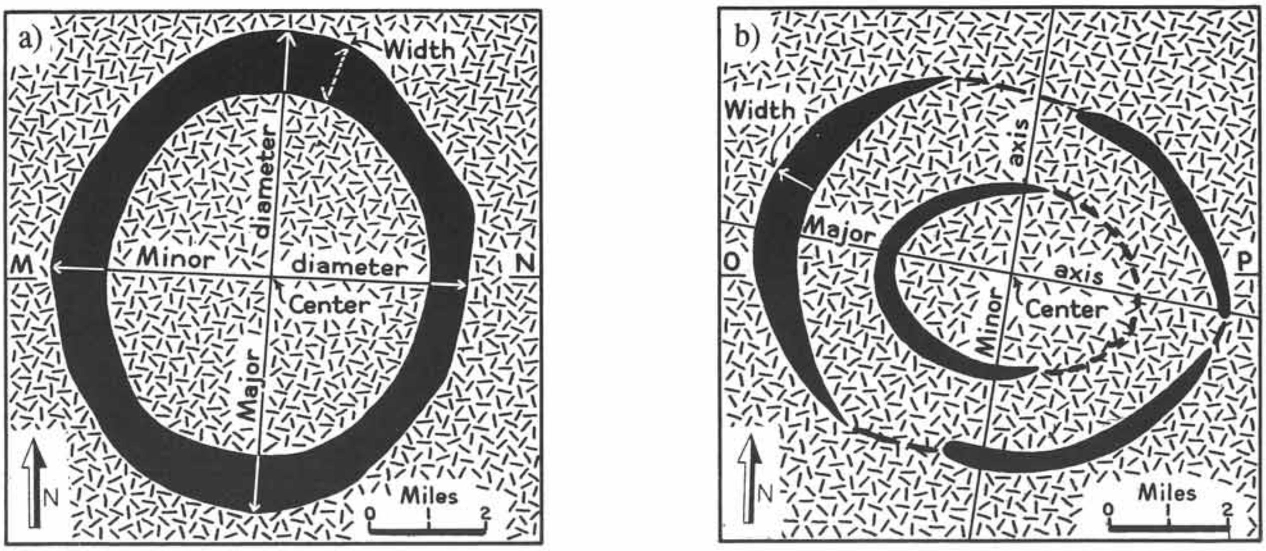


Figure 13-15: a) & b) Geological maps for exercise 13-2.

☐Exercise 13-3: Complete section Q-R across the map of Figure 13-16 to illustrate the subsurface extension of the central intrusion.

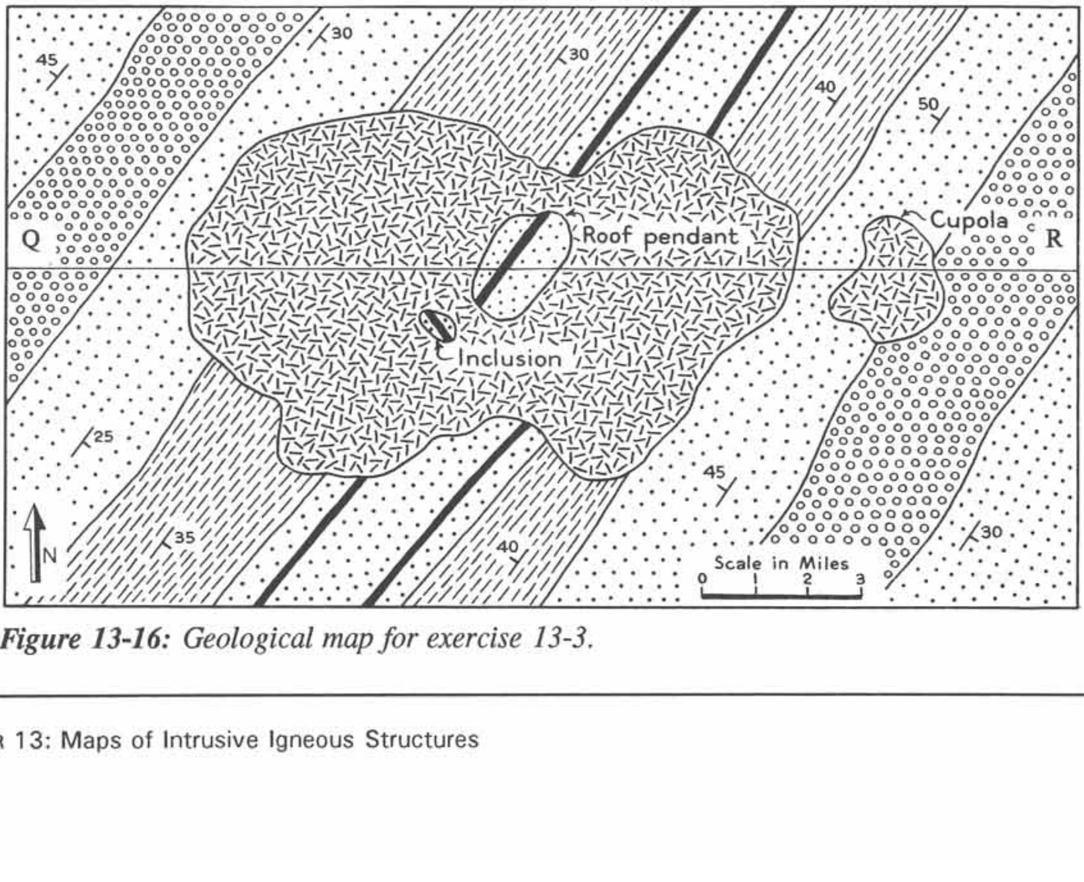


Figure 13-16: Geological map for exercise 13-3.

☐Exercise 13-4: The map of Figure 13-17 outlines the orientation of four basic dikes on a topographic base map. Complete section X-Y to clarify the extent of the dikes at depth.

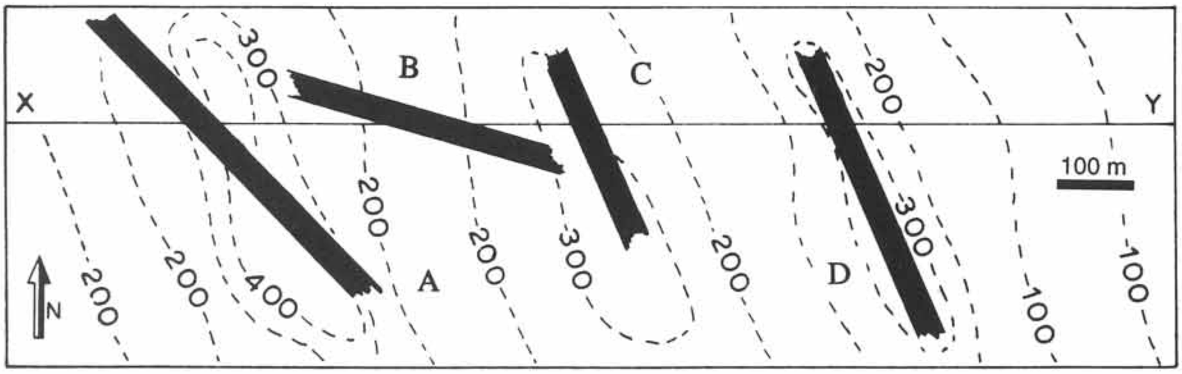


Figure 13-17: Outcrop pattern of igneous dikes on topographic base map. See exercise 13-4.

13-3 Zoned plutons and ring dike complexes

Plutons are bodies of intrusive igneous rocks, solidified from a cooling magma. A batholith is formed by a collection of plutons. The final appearance of plutons and batholiths depends on a variety of physical quantities and conditions and, thus, displays a range of possible shapes and sizes. Plutons are commonly of acid composition and intrude into relatively cold country rock from below, with internal temperatures of 700° to 900° centigrade. Contact metamorphism bakes the wall-rock into hornfelses, forming metamorphic aureoles of up to three kilometers thick around the igneous intrusion. The pluton itself is cooled by the country rock during the emplacement, and this may lead to *magmatic fractionation* and *differentiation*. The map of the Loch Doon pluton, southwest Scotland, illustrates the compositional zonation, mapped at the modern ground surface (Fig. 13-18). The *zonation* reflects the magmatic differentiation that took place either during the emplacement of the batholith or in the magma chamber before the emplacement of the successive magma batches that constitute the pluton. The core of the pluton is of granitic composition, and the margins are dioritic. The map of Figure 13-19 illustrates another *zoned pluton* from central Peru. The internal zonation of such igneous bodies is essentially formed during a single magmatic episode.

In other regions, patterns of intersecting cone sheets and ring dikes suggest that the emplacement of parts of igneous complexes occurred in distinct pulses. The map of the Tertiary ring dike complex on the island of Mull, Scotland, shows several distinct generations of ring dikes (Fig. 13-20). Similarly, the *subvolcanic complex* of Ardnamurchan involves ring dikes and cone sheets of, at least, three successive centers of magmatic activity (Fig. 13-21). It is possible that the underlying pluton was emplaced in a single *magmatic episode*, but that the subsequent intrusion of ring dikes and subsidence of cone sheets occurred during several episodes of volcanic outburst, associated with the slow degassing and settling of a *magma chamber*, cooling in the subsurface.

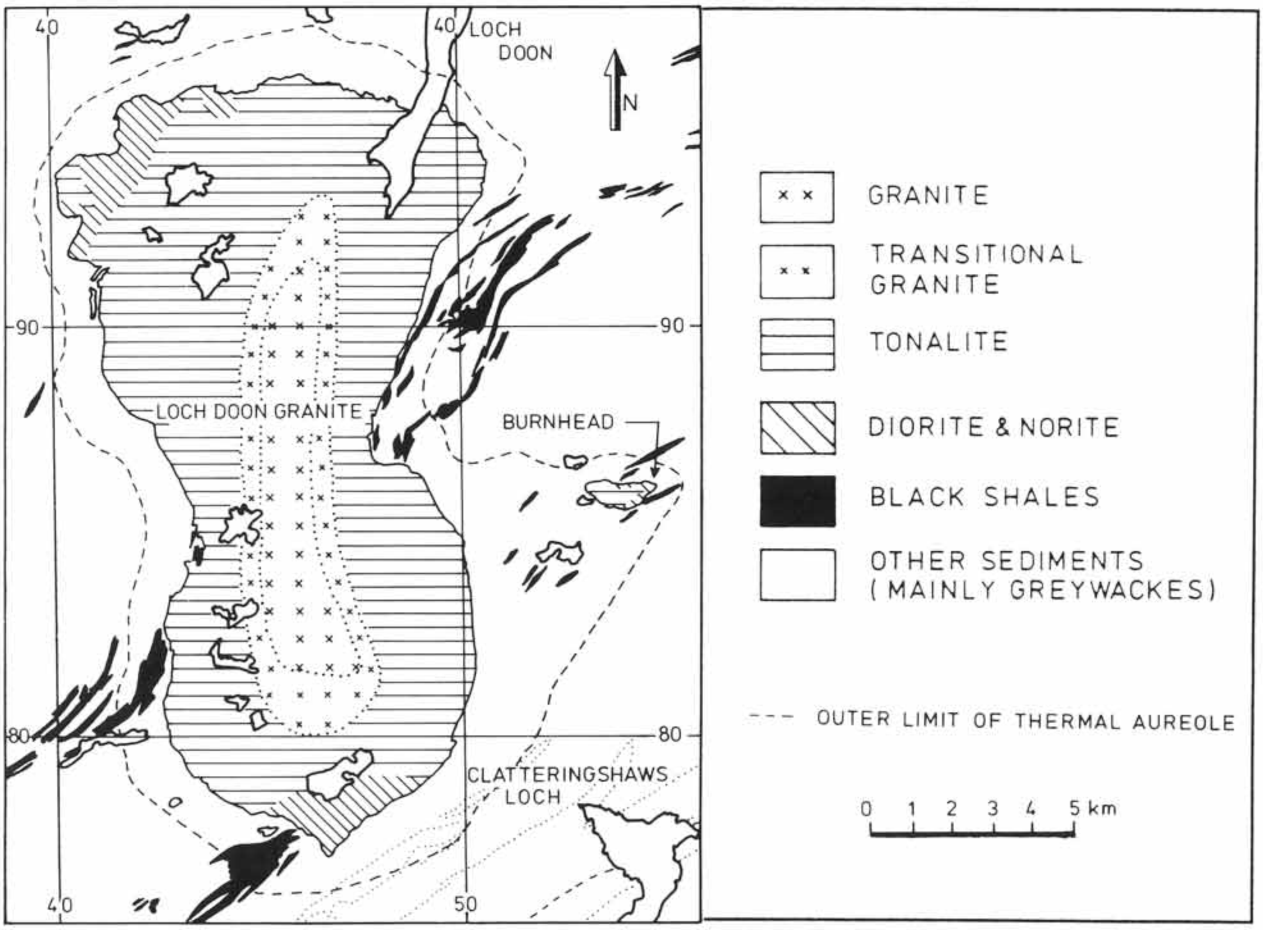


Figure 13-18: Zoned pluton of Loch Doon, southwest Scotland.

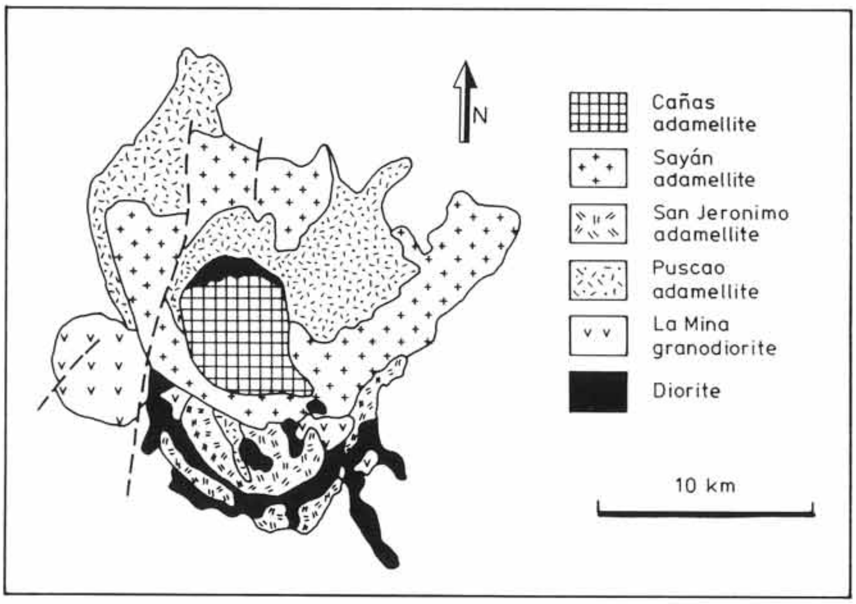
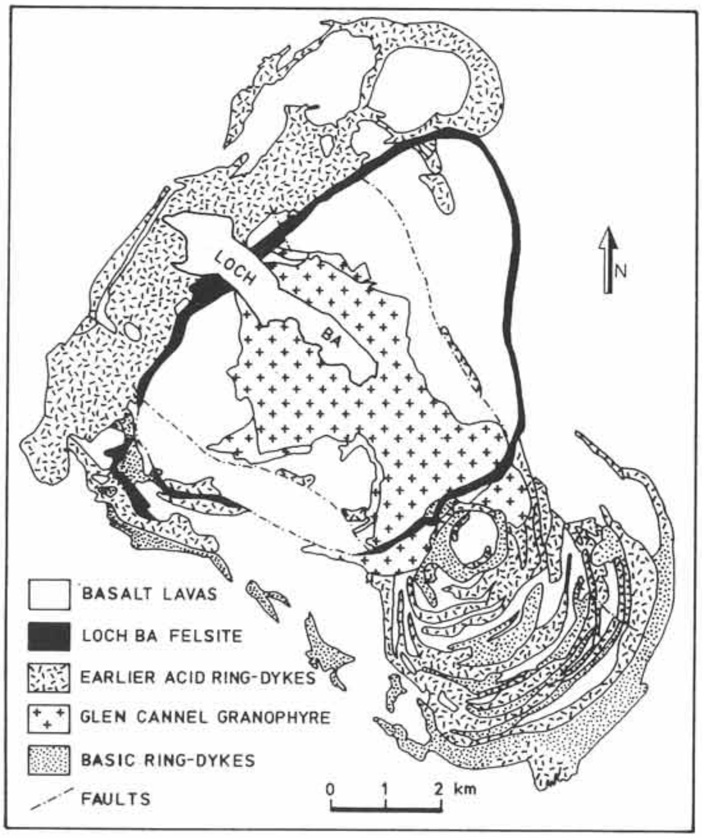


Figure 13-19: Zoned pluton, central Peru.

Figure 13-20: Geological map of Tertiary ring dikes and igneous complex of Mull, Scotland. For location see Figure 13-2.



☐Exercise 13-5: Study the map of Figure 13-20, and distinguish intrusion centers and their sequence, similar to the distinction made for the central intrusive complex of Ardnamurchan in Figure 13-21.

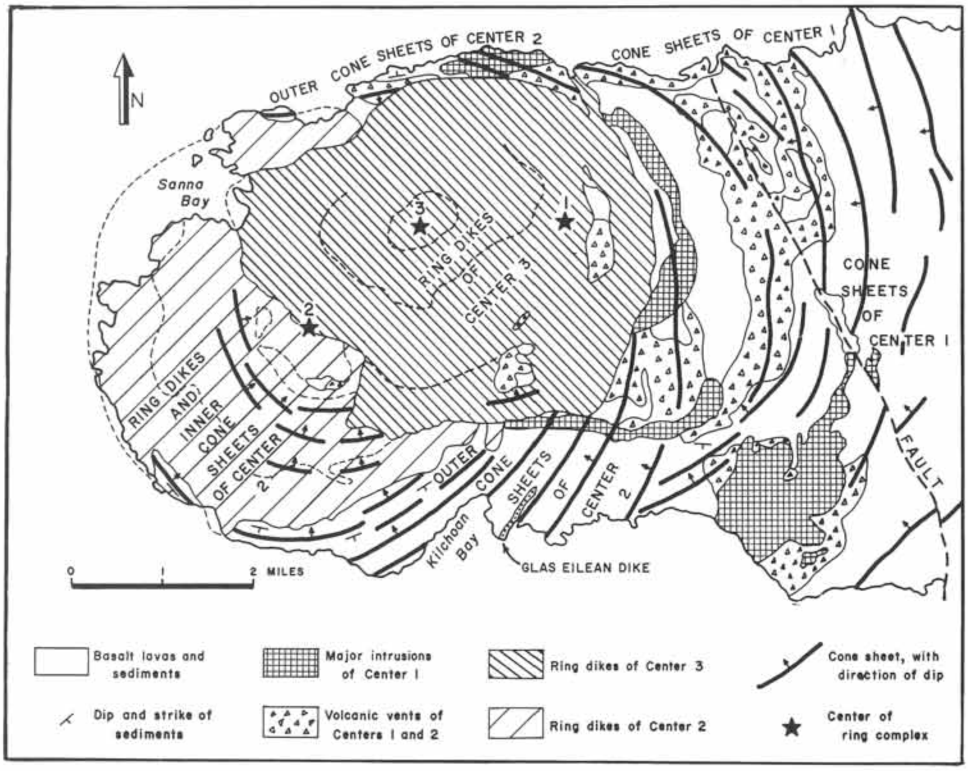


Figure 13-21: Geological map of the Tertiary central intrusive complex of Ardnamurchan, Scotland. For location see Figure 13-2.

13-4 Nested plutons and mantled gneiss-domes

Many plutons are emplaced in the core of orogens, formed along active continental margins. The plutons may be numerous and tend to coalesce at depth to define a *magmatic belt* of interconnected plutons. Such magmatic belts are found in the interior of the Himalayas, Alps, Pyrenees, Andes, and Rocky Mountains. The magmatic belts create batholiths, that commonly cut across the folded layering of the country rock and represent an advanced stage in the formation of a mountain range. For example, Figure 13-22 illustrates the coalescence or nesting of several plutons in the core of the Sierra Nevada, in the heart of the North American Cordillera. These plutons are *syntectonic*, which means that they were emplaced during the orogenic episode that involved folding of the country rock. The plutons partly cut across existing fold trends but, also, follow the grain of the fold belt, which locally wraps around the plutons.

Most Precambrian terrains are characterized by the occurrence of so-called *mantled gneiss-domes*. These are pluton-shaped masses of granite-gneiss, nested in overlying layered metasediments or supracrustals. Mantled gneiss-domes differ from the ordinary nested plutons by their higher degree of metamorphism and by the consistently concordant relationship of their boundary with structures in the host rocks. The map of Figure 13-23 illustrates gneiss domes mantled by supracrustals, from the Canadian Precambrian shield region near Halliburton-Bancroft. The form lines, outlined by the foliation within these gneiss-domes, remain subparallel with the contact surface of the host rock, suggesting that the *foliation* formed coeval with the dome

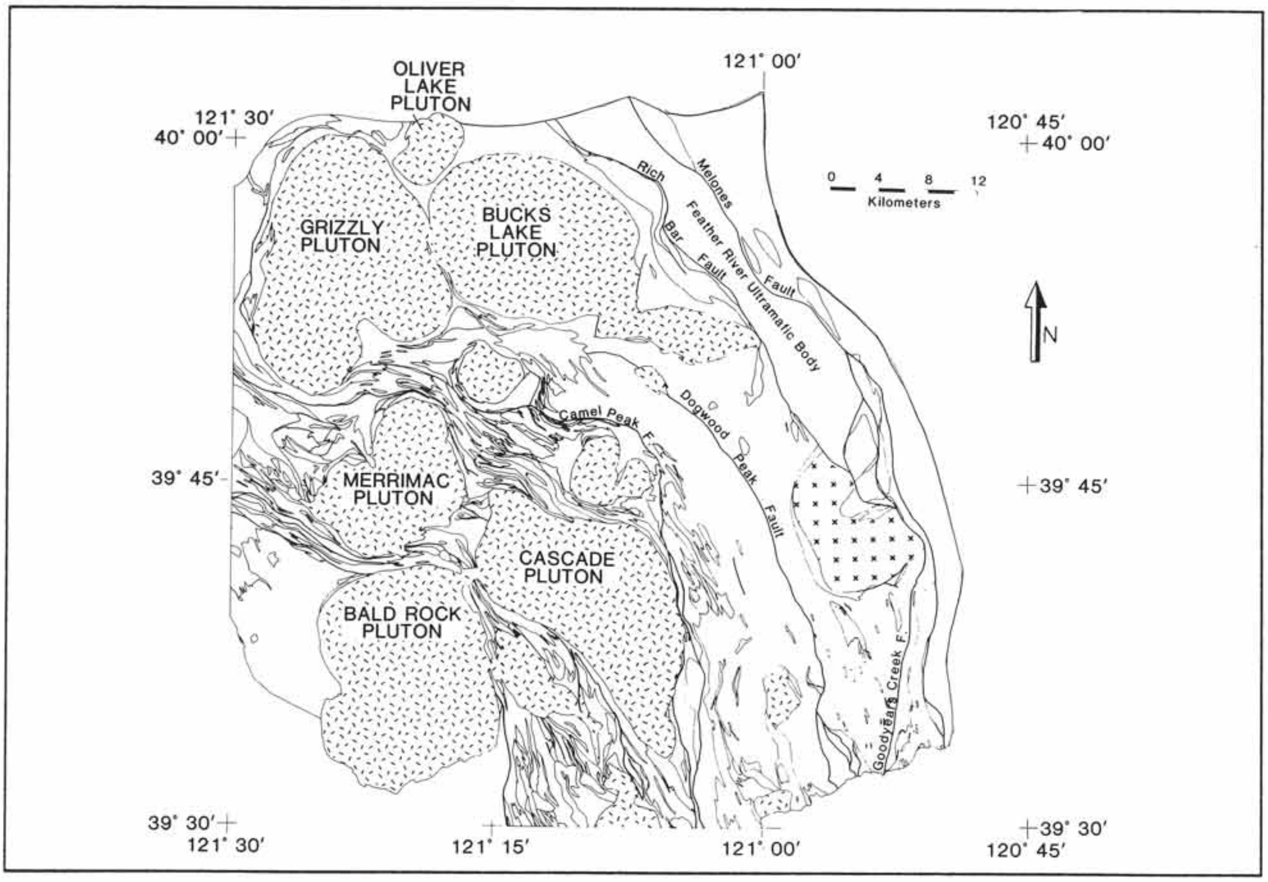
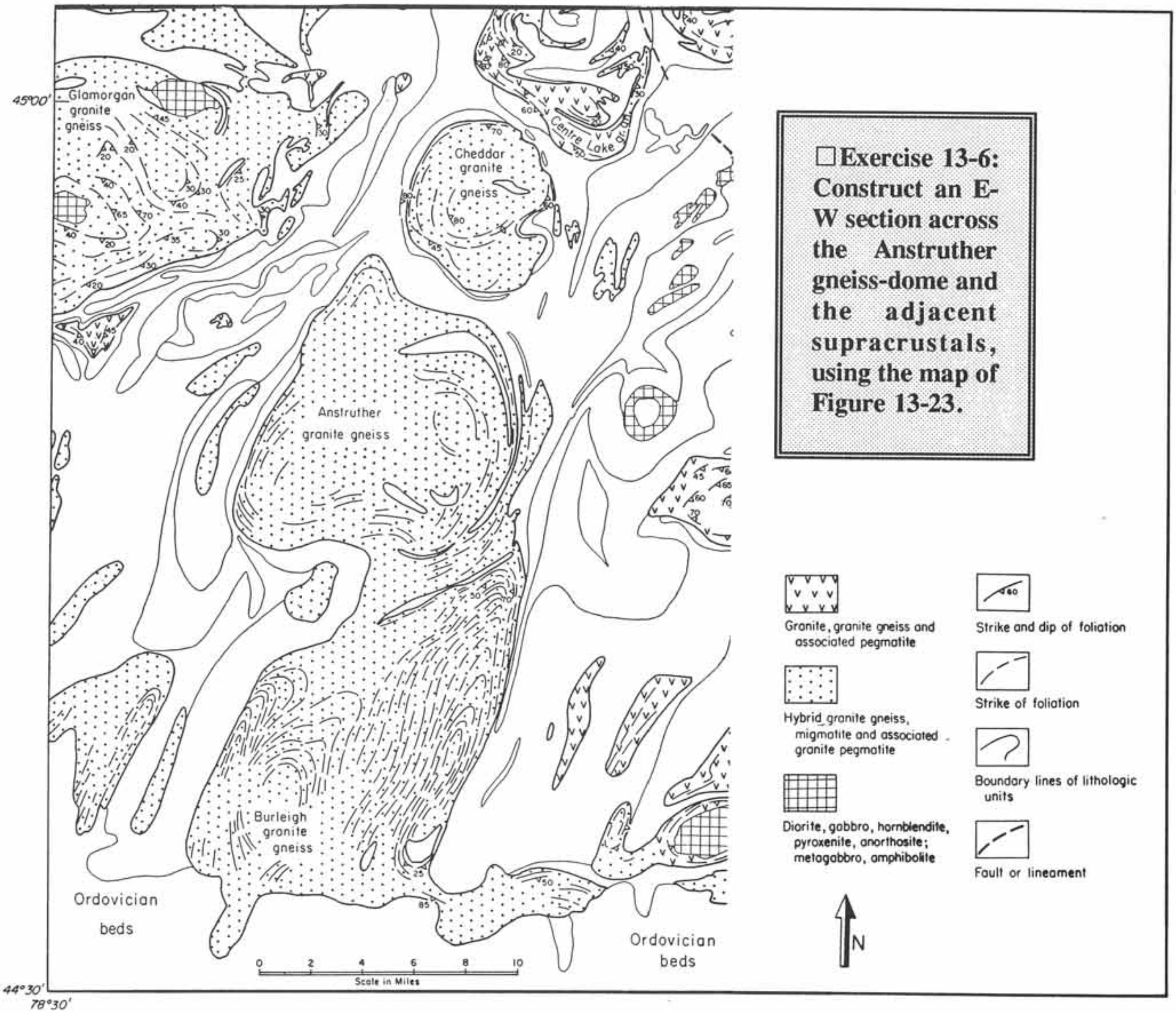


Figure 13-22: Geological map of nesting plutons in the central part of the Sierra Nevada, California.

emplacement. Some of the best-known, mantled gneiss-domes occur in the Archean greenstone-granodiorite rocks of the Zimbabwe craton, Africa (Fig. 13-24). The plutons are enveloped in strongly folded and foliated greenstone schists, concordant with the intrusive contacts. The interior of the plutons may still possess an igneous or magmatic texture, but their marginal zones are plastically deformed under metamorphic conditions, that commonly created an internal fabric or *gneissosity*.

Perhaps the most complex map patterns occur in geologic terrains, exposing deeply eroded gneiss-domes. The map of Figure 13-25 illustrates a region of the Proterozoic shield rocks in west Greenland. The form lines, that follow the gneissic foliation and compositional layering, outline a pattern of interconnected domes and basins. A more detailed map of the same area and a block diagram of the Tovqussap dome are illustrated in Figure 13-26a and b.



☐Exercise 13-6: Construct an E-W section across the Anstruther gneiss-dome and the adjacent supracrustals, using the map of Figure 13-23.

Figure 13-23: *Geological map of mantled gneiss-domes in Precambrian shield of Halliburton, Bancroft area, Canada.*

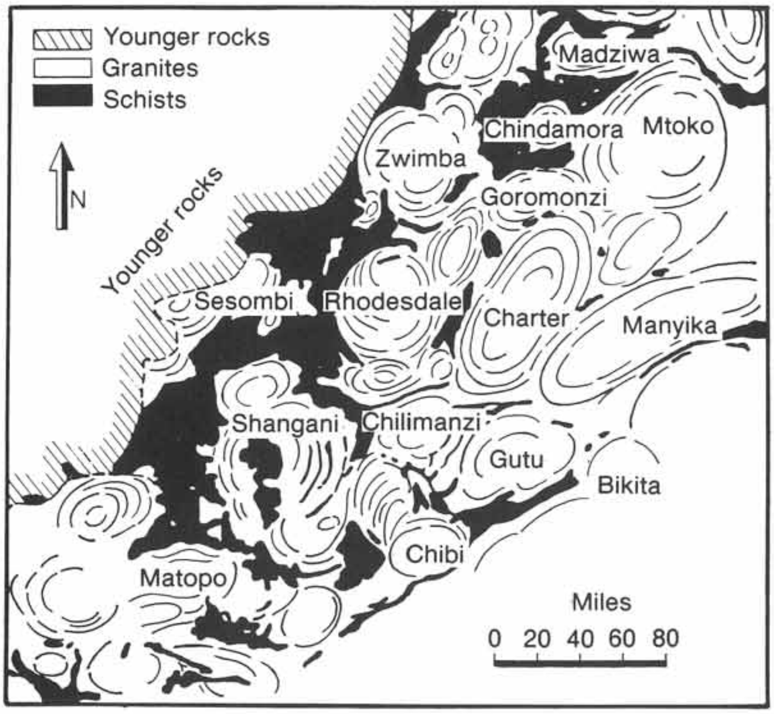


Figure 13-24: *Mantled gneiss-domes of the Archean Zimbabwe craton, Africa.*

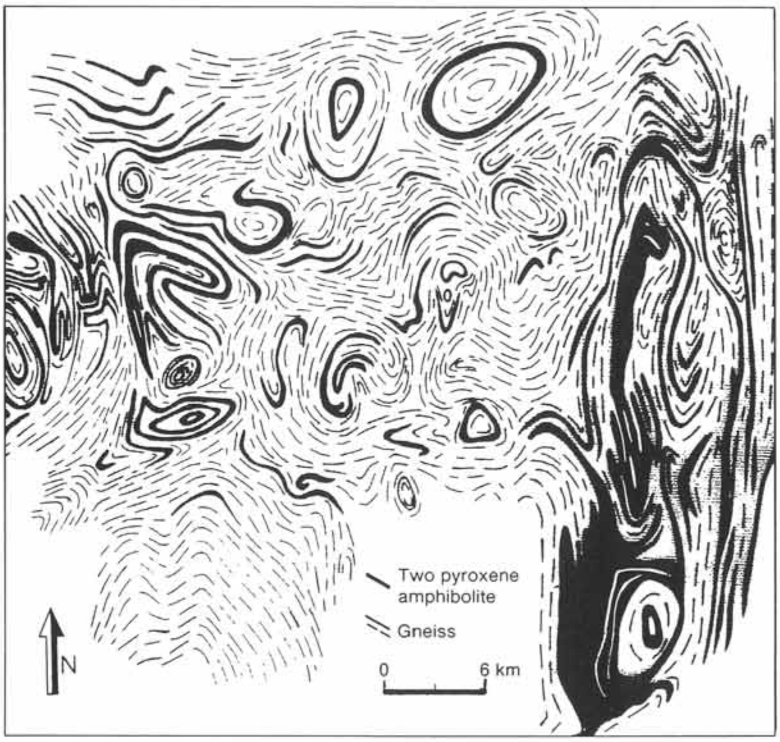


Figure 13-25: *Deeply eroded gneiss-domes of Proterozoic shield in Fiskefjord region, west Greenland.*

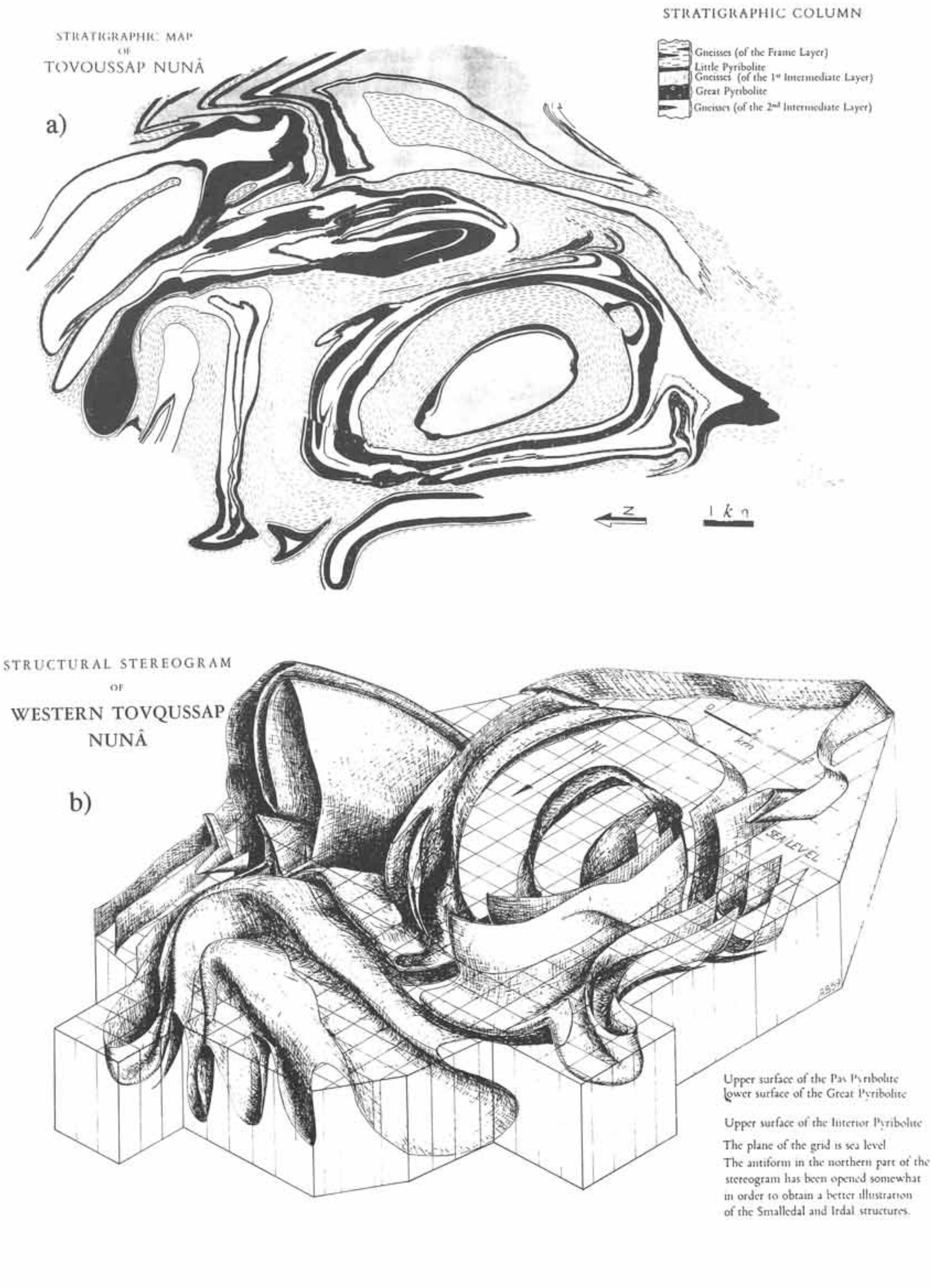


***Figure 13-26:** a) & b) Map and perspective diagram of the Tovqussap gneiss-dome, west Greenland.*

☐Exercise 13-7: The Landsat image of Figure 13-27 covers the Archean granite-greenstone terrain of the Pilbara block in the Precambrian shield of northwest Australia. Construct a simple, form-line contour-map of the basic features in this terrain of mantled gneiss-domes.

Figure 13-27: *Landsat image of granite plutons (light albedo) and surrounding supracrustals (dark) of the Archean Pilbara block, NW Australia. Image is 100 kilometers wide.*