Chapter 3: Cumulate Textures

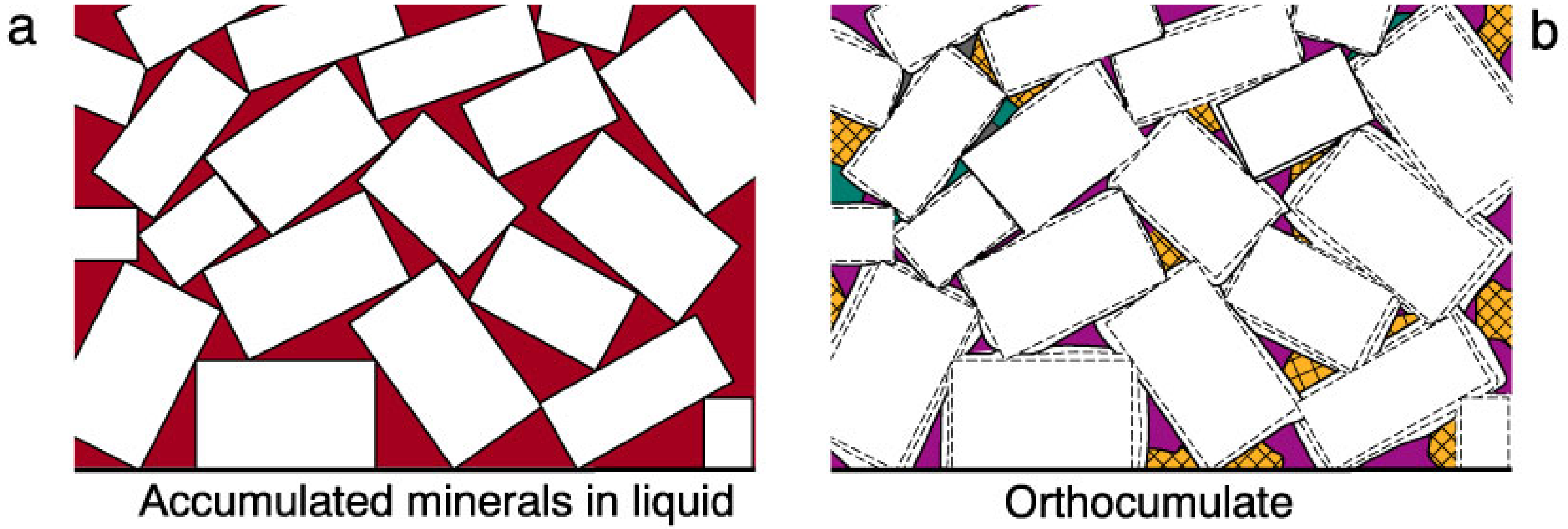


Figure 3.14. Development of **cumulate textures**. **a.** Crystals accumulate by crystal settling or simply form in place near the margins of the magma chamber. In this case plagioclase crystals (white) accumulate in mutual contact, and an intercumulus liquid (red) fills the interstices. **b.** Orthocumulate: intercumulus liquid crystallizes to form additional plagioclase rims plus other phases in the interstitial volume (colored). There is little or no exchange between the intercumulus liquid and the main chamber. After Wager and Brown (1967), *Layered Igneous Rocks*. © Freeman. San Francisco.

Chapter 3: Cumulate Textures

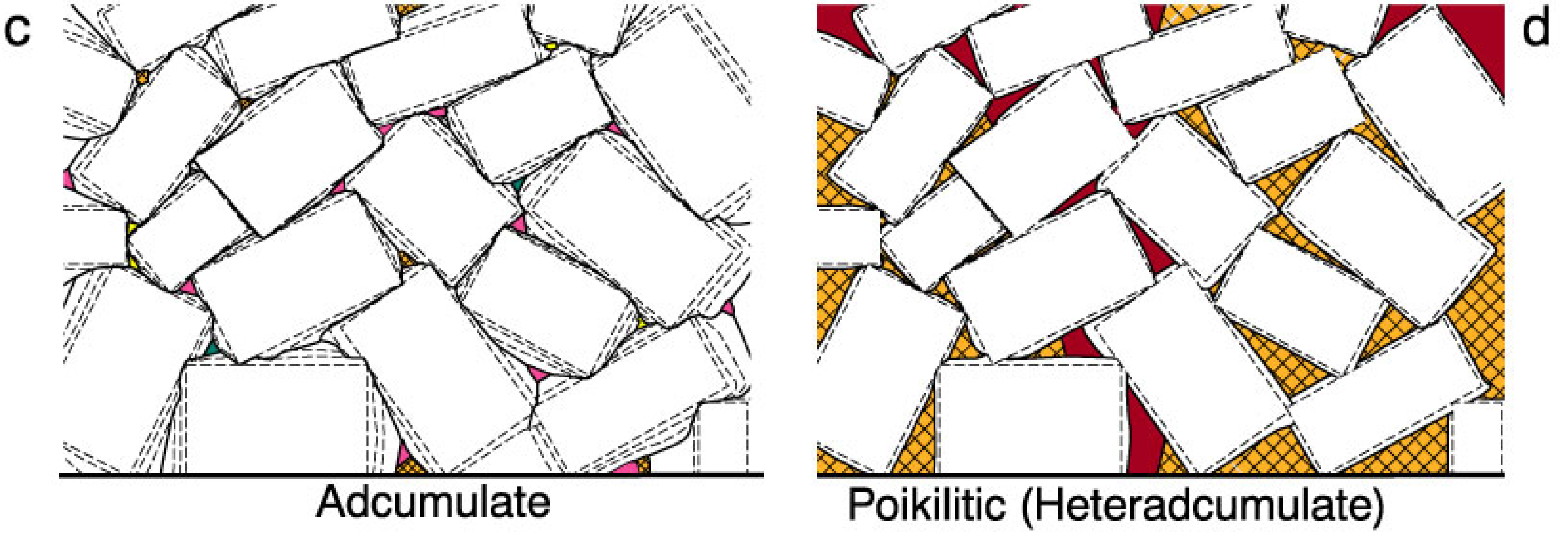
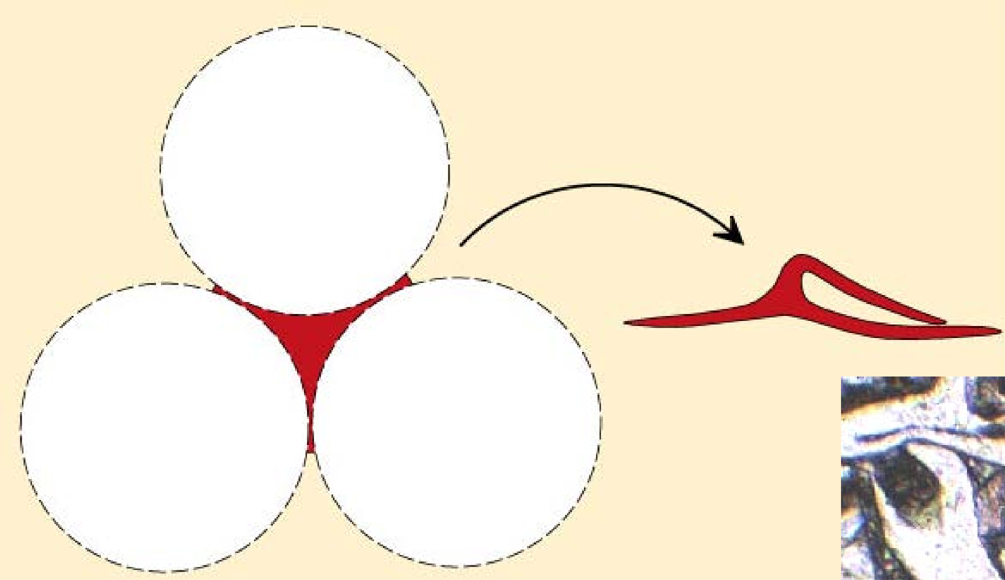


Figure 3.14. Development of **cumulate textures**. **c. Adcumulates**: open-system exchange between the intercumulus liquid and the main chamber (plus compaction of the cumulate pile) allows components that would otherwise create additional intercumulus minerals to escape, and plagioclase fills most of the available space. **d. Heteradcumulate**: intercumulus liquid crystallizes to additional plagioclase rims, plus other large minerals (hatched and shaded) that nucleate poorly and poikilitically envelop the plagioclases. . After Wager and Brown (1967), *Layered Igneous Rocks*. © Freeman. San Francisco.

Pyroclastic Textures



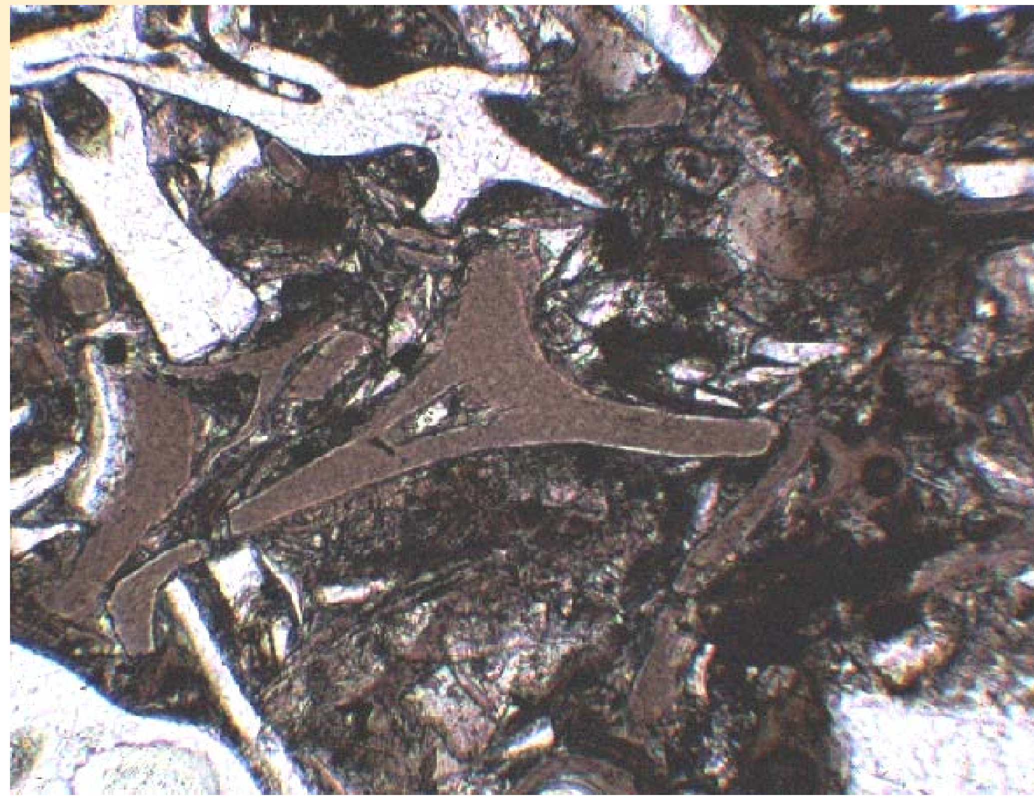


Figure 3.16a. The interstitial liquid (red) between bubbles in pumice (left) become 3-pointed-star-shaped glass shards in ash containing pulverized pumice. If they are sufficiently warm (when pulverized or after accumulation of the ash) the shards may deform and fold to contorted shapes, as seen on the right and **b.** in the photomicrograph of the Rattlesnake ignimbrite, SE Oregon. Width 1 mm.

Figure 3.18. a. Carlsbad twin in orthoclase. Wispy perthitic exsolution is also evident. Granite, St. Cloud MN. Field widths ~1 mm. © John Winter and Prentice Hall.

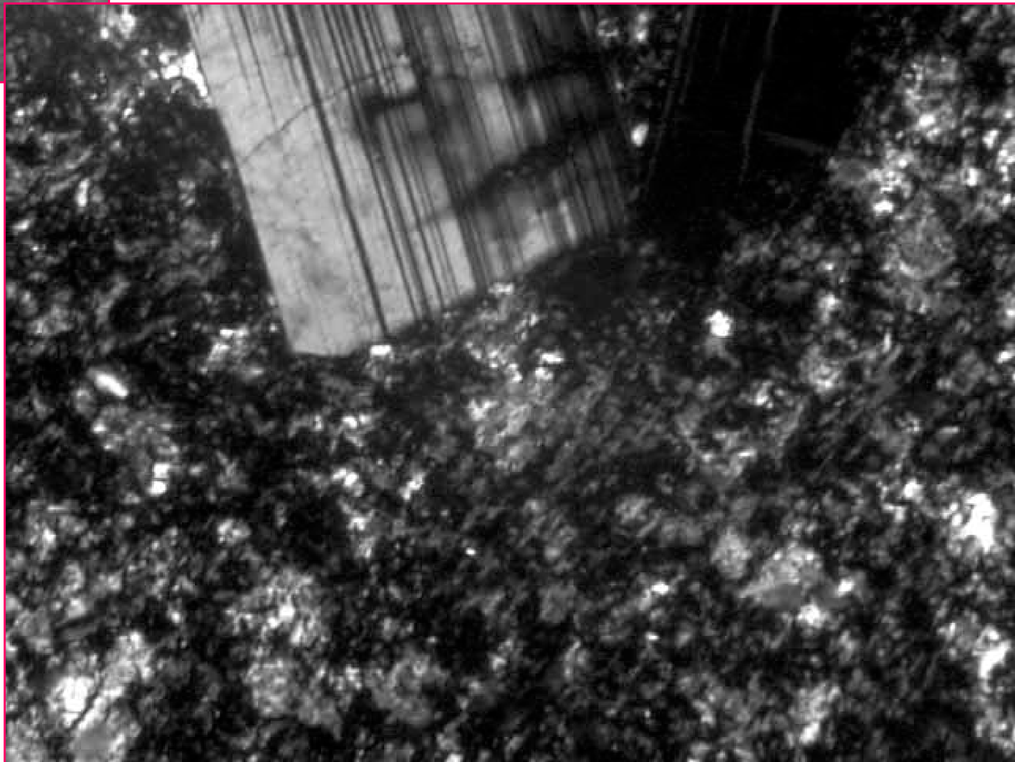


Figure 3.18. b. Very straight multiple **albite twins** in plagioclase, set in felsitic groundmass. Rhyolite, Chaffee, CO. Field widths ~1 mm. © John Winter and Prentice Hall.

Figure 3.18. (c-d) Tartan twins in microcline. Field widths ~1 mm. © John Winter and Prentice Hall.

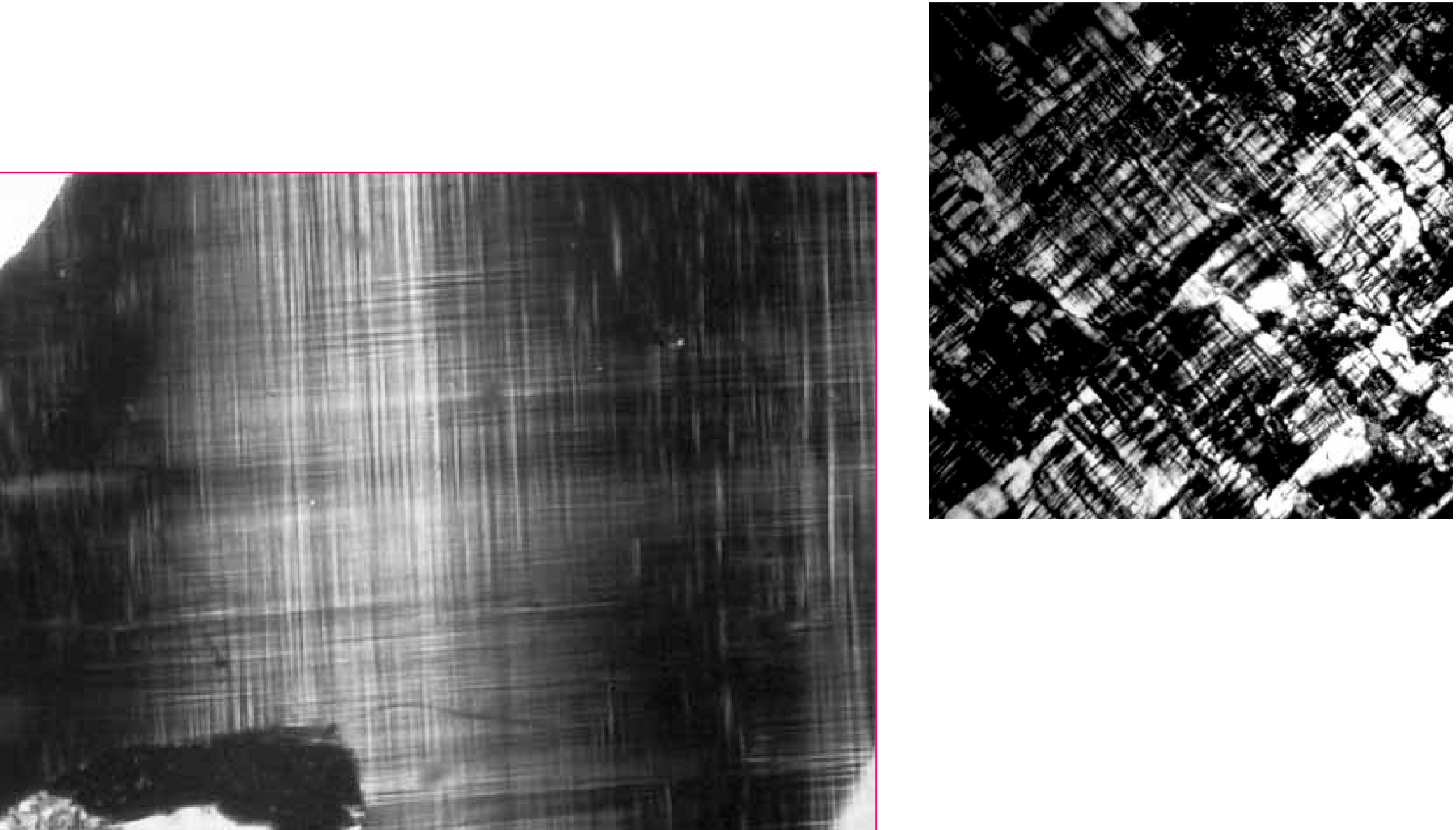


Figure 3.19. Polysynthetic **deformation twins** in plagioclase. Note how they concentrate in areas of deformation, such as at the maximum curvature of the bent cleavages, and taper away toward undeformed areas. Gabbro, Wollaston, Ontario. Width 1 mm.

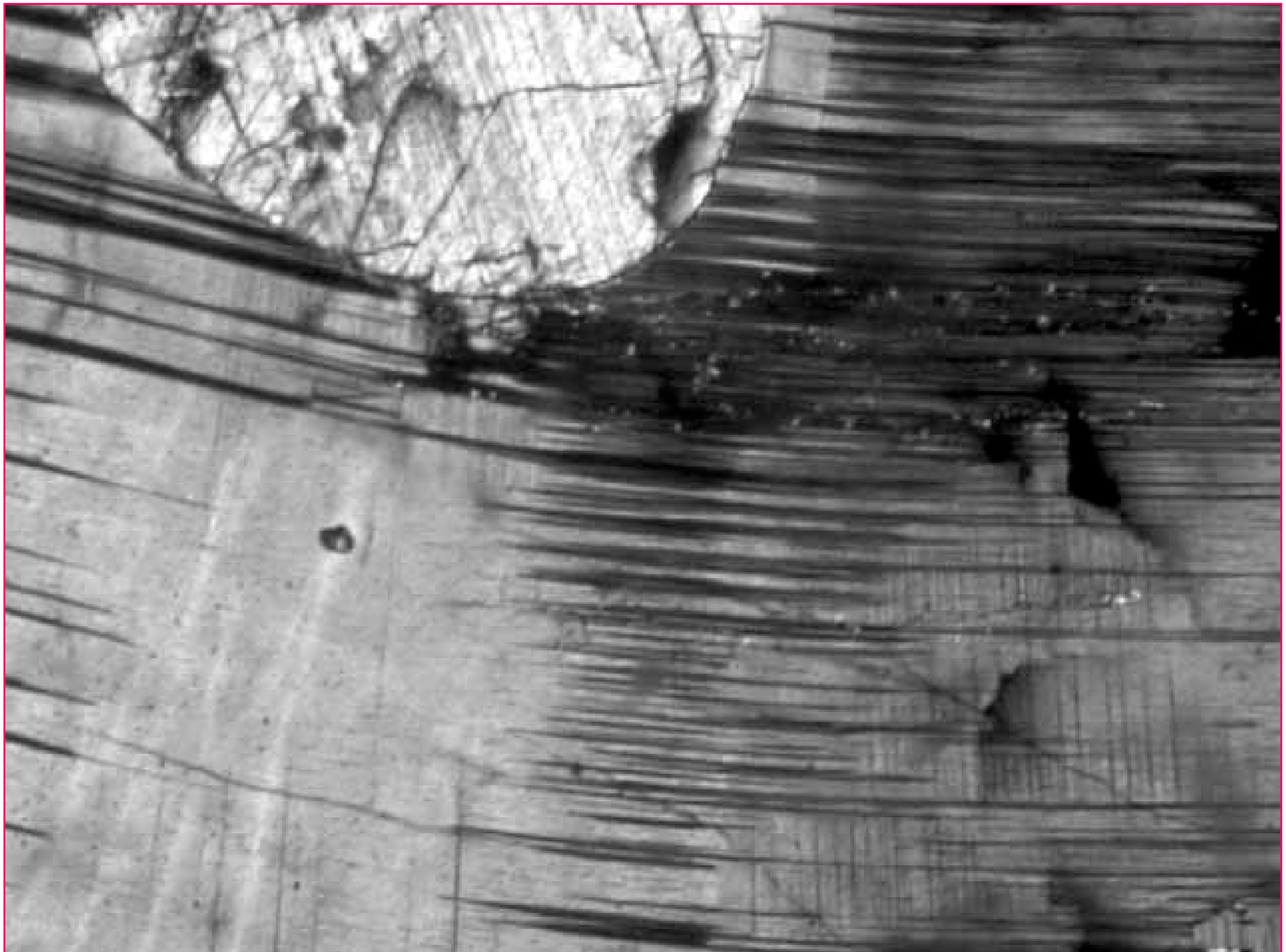
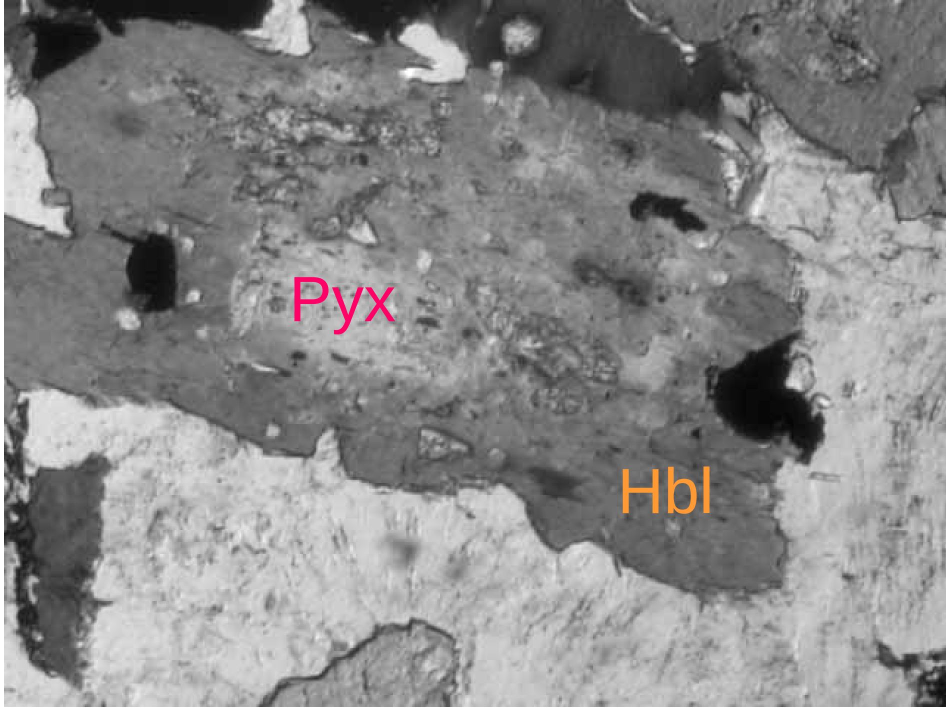
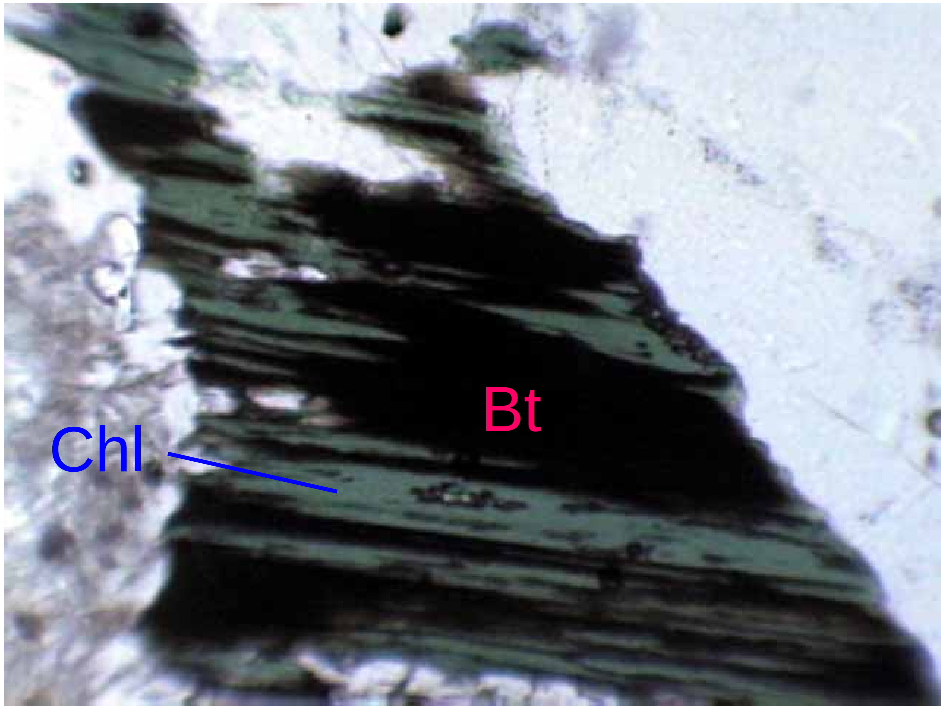
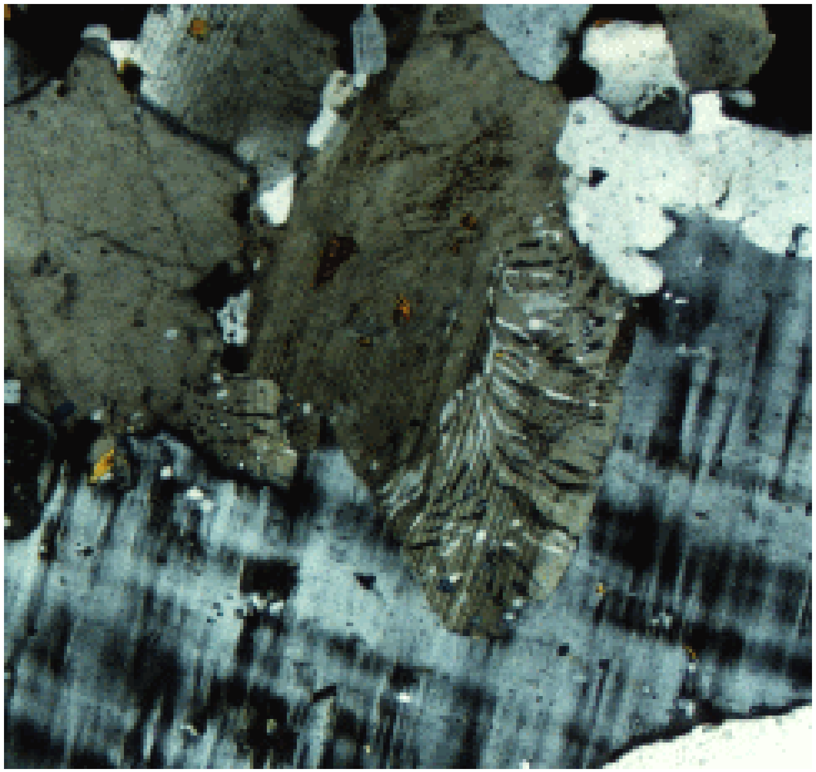


Figure 3.20. a. Pyroxene largely **replaced** by hornblende. Some pyroxene remains as light areas (Pyx) in the hornblende core. Width 1 mm. **b.** Chlorite (green) replaces biotite (dark brown) at the rim and along cleavages. Tonalite. San Diego, CA. Width 0.3 mm. © John Winter and Prentice Hall.







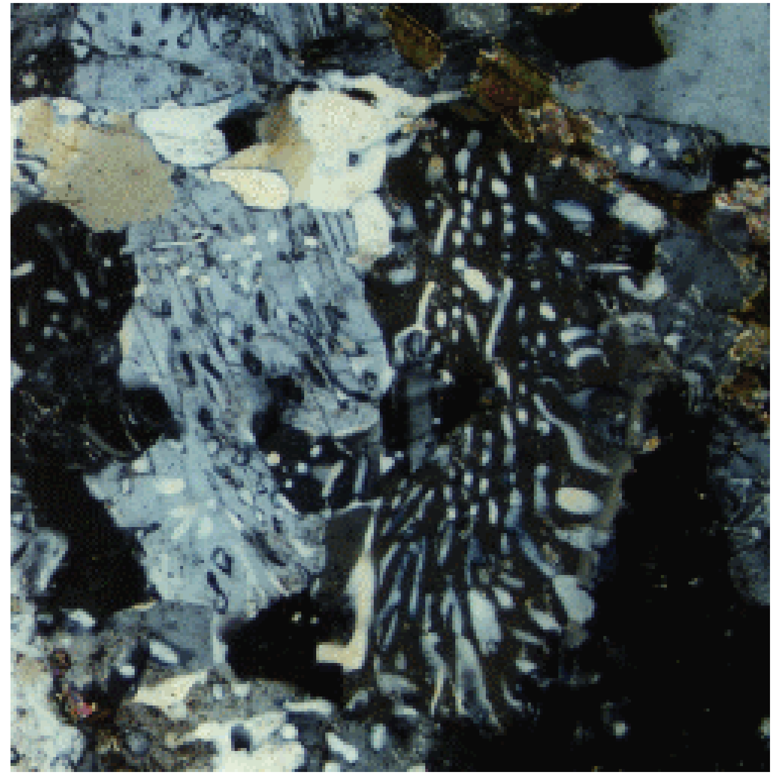


Figure 3.21. **Myrmekite** formed in plagioclase at the boundary with K-feldspar. Photographs courtesy © L. Collins. http://www.csun.edu/~vcgeo005

Chapter 4: Igneous Structures and Field Relationships

- Questions to be considered in this chapter:
- 1- Types of field settings for volcanic & plutonic rocks
- 2- Properties of magmas?
- 3- Types of volcanic landforms?
- 4- Shapes of plutonic rock masses – relate to intrusion style
- 5- Outcrop-scale features of volcanic & plutonic rocks
- 6 – Features of contacts
- 7- How are plutons emplaced?

Chapter 4: Igneous Structures and Field Relationships

- **4.1.1. Properties of magma & eruptive styles**
  - The style of volcanic eruption (& resulting deposits) are determined by ***physical properties of the magma*** – in particular the ***viscosity*** and ***volatile (gas)*** content
  - ***Viscosity*** – i.e., resistance to flow is determined by the ***composition*** and ***temperature*** of the magma
  - The strong Si-O and Al-O bonds in silicate melts can **polymerize** (link together) form extensive molecular networks

Chapter 4: Igneous Structures and Field Relationships

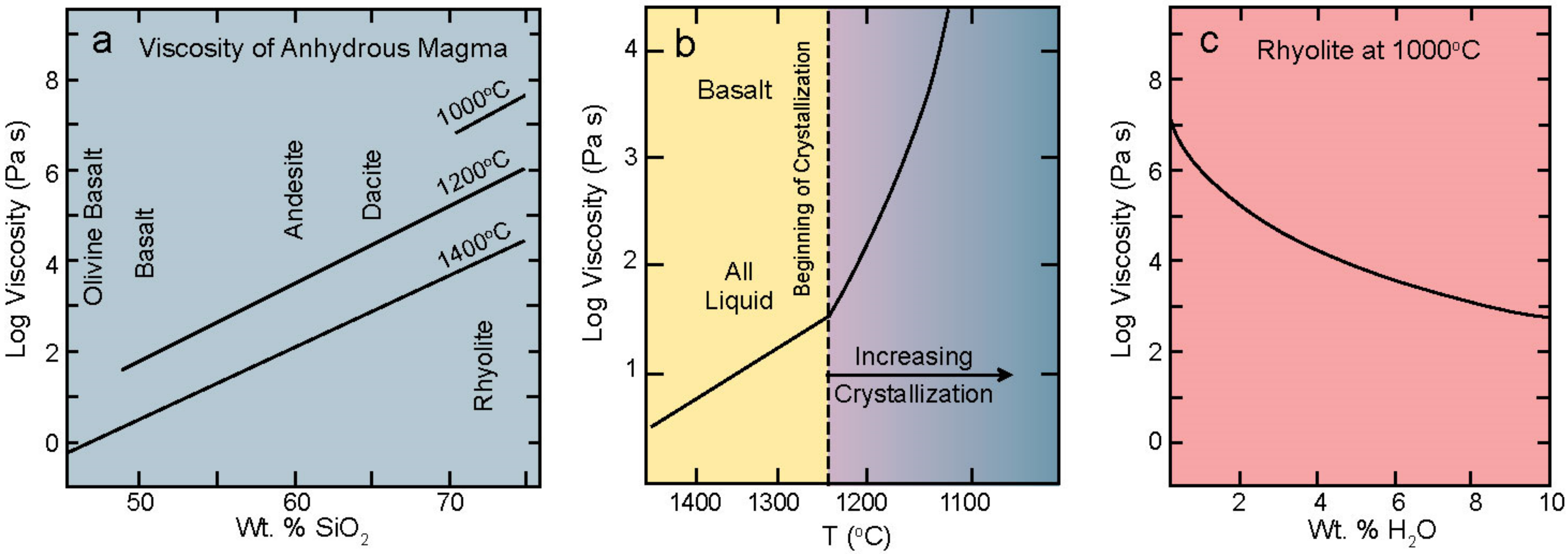


Figure 4.1a. Calculated viscosities of anhydrous silicate liquids at one atmosphere pressure, calculated by the method of Bottinga and Weill (1972) by Hess (1989), Origin of Igneous Rocks. Harvard University Press. **b.** Variation in the viscosity of basalt as it crystallizes (after Murase and McBirney, 1973), Geol. Soc. Amer. Bull., **84**, 3563-3592. **c.** Variation in the viscosity of rhyolite at 1000°C with increasing H_2O content (after Shaw, 1965, Amer. J. Sci., **263**, 120-153).

Chapter 4: Igneous Structures and Field Relationships

- **4.1.2. Central Vent Landforms**
  - Magma can extrude from either a central vent or fissure
  - Vent eruption – lavas erupt from a cylindrical (generally) pipe-like conduit through a subcircular surface hole
  - ***Crater*** – bowl- or funnel-shaped depression at the vent

Chapter 4: Igneous Structures and Field Relationships

- **4.1.2. Central Vent Landforms**
  - **Shield volcanoes –**
    - Range in size from a few kilometers across to the largest vent landforms
    - Lavas are predominantly basaltic
    - Low viscosities – lava flows predominate and cover a large area producing a convex upward profile and low slope (generally <10° and commonly closer to 2-3°)
    - E.g., Hawaii

Chapter 4: Igneous Structures and Field Relationships

- **4.1.2. Central Vent Landforms**
  - **Composite/ Strato volcanoes –**
    - Steep-sided cones are usually concave upward and have slopes up to 36°
    - Average ~2 km in height and are ~1/100 the volume of a large shield volcano
    - Large range of magma compositions (Chapters 16 and 17); more silicic than shield volcanoes – typically ‘andesitic’ in composition
    - Typically associated with pyroclastic activity
    - E.g., Mt. St. Helens, Mt. Fuji

Structures and Field Relationships

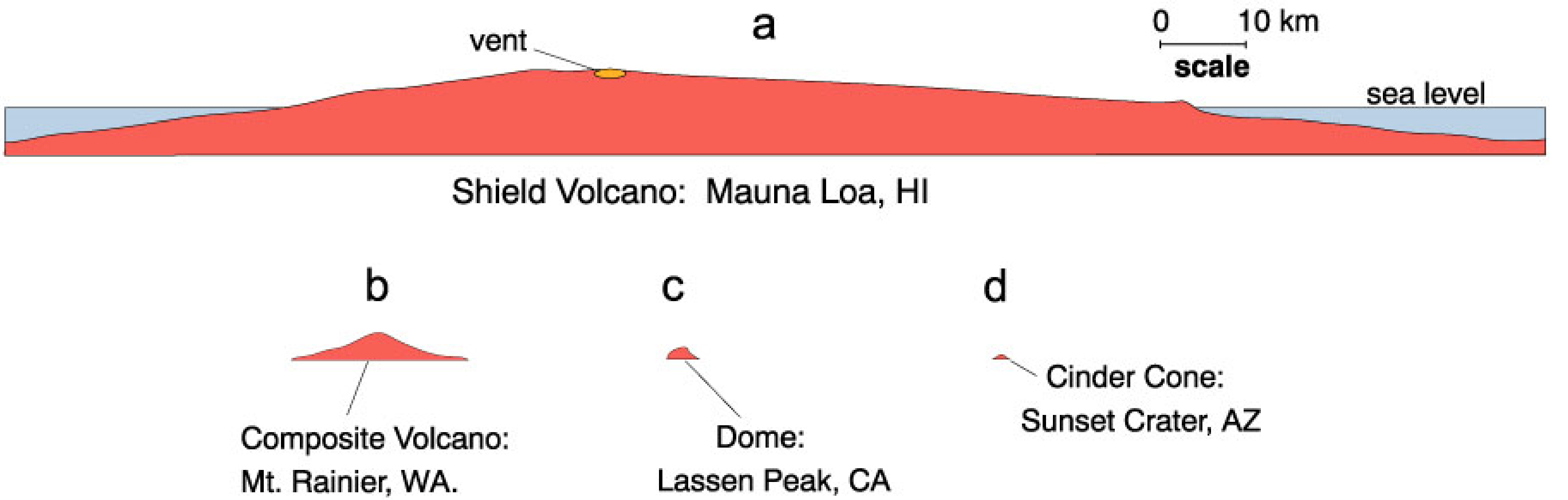


Figure 4.2. Volcanic landforms associated with a central vent (all at same scale).

Structures and Field Relationships

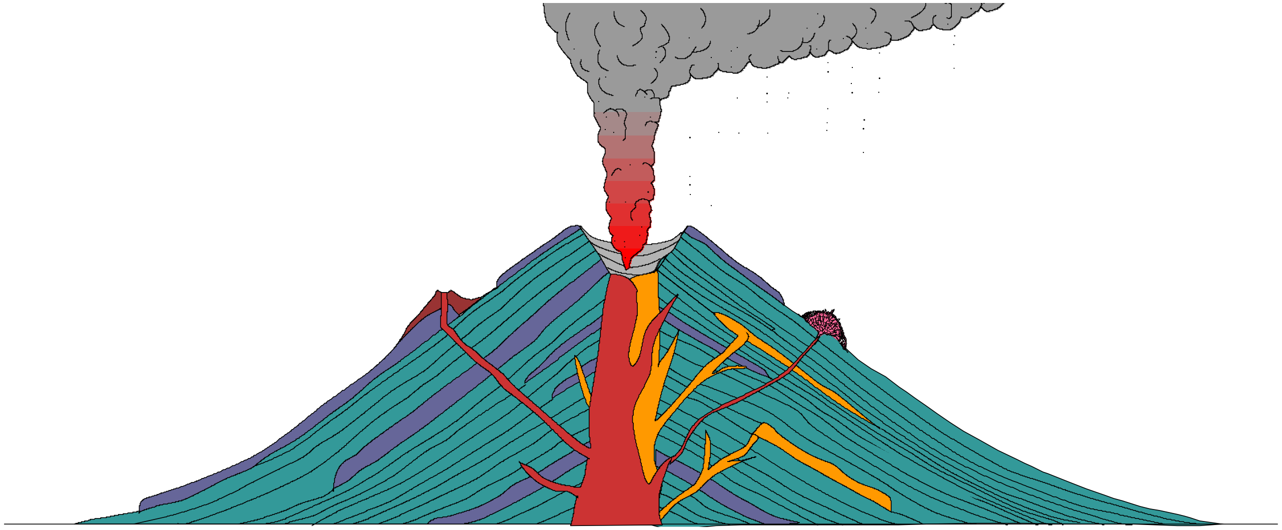


Figure 4.3a. Illustrative cross section of a **stratovolcano**. After Macdonald (1972), *Volcanoes*. Prentice-Hall, Inc., Englewood Cliffs, N. J., 1-150. **b.** Deeply glaciated north wall of Mt. Rainier, WA, a stratovolcano, showing layers of pyroclastics and lava flows.

Structures and Field Relationships

Example of Volcano Complex

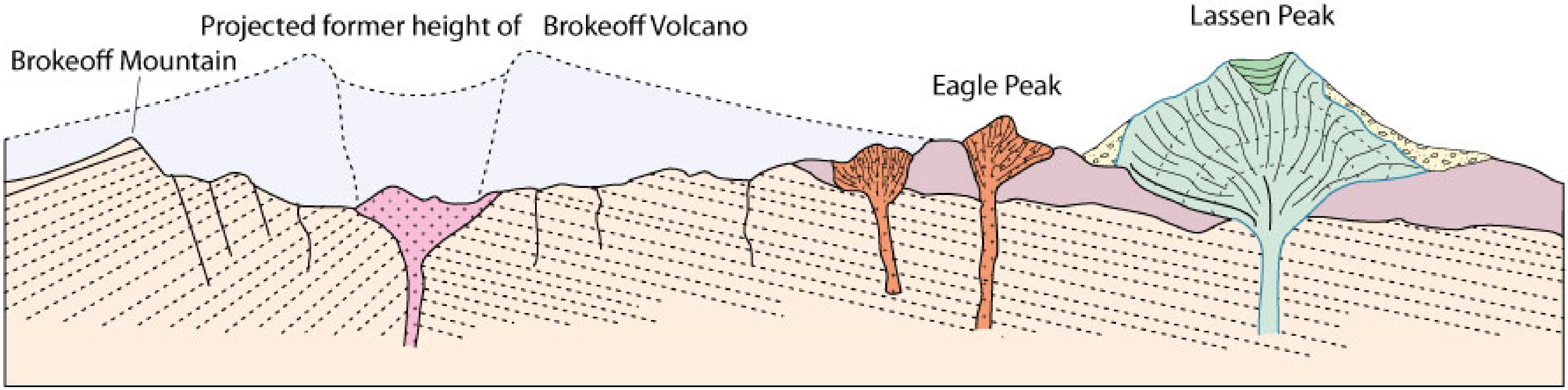


Figure 4.4. Schematic cross section of the Lassen Peak area. After Williams (1932), *Univ. of Cal. Publ. Geol. Sci. Bull.*, 21.

Structures and Field Relationships

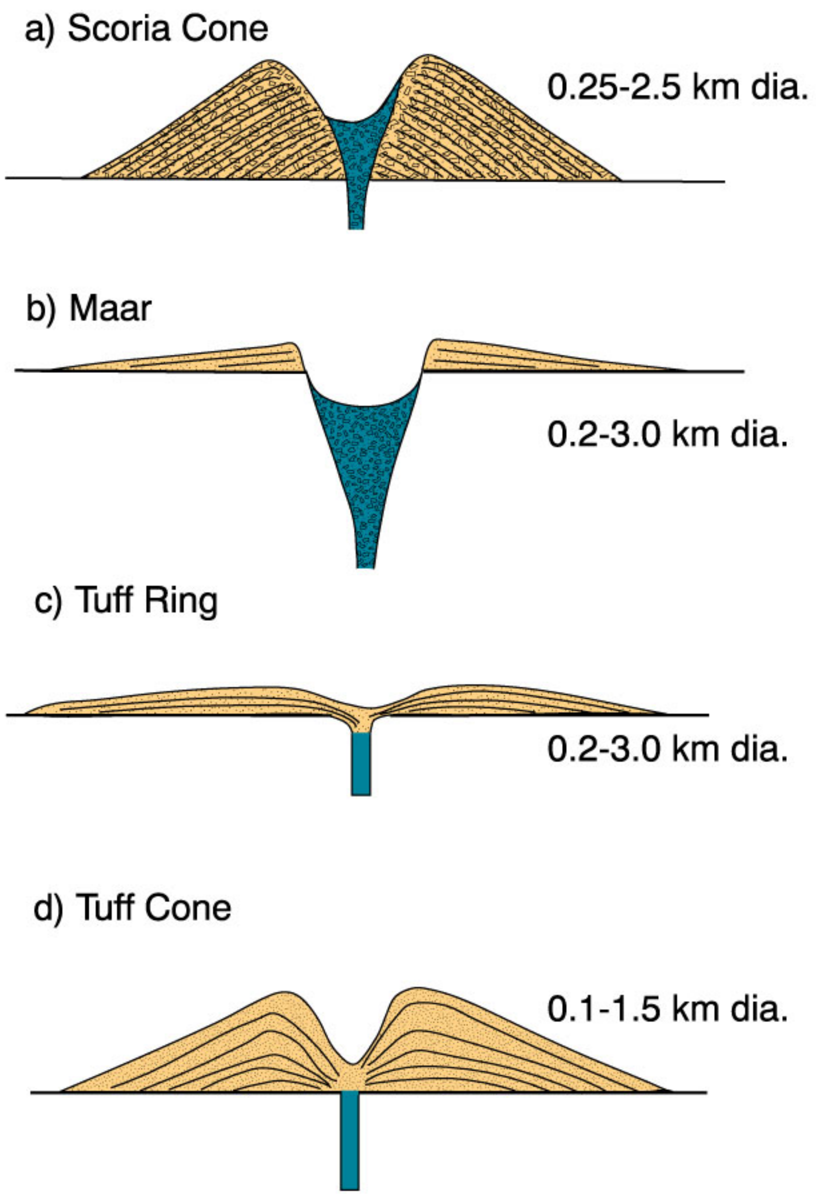


Figure 4.5. Cross sectional structure and morphology of small explosive volcanic landforms with approximate scales. After Wohletz and Sheridan (1983), *Amer. J. Sci*, **283**, 385-413.

Figure 4.6a. Maar, Hole-in-the-Ground, Oregon (upper courtesy of USGS, lower my own). **b. Tuff ring,** Diamond Head, Oahu, Hawaii (courtesy of Michael Garcia). **c. Scoria cone**, Surtsey, Iceland, 1996 (© courtesy Bob and Barbara Decker).

Structures and Field Relationships

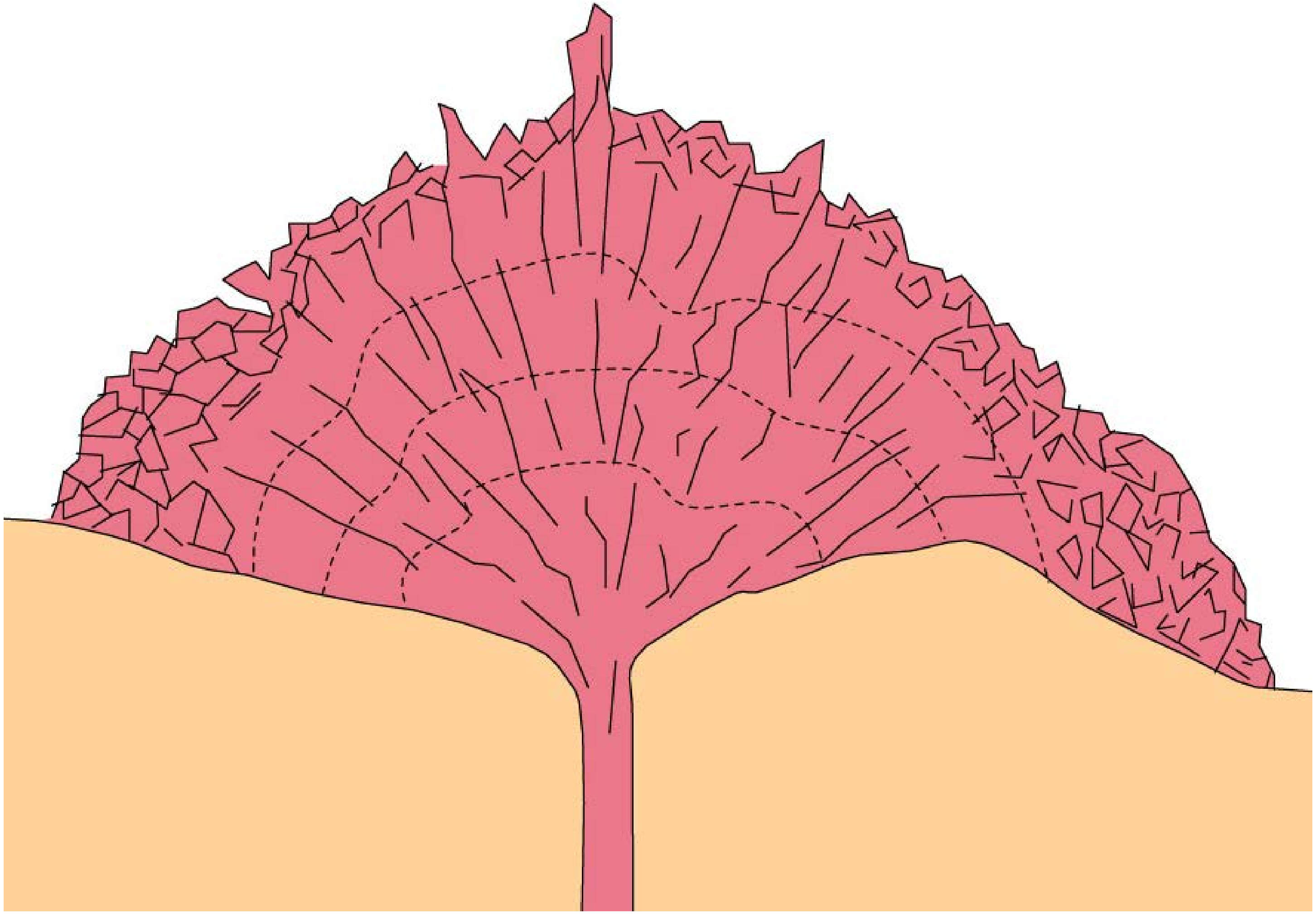


Figure 4.7. Schematic cross section through a **lava dome**.

Photo credit: Shan de Silva. 2009 picture of Chao, a **very large lava dome** in the Andes.
Note that the flow front you are seeing is as high as 700m in places and Chao itself is over 14km long!!

Structures and Field Relationships

Figure 4.8. **Pressure ridges** on the surface of Big Obsidian Flow, Newberry Volcano, OR. Flow direction is toward the left. © John Winter and Prentice Hall.

Pressure ridges

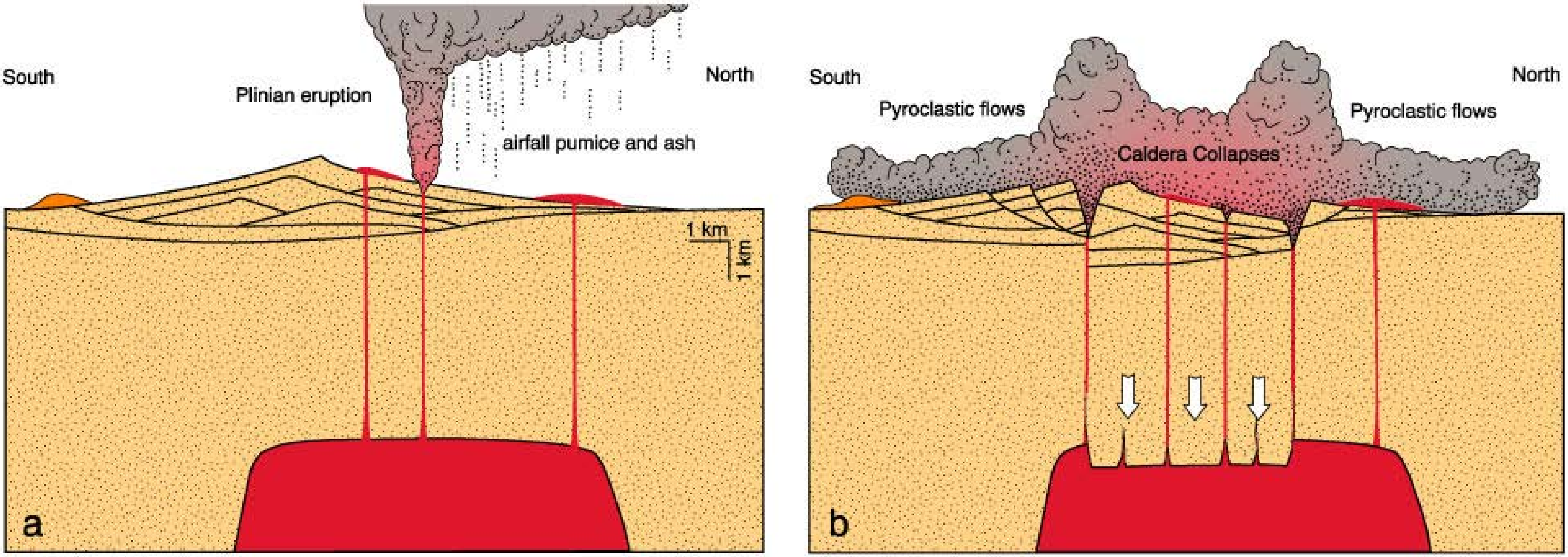
Chao, as seen in this satellite image, is an excellent example of a coulée. Note the large **pressure ridges** visible on the surface of the lava.

The ridges on Chao can be over 30m high.

Chapter 4: Igneous Structures and Field Relationships

- **CALDERAS**
  - Large-scale collapse features that typically form at a central vent fairly late into an eruptive cycle
  - Denser, solid strata above a shallow magma chamber falls into the emptying (or ‘draining’) chamber
  - Magma may ascend as a flank eruption, or up fractures separating the blocks of the collapsing roof
  - If caldera fills with magma from below (common in shield volcanoes), then creates a “lava lake”
  - E.g., large caldera - Yellowstone

Structures and Field Relationships



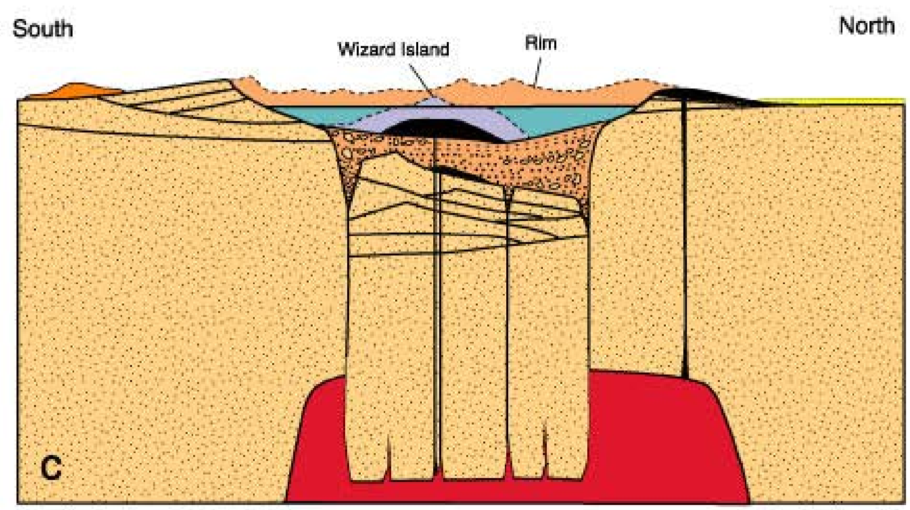


Figure 4.9. Development of the **Crater Lake caldera.** After Bacon (1988). Crater Lake National Park and Vicinity, Oregon. 1:62,500-scale topographic map. U. S. Geol. Surv. Natl. Park Series.

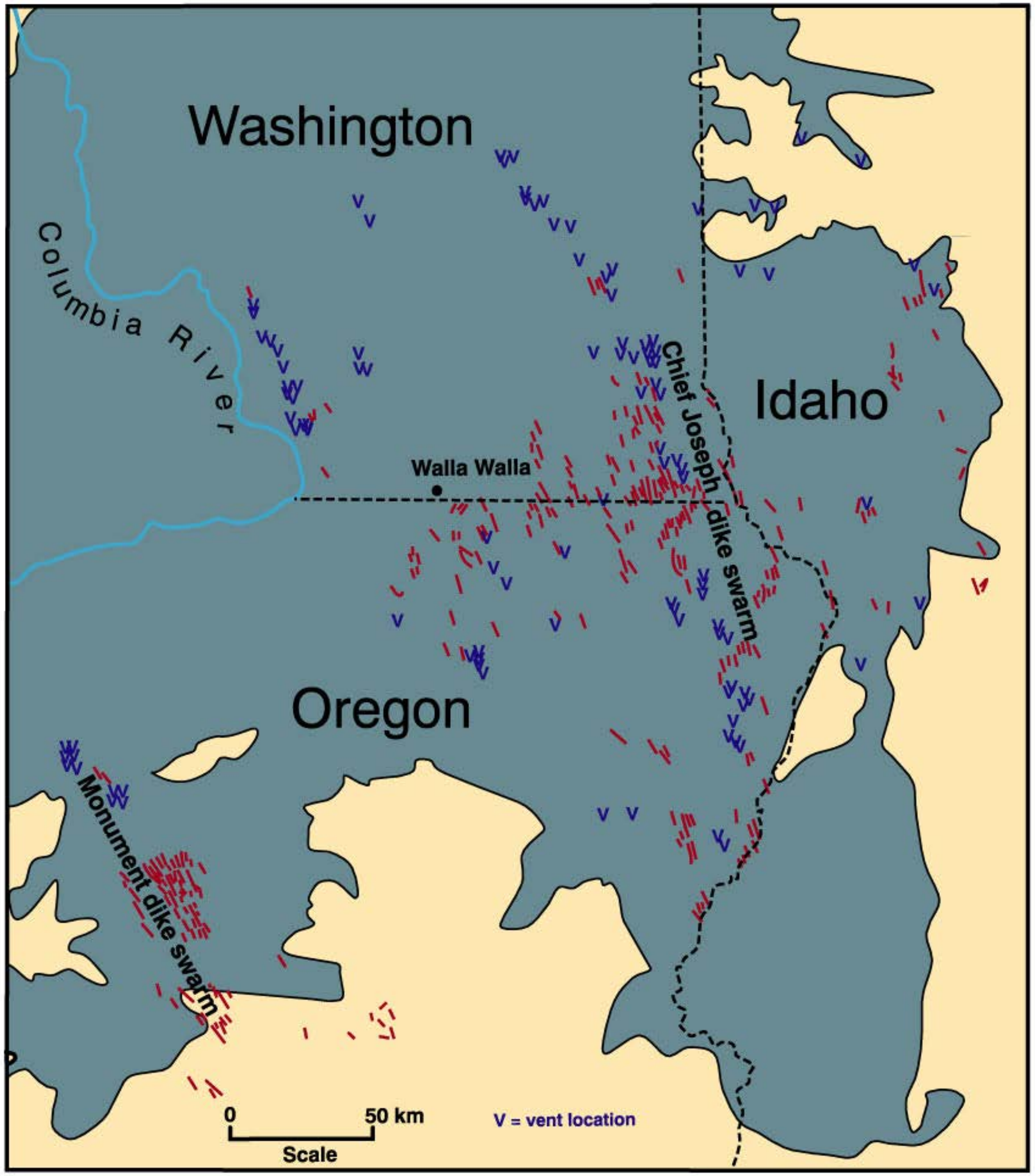
Mount Mazama – 6850 years ago; composite volcano ~3600 m high

Chapter 4: Igneous Structures and Field Relationships

- **Fissure Eruptions**
  - Magma erupts to the surface either along a single fracture or set of fractures
  - The planar conduits, when exposed by erosion, are filled with solidified magma and are referred to as **feeder dikes**.
  - Fractures may form singly or in multiple sets – in a **concentric or radial pattern about the vent**, or in **parallel sets**
  - Can occur in larger areas undergoing regional extension; e.g., basin and range province

Structures and Field Relationships

Figure 4.10. **Location of the exposed feeder dikes** (heavy lines) and vents (V's) of the southeastern portion of the Columbia River Basalts. Unshaded area covered by CRB. After Tolan *et al*. (1989), © *Geol. Soc. Amer. Special Paper*, **239**. pp. 1-20.



Chapter 4: Igneous Structures and Field Relationships

- **Lava Flow Features**
  - Dominant form of volcanism on Earth
  - Occur predominantly in low viscosity, low volatile content lava
  - Some flows associated with flood basaltic provinces are of enormous size
  - E.g. some individual flow units of the Columbia River Basalt cover nearly 120,000 km^2 (Fig. 4.11 – next slide) and approach 3000 km^3 in volume

Structures and Field Relationships

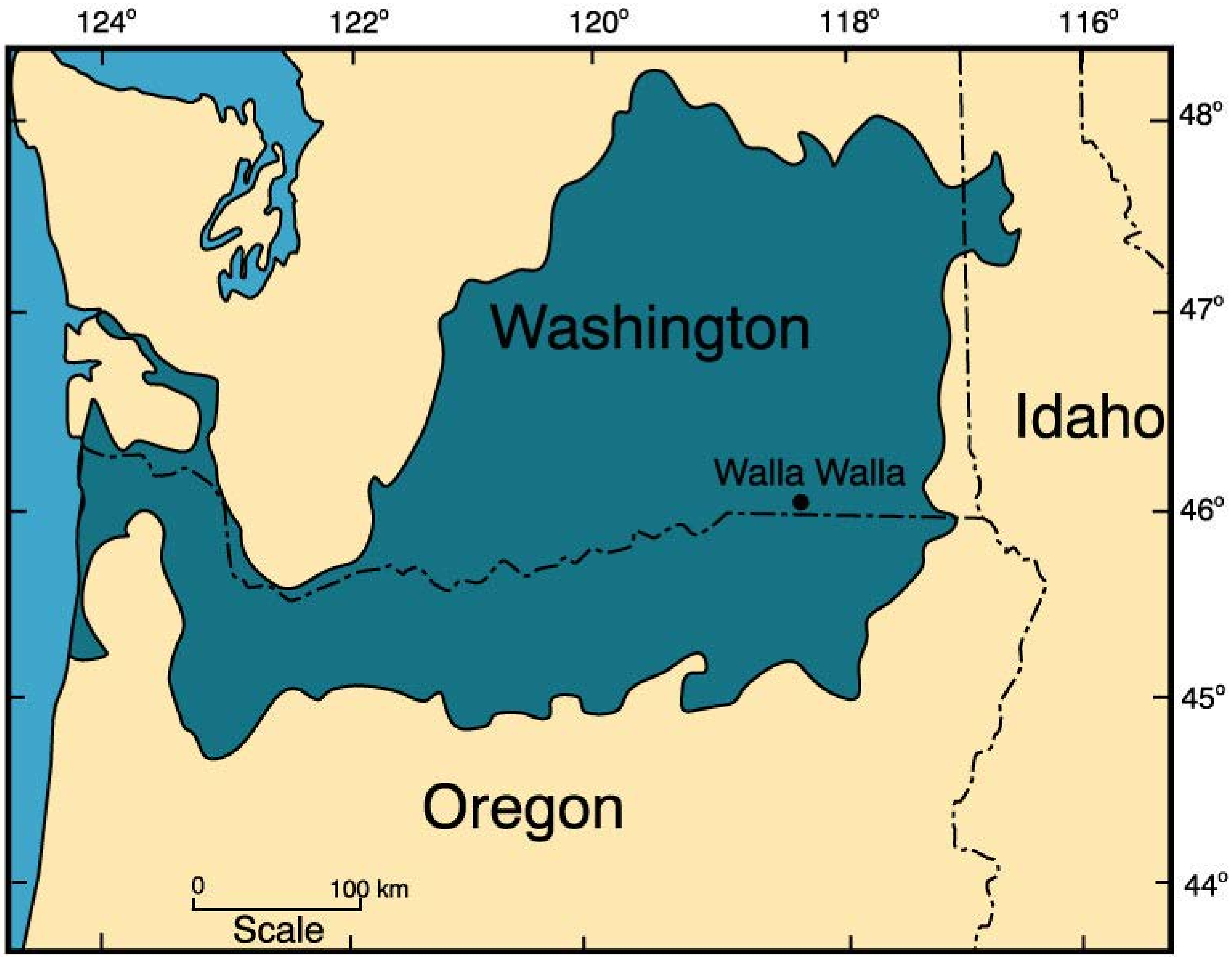
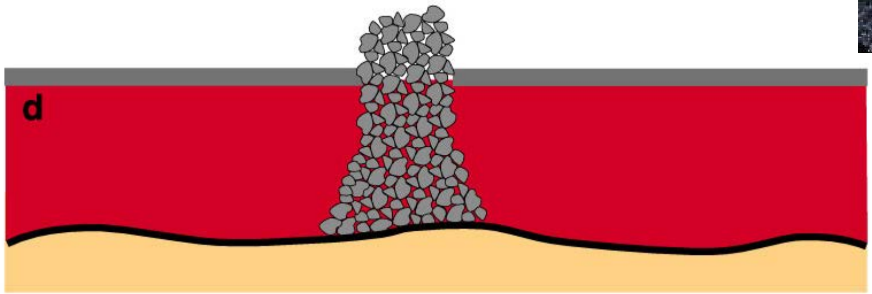


Figure 4.11. Aerial extent of the N2 Grande Ronde flow unit (approximately 21 flows). After Tolan *et al.* (1989). © *Geol. Soc. Amer. Special Paper*, **239**. pp. 1-20.

Figure 4.12. a. Ropy surface of a pahoehoe flow, 1996 flows, Kalapana area, Hawaii. © John Winter and Prentice Hall.

Figure 4.12. b. Pahoehoe (left) and aa (right) meet in the 1974 flows from Mauna Ulu, Hawaii. © John Winter and Prentice Hall.



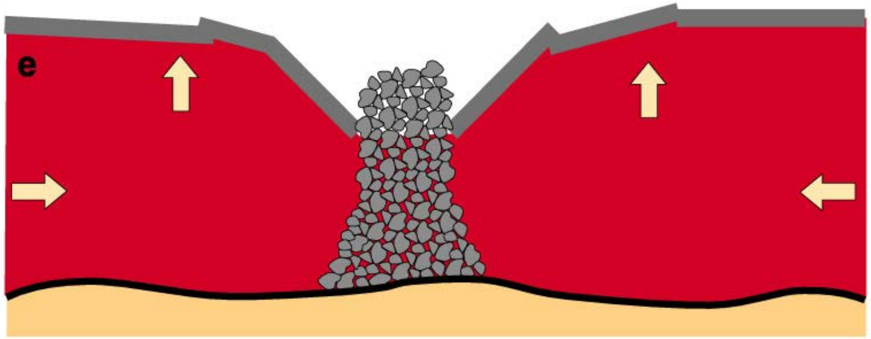


Figure 4.12. c-e. Illustration of the development of an inflated flow. In **d**, a thin flow spreads around a rock wall. In (**e**), the flow is inflated by the addition of more lava beneath the earlier crust. A old stone wall anchors the crust, keeping it from lifting. The wall can be seen in the low area in part (c). © John Winter and Prentice Hall.

Chapter 4: Igneous Structures and Field Relationships

- **Lava Flow Features**
  - Subaerial lava flows – i.e., those that flow on land – and some shallow sheet-like intrusions may develop a characteristic jointing pattern called **columnar joints** (Fig. 4.13 – next slide)
  - Result of:
    - Based on magma convection currents?
    - Diffusion?
    - **Contraction of the flow as it cools** (most widely accepted mechanism)
    - Tensional stresses result since bottom and top of lava flow cool faster than center of flow – results in a regular set of joints

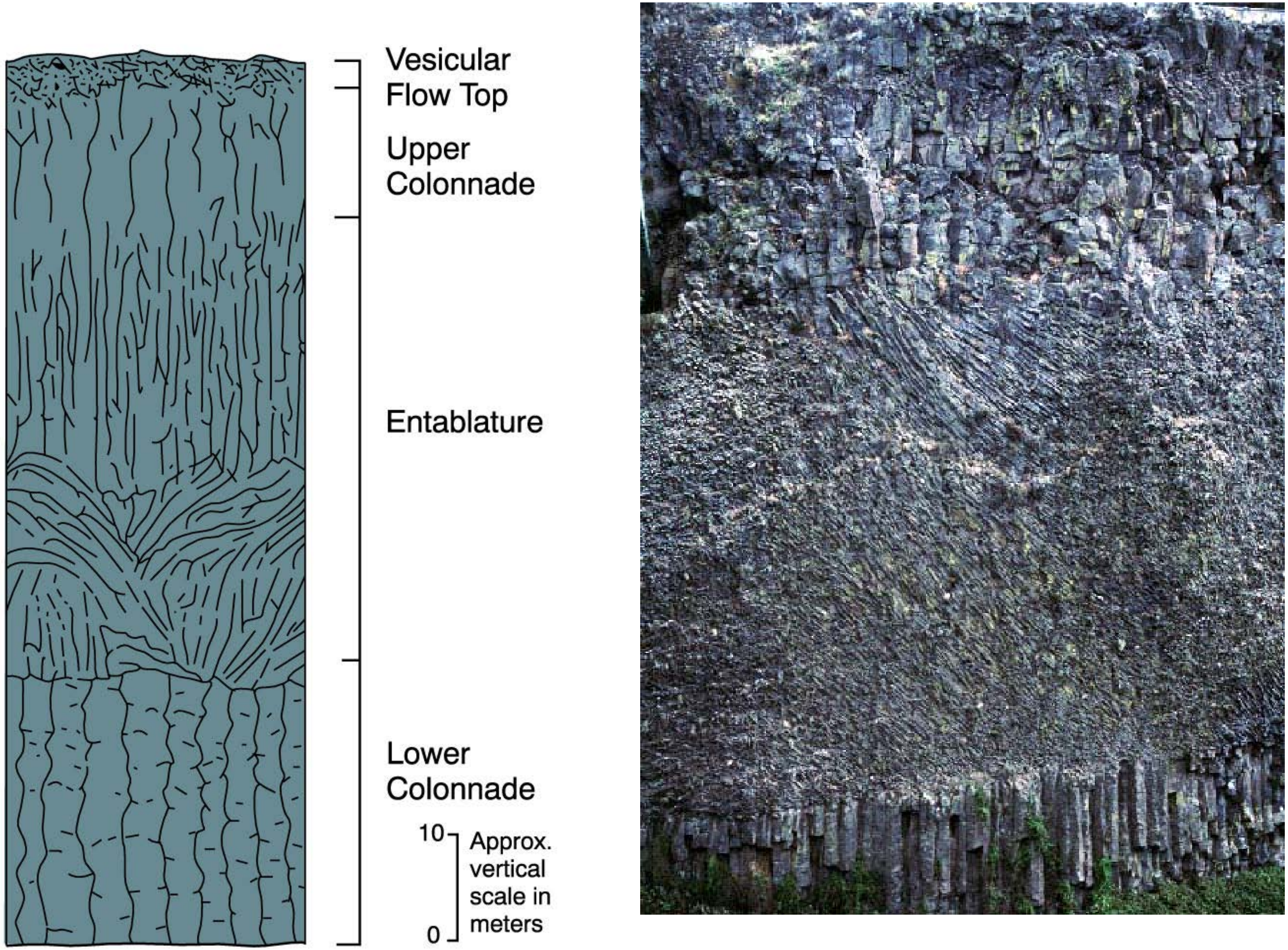


Figure 4.13. **a.** Schematic drawing of **columnar joints** in a basalt flow, showing the four common subdivisions of a typical flow. The column widths in (a) are exaggerated about 4x. After Long and Wood (1986) © *Geol. Soc. Amer. Bull.*, **97**, 1144-1155.

b. Colonnade-entablature-colonnade in a basalt flow, Crooked River Gorge, OR. © John Winter and Prentice Hall.

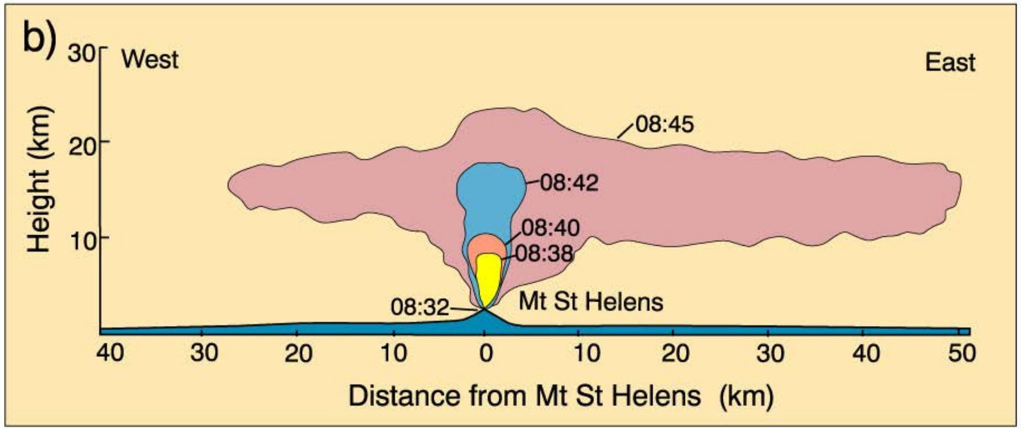
Structures and Field Relationships

Figure 4.14. Subaqueous pillow basalts, Olympic Peninsula, Washington.

Hammer for scale

Chapter 4: Igneous Structures and Field Relationships

- **Pyroclastic Deposits**
  - **Volcanoclastic** – refers to any fragmental aggregate of volcanic material, regardless of how it formed
  - **Pyroclastic** – are a subset of volcaniclastics that consist of fragmented material formed from explosive volcanic activity or aerial explusion from a volcanic vent



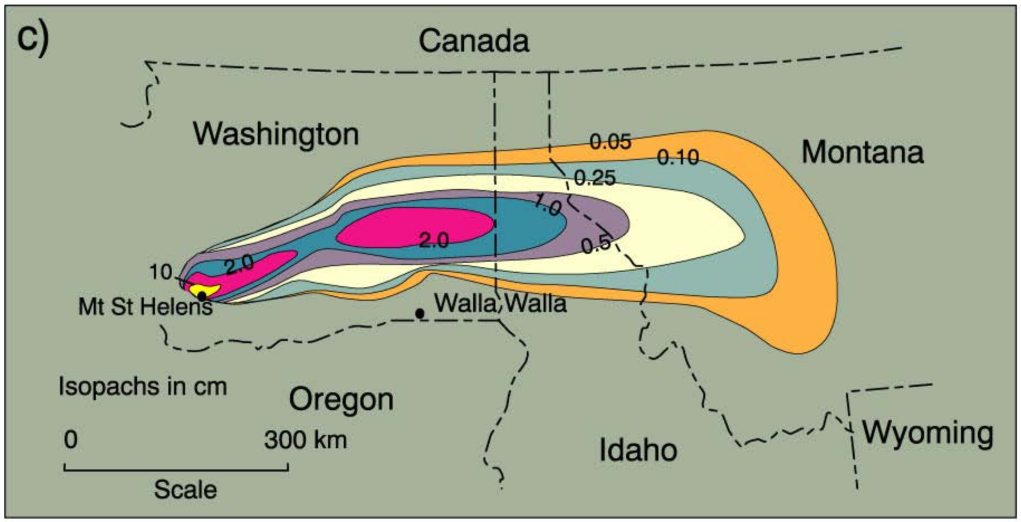


Figure 4.15. Ash cloud and deposits of the 1980 eruption of Mt. St. Helens. **a.** Photo of Mt. St. Helens vertical ash column, May 18, 1980 (courtesy USGS). **b.** Vertical section of the ash cloud showing temporal development during first 13 minutes. **c.** Map view of the ash deposit. Thickness is in cm. After Sarna-Wojcicki *et al.* (1981) in *The 1980 Eruptions of Mount St. Helens, Washington. USGS Prof. Pap.*, **1250**, 557-600.

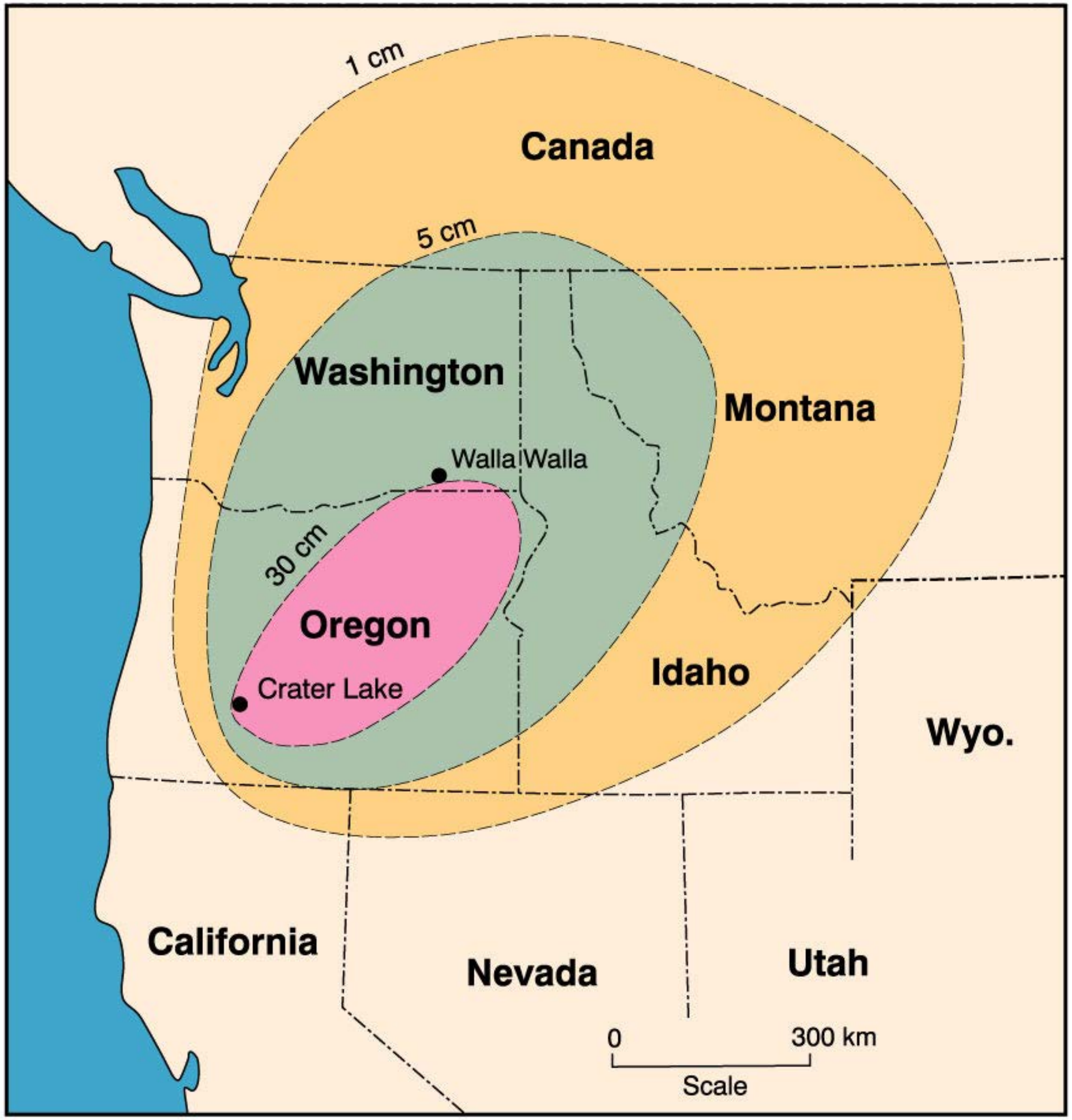


Figure 4.16. Approximate aerial extent and thickness of Mt. Mazama (Crater Lake) ash fall, erupted 6950 years ago. After Young (1990), Unpubl. Ph. D. thesis, University of Lancaster. UK.

Figure 4.17. Maximum aerial extent of the Bishop ash fall deposit erupted at Long Valley 700,000 years ago. After Miller *et al*. (1982) *USGS Open-File Report* 82-583.

Figure 4.18. Types of pyroclastic flow deposits. After MacDonald (1972), *Volcanoes*. Prentice-Hall, Inc., Fisher and Schminke (1984), *Pyroclastic Rocks*. Springer-Verlag. Berlin.

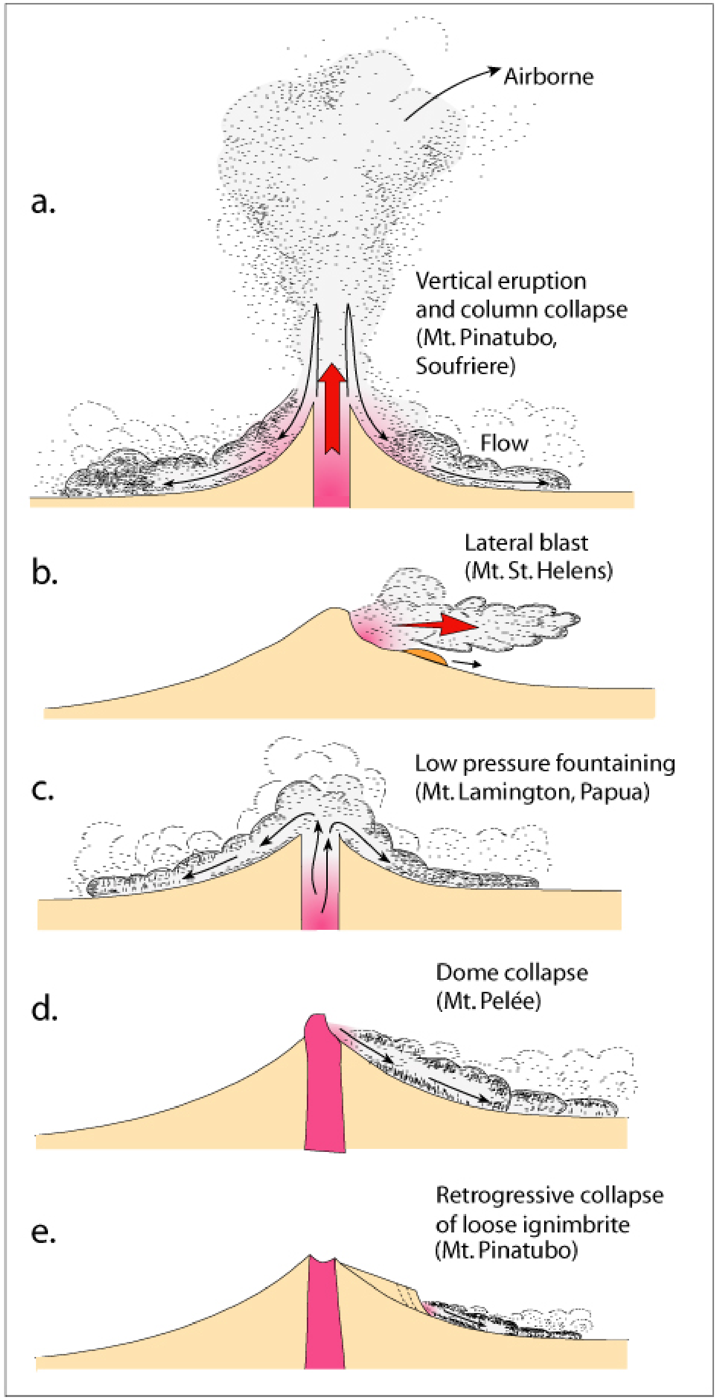
a. Collapse of a vertical explosive or plinian column that falls back to earth, and continues to travel along the ground surface.

b. Lateral blast, such as occurred at Mt. St. Helens in 1980.

c. "**Boiling-over**" of a highly gas-charged magma from a vent.

d. Gravitational collapse of a hot dome.

e. Retrogressive collapse of an earlier, unstably perched ignimbrite.



Structures and Field Relationships

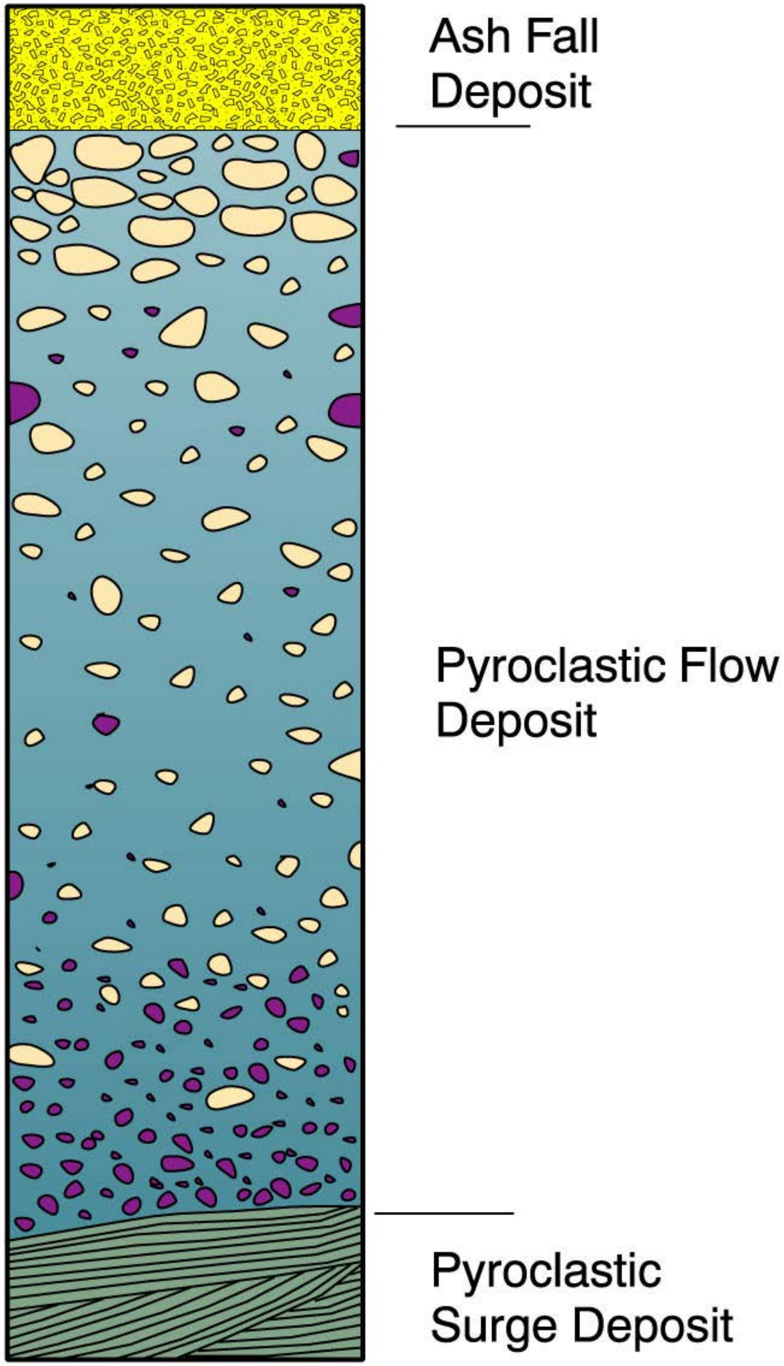


Figure 4.19. Section through a typical ignimbrite, showing basal surge deposit, middle flow, and upper ash fall cover. Tan blocks represent pumice, and purple represents denser lithic fragments. After Sparks *et al*. (1973) *Geology*, **1**, 115-118. Geol. Soc. America

Structures and Field Relationships

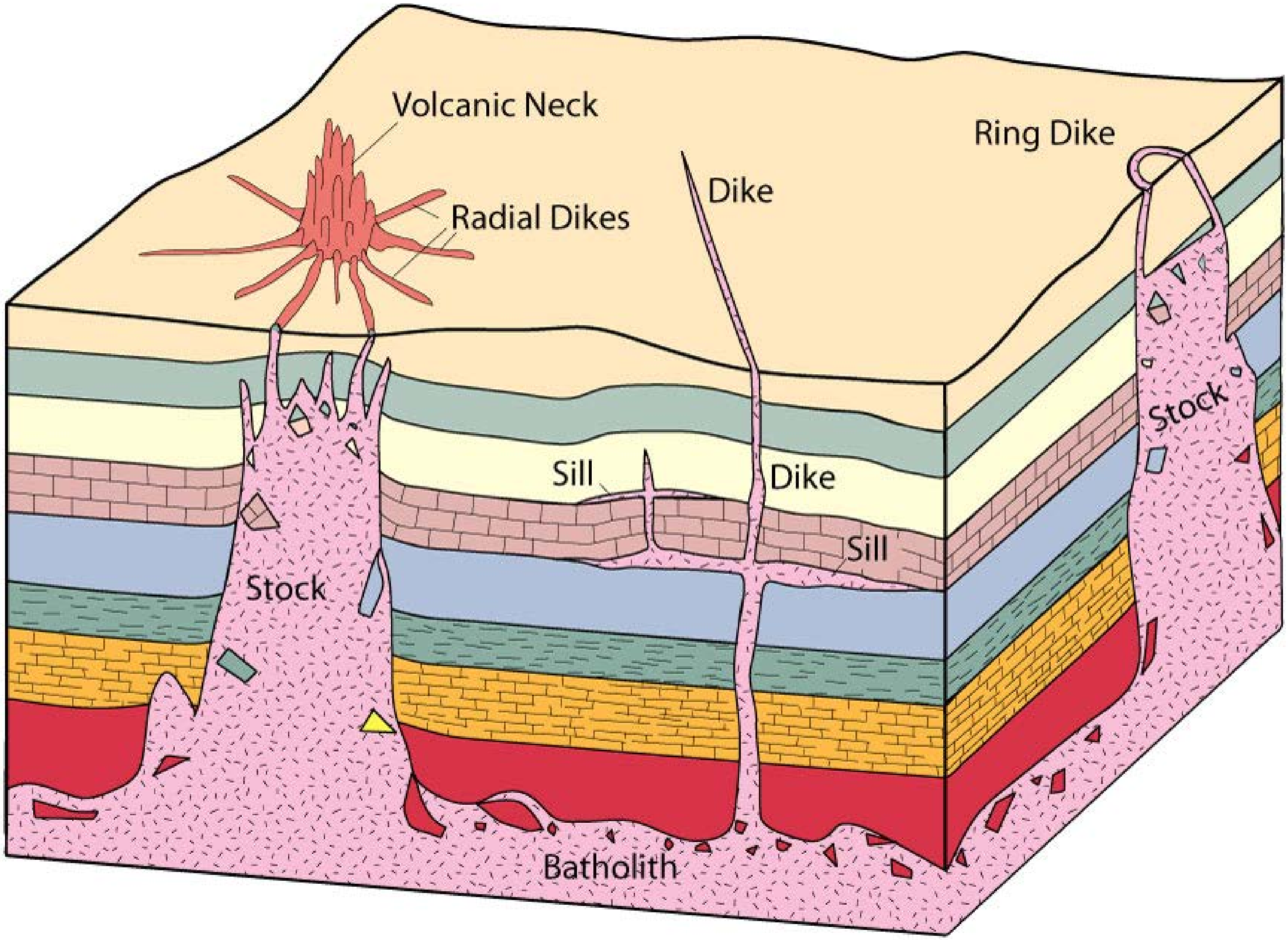


Figure 4.20. Schematic block diagram of some intrusive bodies.

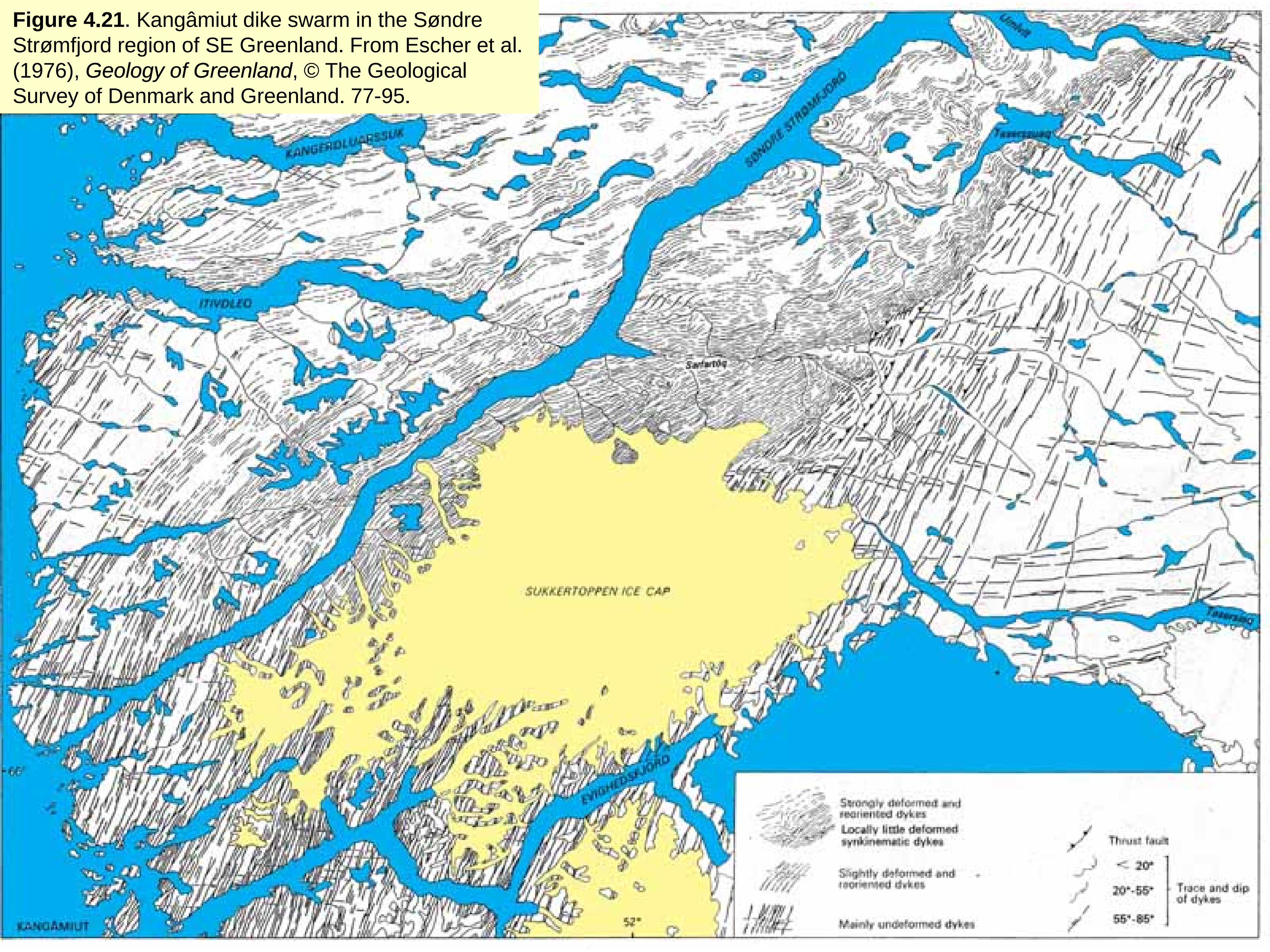


Figure 4.21. Kangâmiut dike swarm in the Søndre Strømfjord region of SE Greenland. From Escher et al. (1976), *Geology of Greenland*, © The Geological Survey of Denmark and Greenland. 77-95.

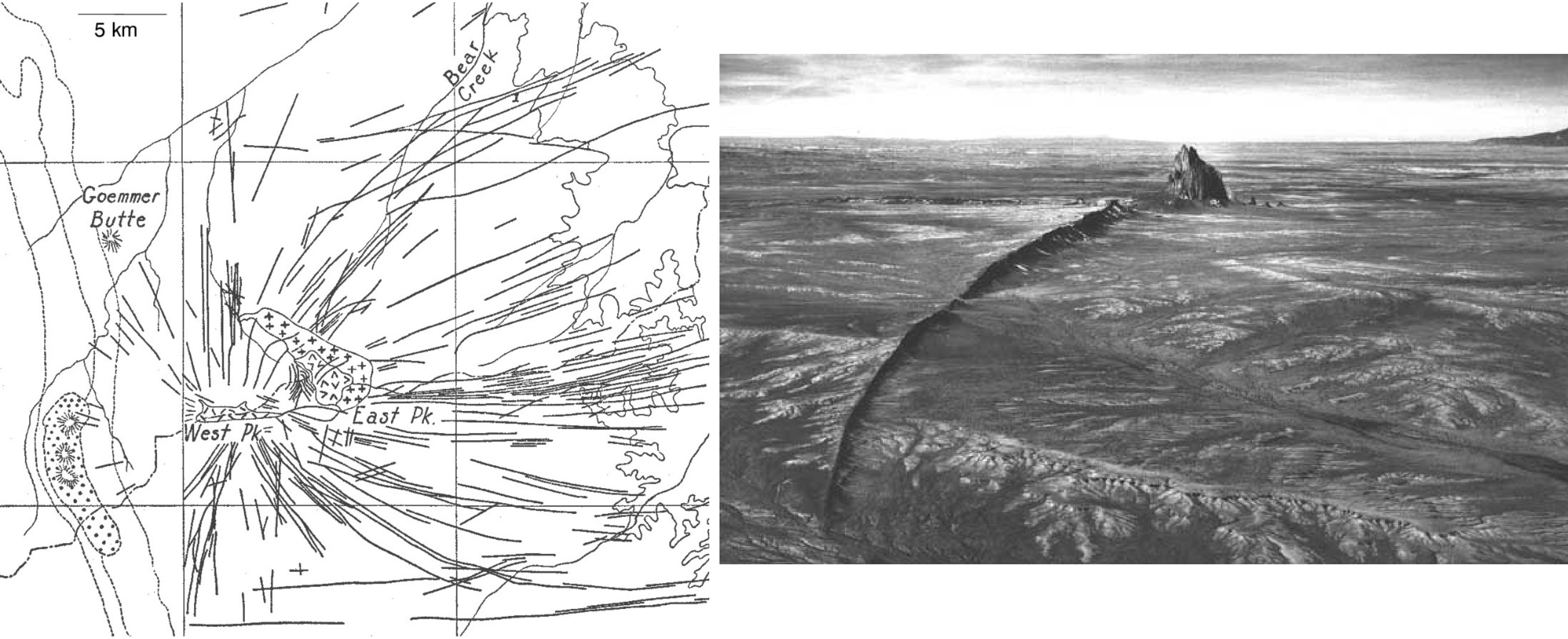


Figure 4.22. **a.** Radial dike swarm around Spanish Peaks, Colorado. After Knopf (1936), *Geol. Soc. Amer. Bull.*, **47**, 1727-1784. **b.** Eroded remnant of a volcanic neck with radial dikes. Ship Rock, New Mexico. From John Shelton © (1966) *Geology Illustrated*. W. H. Freeman. San Francisco.

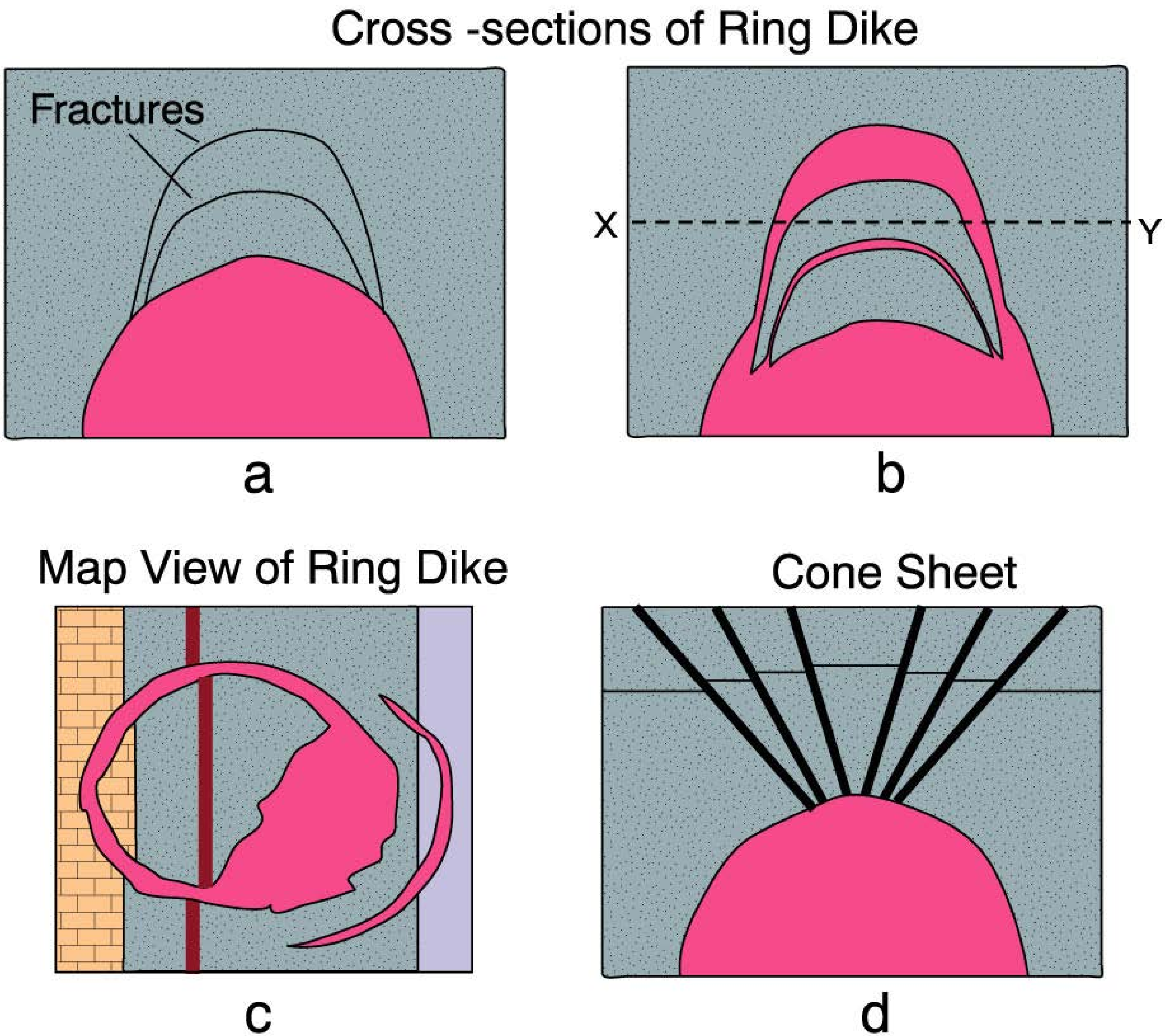


Figure 4.23. The formation of ring dikes and cone sheets.

a. Cross section of a rising pluton causing fracture and stoping of roof blocks. **b.** Cylindrical blocks drop into less dense magma below, resulting in ring dikes. **c.** Hypothetical map view of a ring dike with N-S striking country rock strata as might result from erosion to a level approximating X-Y in (**b**).

d. Upward pressure of a pluton lifts the roof as conical blocks in this cross section. Magma follows the fractures, producing cone sheets. Original horizontal bedding plane shows offsets in the conical blocks. (a), (b), and (d) after Billings (1972), *Structural Geology***.** Prentice-Hall, Inc. (c) after Compton (1985), *Geology in the Field.* © Wiley. New York.

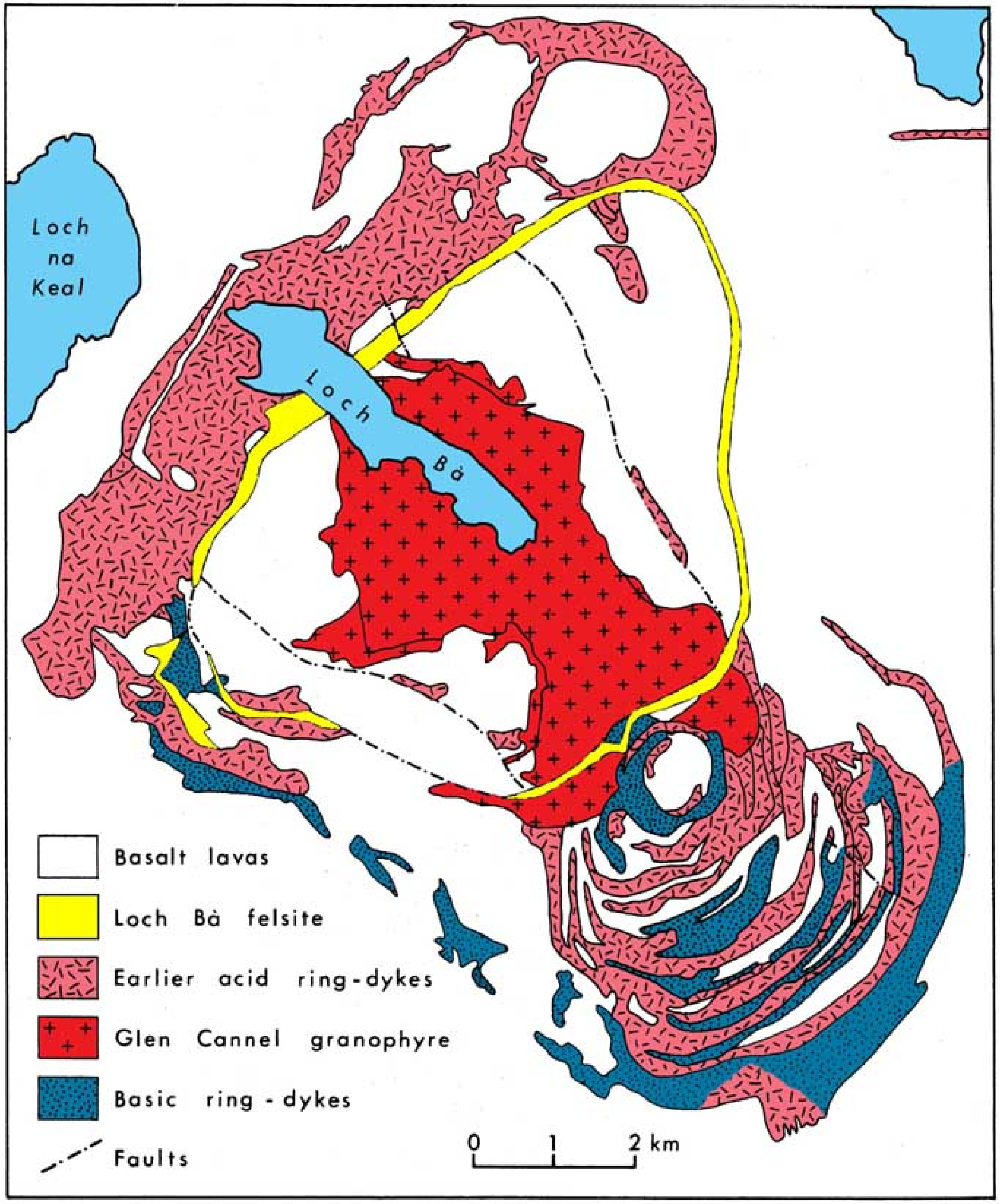


Figure 4.24. **a.** Map of **ring dikes**, Island of Mull, Scotland. After Bailey *et al*. (1924), *Tertiary and post-tertiary geology of Mull, Loch Aline and Oban*. Geol. Surv. Scot. Mull Memoir. Copyright British Geological Survey.

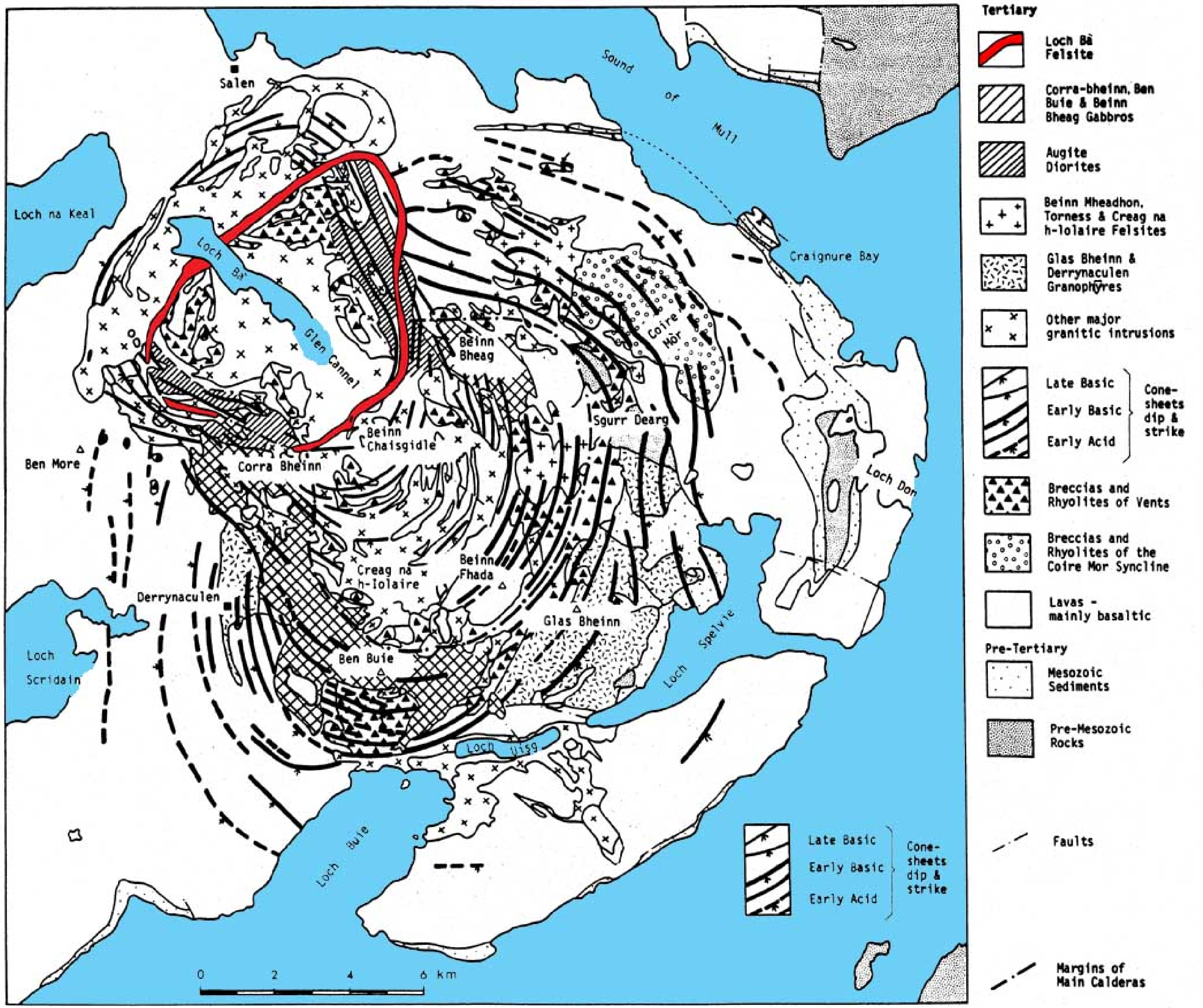


Figure 4.24. **b.** **Cone sheets** in the same area of Mull, after Ritchey (1961), *British Regional Geology. Scotland, the Tertiary Volcanic Districts*. Note that the yellow felsite ring dike in part (a) is shown as the red ring in the NW of part (b). British Geological Survey.

Structures and Field Relationships

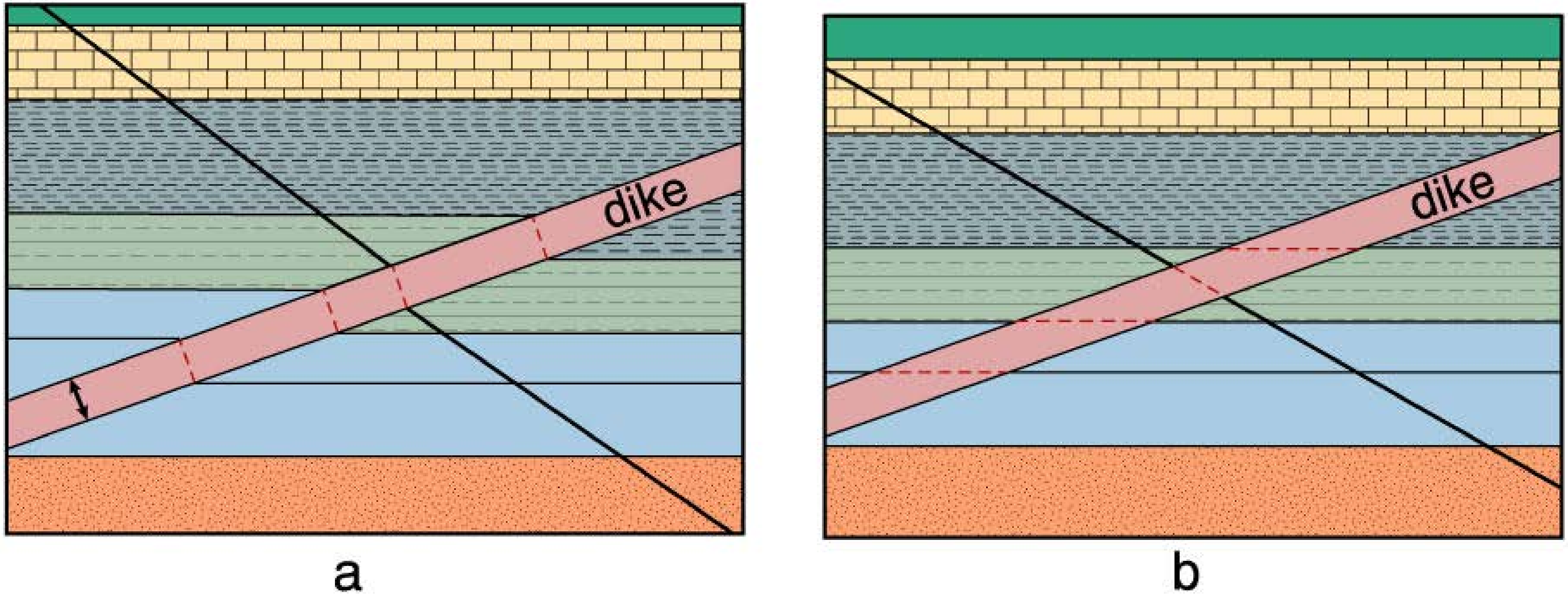


Figure 4.25. Types of tabular igneous bodies in bedded strata based on method of emplacement. **a.** Simple **dilation** (arrows) associated with **injection**. **b.** No dilation associated with **replacement** or **stoping**.

Structures and Field Relationships

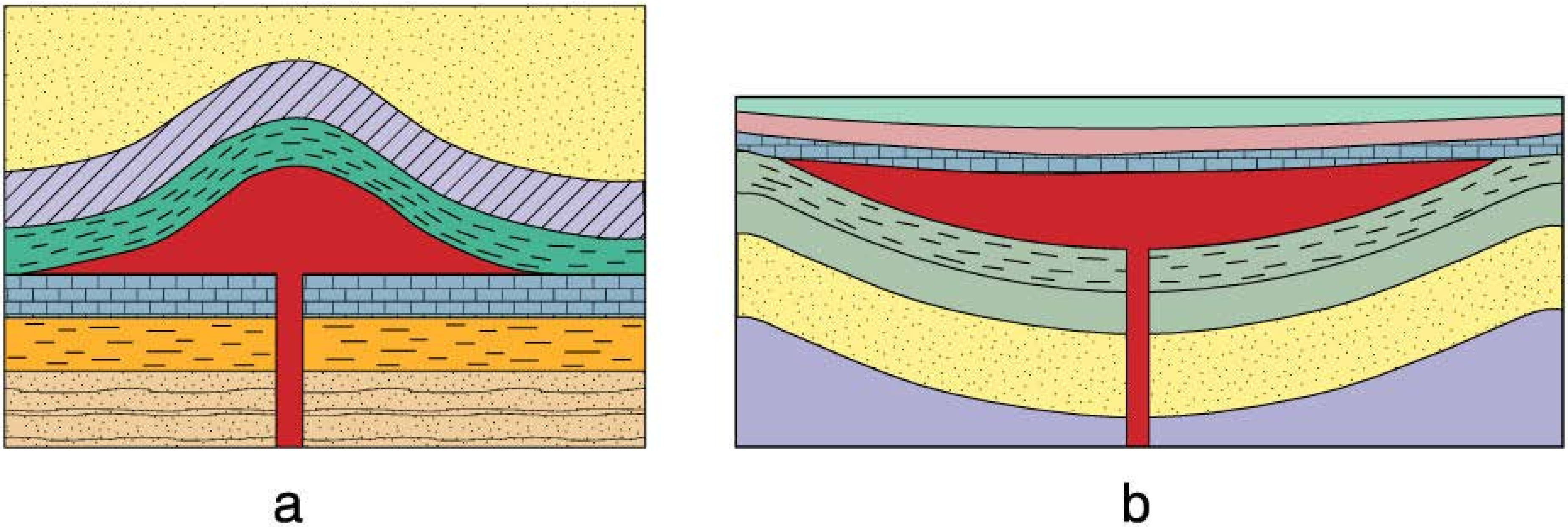


Figure 4.26. Shapes of two concordant plutons. **a. Laccolith** with flat floor and arched roof. **b. Lopolith** intruded into a structural basin. The scale is not the same for these two plutons, a lopolith is generally much larger. © John Winter and Prentice Hall.

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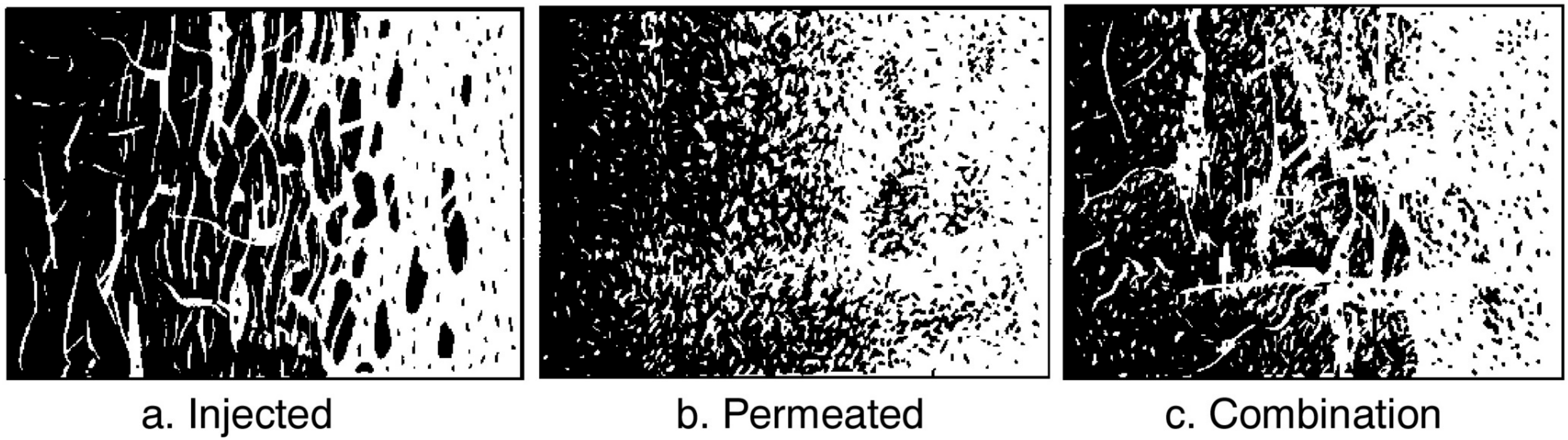

Figure 4.27. **Gradational border zones** between homogeneous igneous rock (light) and country rock (dark). After Compton (1962), *Manual of Field Geology*. © R. Compton.

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Figure 4.28. **Marginal foliations** developed within a pluton as a result of differential motion across the contact. From Lahee (1961), *Field Geology.* © McGraw Hill. New York.

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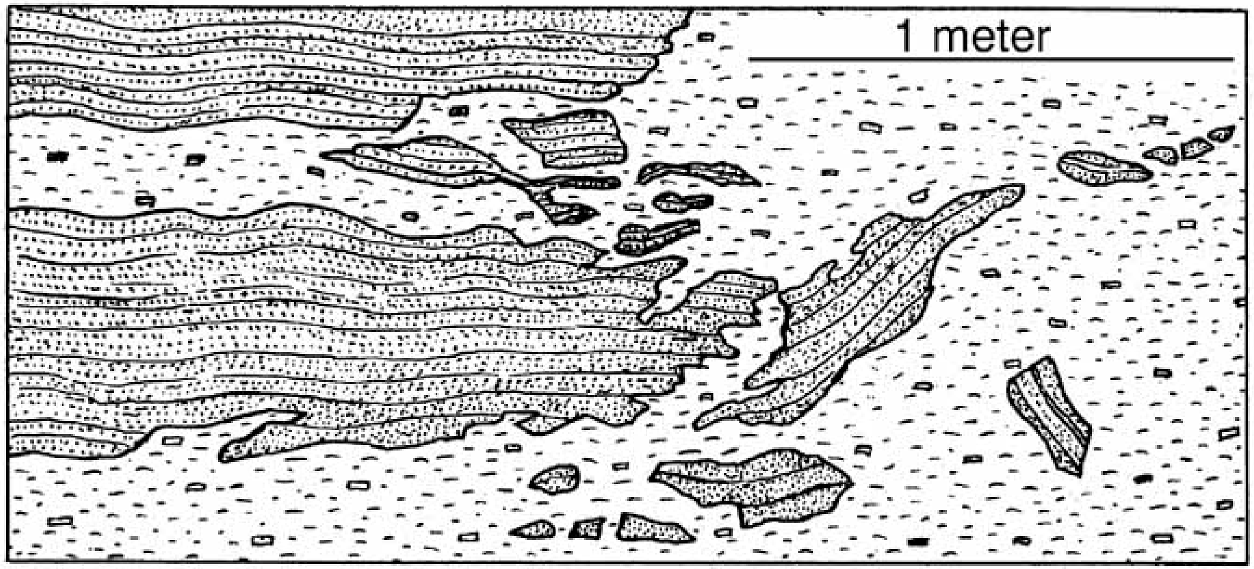

Figure 4.29. **Continuity of foliation** across an igneous contact for a pre- or syn-tectonic pluton. From Compton (1962), *Manual of Field Geology*. © R. Compton.

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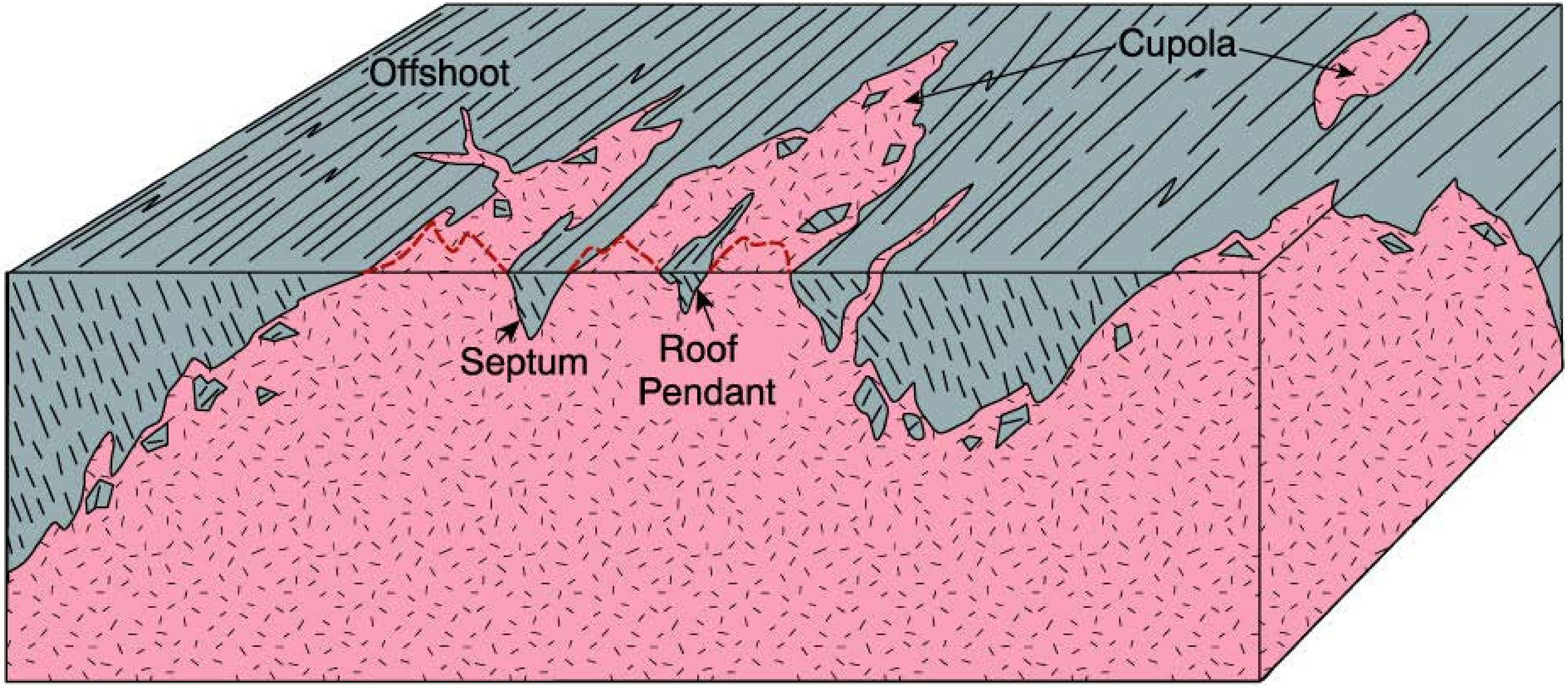

Figure 4.30. Block diagram several kilometers across, illustrating some relationships with the country rock near the top of a barely exposed pluton in the epizone. The original upper contact above the surface is approximated by the dashed line on the front plane. From Lahee (1961), *Field Geology.* © McGraw Hill. New York.

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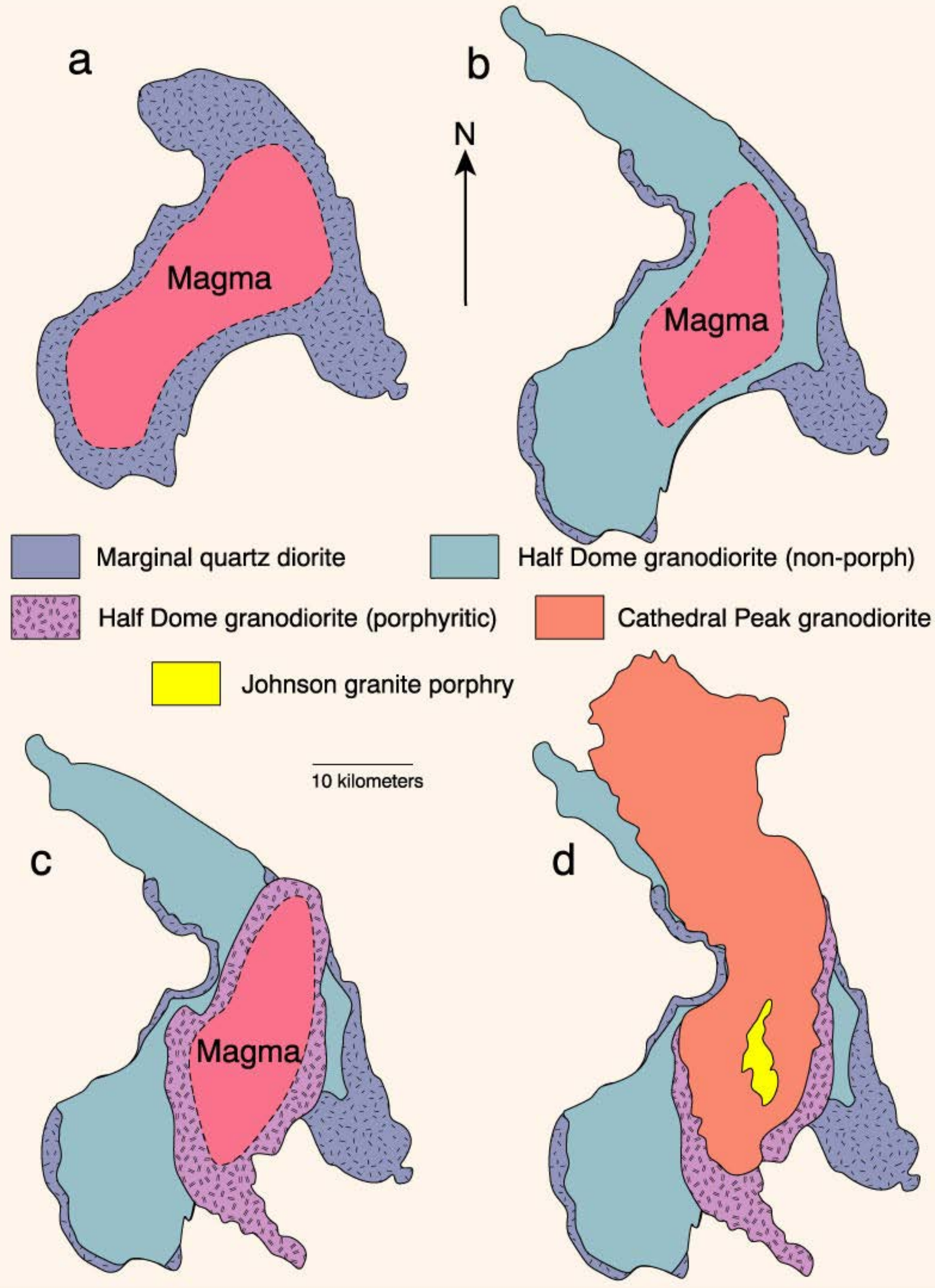

Figure 4.32. Developmental sequence of intrusions composing the Tuolumne Intrusive Series (after Bateman and Chappell, 1979), *Geol. Soc. Amer. Bull.*, **90**, 465-482.

a. Original intrusion and solidification of marginal quartz diorite.

b. Surge of magma followed by solidification of Half Dome Granodiorite.

c. Second surge of magma followed by solidification of porphyritic facies of Half Dome Granodiorite.

d. Third surge of magma followed by solidification of Cathedral Peak Granodiorite and final emplacement of Johnson Granite Porphry.

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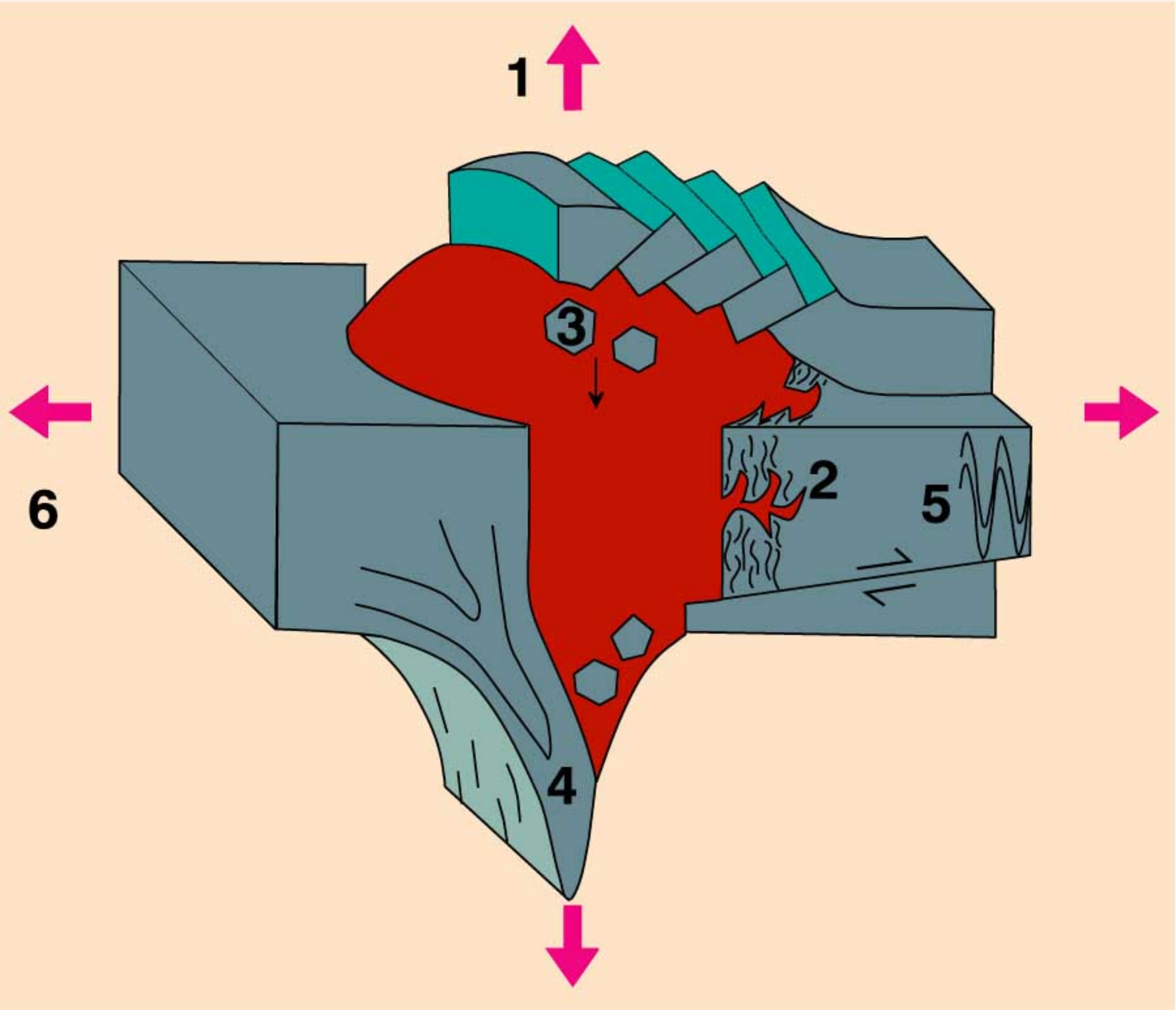

Figure 4.34. Diagrammatic illustration of proposed **pluton emplacement mechanisms**. **1- doming** of roof; **2-** wall rock **assimilation**, partial melting, zone melting; **3- stoping**; **4-** ductile wall rock **deformation** and wall rock **return flow**; **5-** lateral wall rock **displacement** by faulting or folding; **6-** (and 1)- emplacement into **extensional environment**. After Paterson *et al*. (1991), *Contact Metamorphism. Rev. in Mineralogy*, **26**, pp. 105-206. © Min. Soc. Amer.

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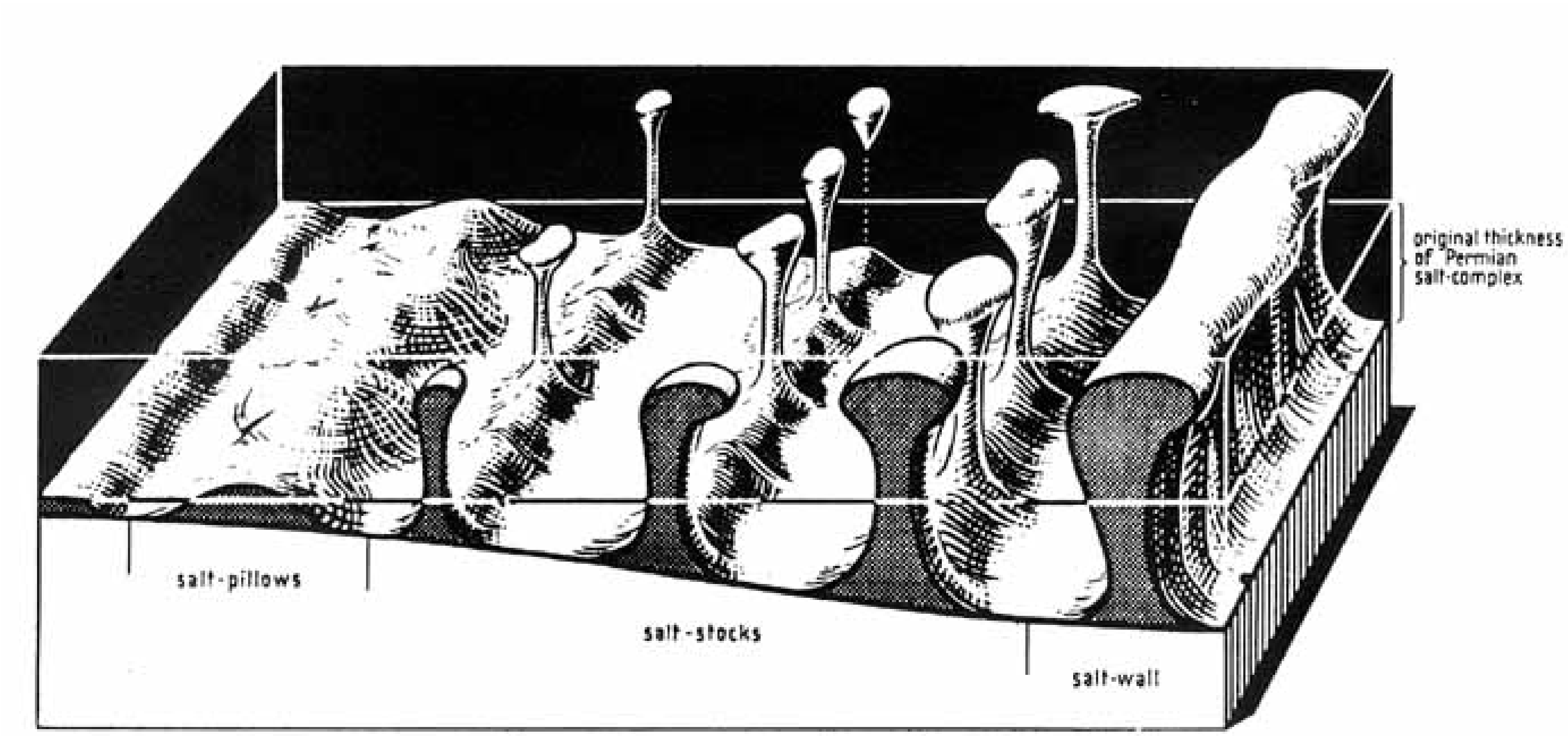

Figure 4.33. Block diagram of subsurface **salt diapirs** in Northern Germany. After Trusheim (1960), *Bull. Amer. Assoc. Petrol. Geol.*, **44**, 1519-1540 © AAPG.

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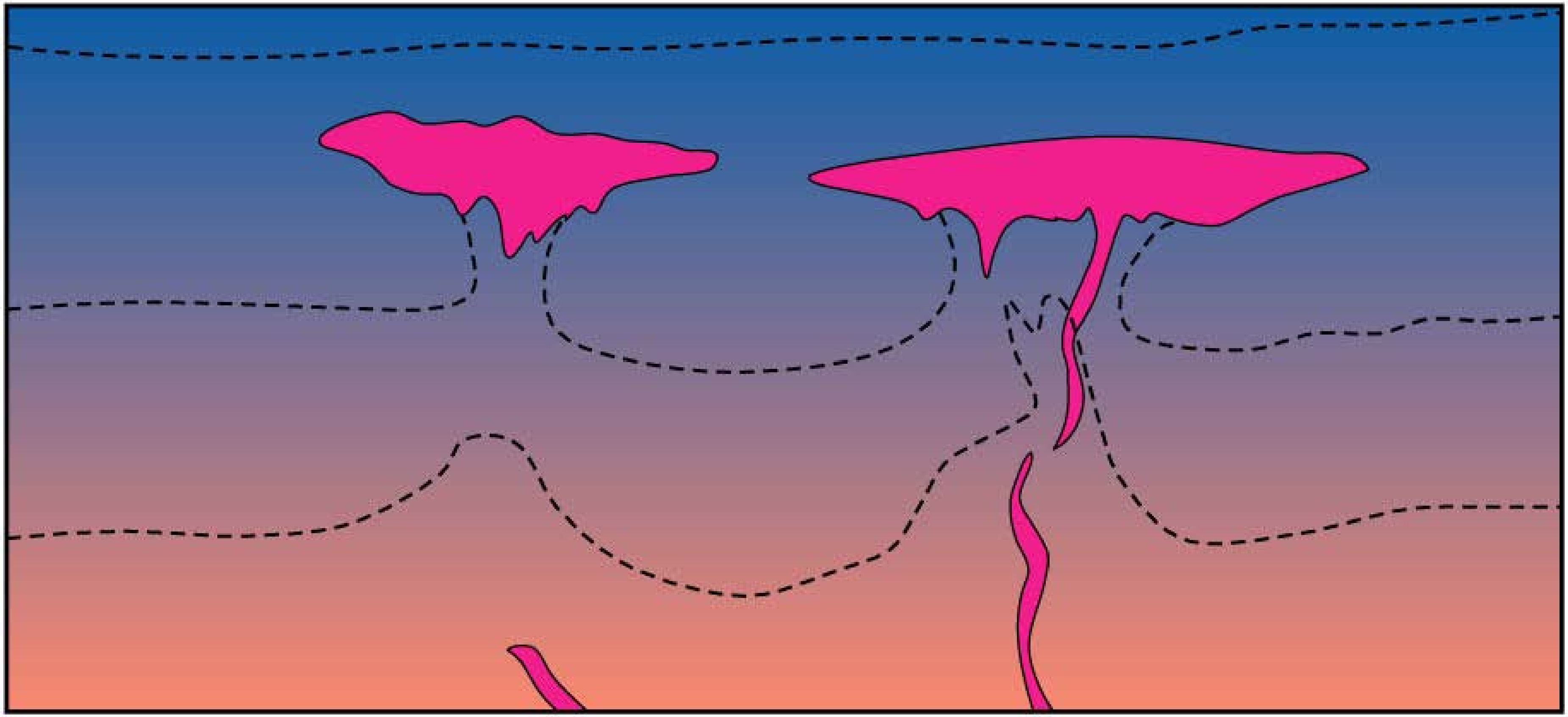

Figure 4.35. Sketches of diapirs in soft putty models created in a centrifuge by Ramberg (1970), In Newell, G., and N. Rast, (1970) (eds.), *Mechanism of Igneous Intrusion*. Liverpool Geol. Soc., Geol. J. Spec. Issue no. **2**.

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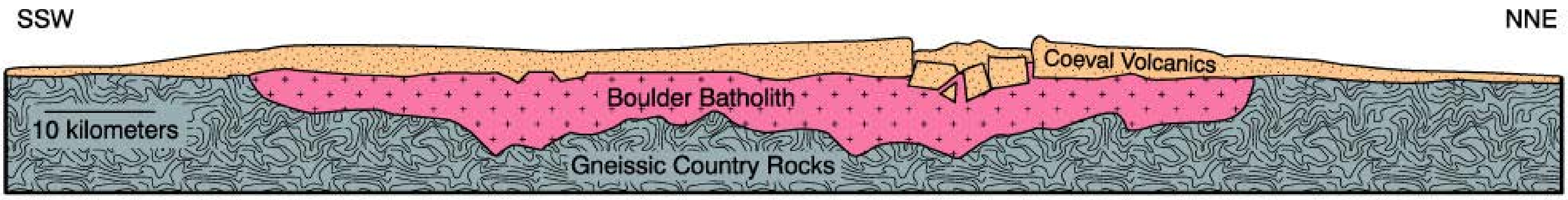

Figure 4.36. Diagrammatic cross section of the Boulder Batholith, Montana, prior to exposure. After Hamilton and Myers (1967), The nature of batholiths. *USGS Prof. Paper*, 554-C, c1-c30.

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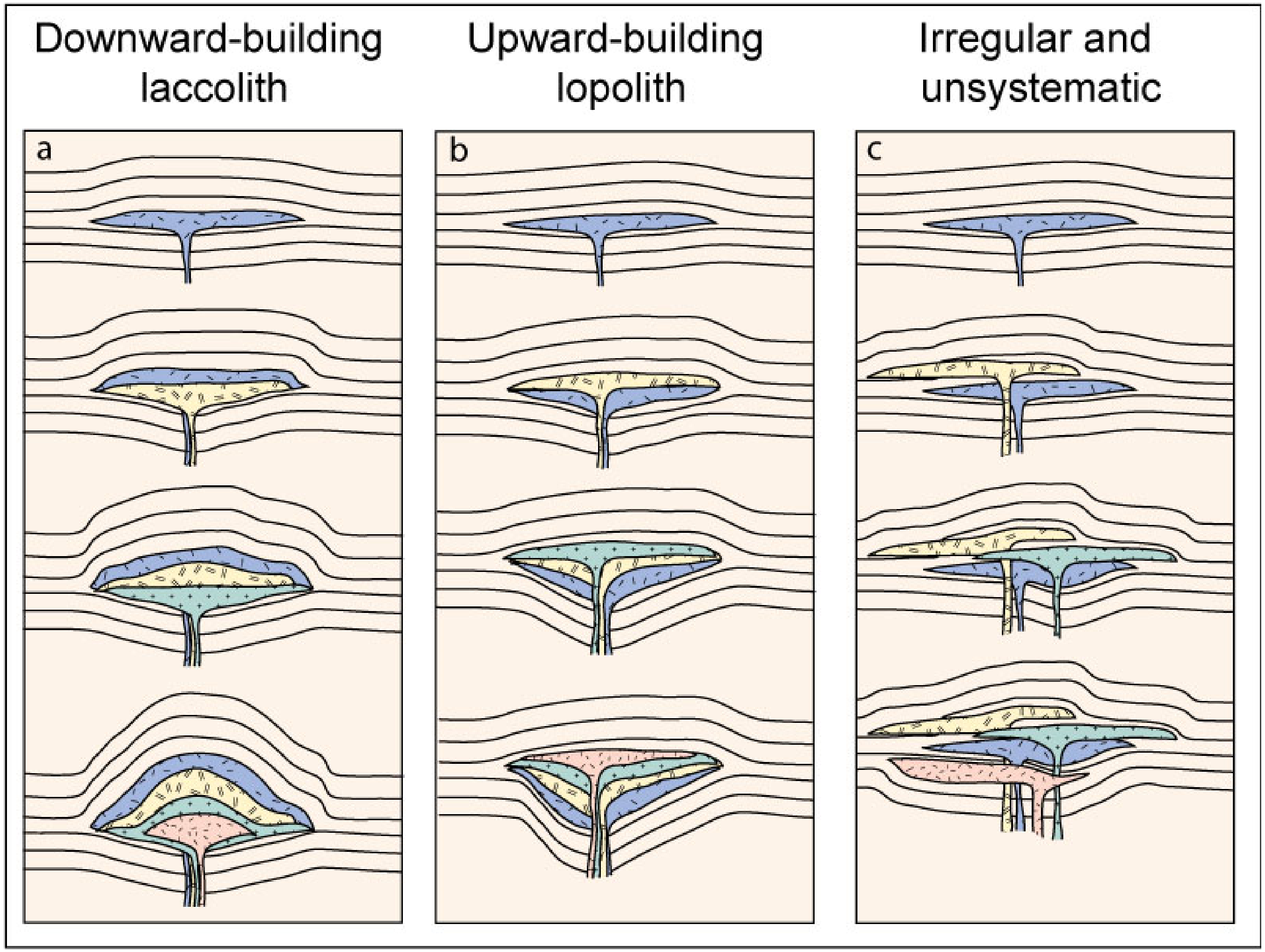

Figure 4.37. Possible methods by which a large batholith may grow by successive small increments over millions of years. Magma rises initially as a series of dikes in an extensional terrane. Each dike spreads laterally as a thick sill upon reaching a level at which it is no longer significantly buoyant. Room may be created by: **a.** lifting the roof rocks if the overburden is small, **b.** depressing the chamber floor as magma is displaced upward and withdrawn from below (Cruden and McCaffrey, 2001; Cruden, 2005), or **c.** some more irregular and sporadic process. Image courtesy of John Bartley.