◄— Previous section
◄— Volume contents

Processes of Laccolithic Emplacement in the Southern Henry Mountains, Southeastern Utah

By Marie Jackson[1]

CONTENTS

References Cited 27

FIGURES

1. Simplified geologic map of the south Henry Mountains 52
2. Interpretive radially oriented cross sections through Mounts Holmes, Ellsworth, and Hillers 54
3. Zijderveldt plots showing the progressive demagnetization of a diorite porphyry sample from sill A in cross section *C–C′* 56
4. G.K. Gilbert's concept of laccoliths in Henry Mountains 56
5. Structure contour maps and cross sections of Mounts Holmes, Ellsworth, and Hillers, illustrating C.B. Hunt's concept of relationships between the stocks and uplifts of the beds 57
6. Vertical cross sections showing states in growth of central intrusions and domes in the Henry Mountains 58

A sequence of sedimentary rocks about 4 km thick was bent, stretched, and uplifted during the growth of three igneous domes in the southern Henry Mountains (fig. 1). Mount Holmes, Mount Ellsworth, and Mount Hillers are all about 12 km in diameter, but the amplitudes (total uplifts) of the domes are about 1.2, 1.85, and 3.0 km, respectively (fig. 2). These mountains record successive stages in the growth of near-surface magma chambers. K-Ar dating of Henry Mountains diorite porphyry by Armstrong (1969) gives Eocene ages (40–48 Ma). Sullivan (1987), however, has found younger ages for these rocks (20–29 Ma), using fission-track methods.

[1] 114 North San Francisco Street, Suite 108, Flagstaff, AZ 86001
e-mail: mjackson@futureone.com

New geologic mapping (Jackson and Pollard, 1988) demonstrates that the sedimentary strata over the domes have a doubly hinged shape, consisting of a concave-upward lower hinge and a concave-downward upper hinge (fig. 2). A limb of approximately constant dip connects these two hinges and dips 20° at Mount Holmes, 50°–55° at Mount Ellsworth, and 75°–80° at Mount Hillers. The distal portion of each dome is composed of a gently dipping peripheral limb 3–4 km long, presumably underlain by sills and minor laccoliths. The host rocks deformed along networks of outcrop-scale faults or along deformation bands marked by crushed grains, consolidation of the porous sandstone, and small displacements of the sedimentary rocks (Jackson and Pollard, 1990). Zones of deformation bands oriented

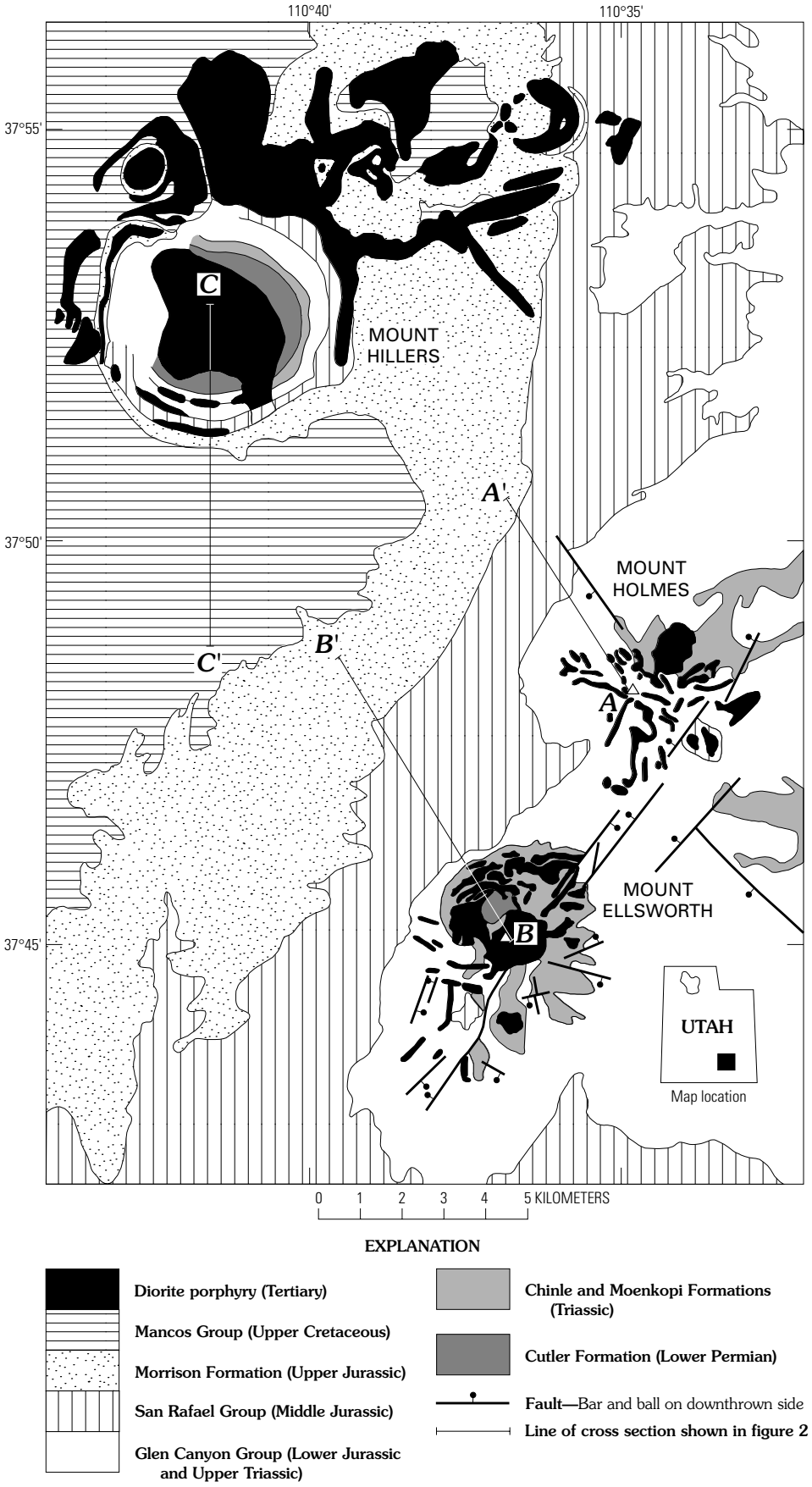


Figure 1. Simplified geologic map of the southern Henry Mountains modified from Hunt and others (1953) and Jackson and Pollard (1988). Younger rocks crop out progressively from east to west. Open triangle, mountain summit. Traverses *A–A′*, *B–B′*, and *C–C′* refer to cross sections in figure 2. Modified from Jackson and Pollard (1990, fig. 1).

parallel to the beds and formation contacts subdivided the overburden into thin layers that slipped over one another during doming.

Measurements of outcrop-scale fault populations at the three mountains reveal a network of faults that strikes at high angles to the sedimentary beds, which themselves strike tangentially about the domes (Jackson and Pollard, 1990). These faults have normal and reverse components of slip that accommodated bending and stretching strains within the strata. An early stage of this deformation is observed at Mount Holmes, where states of stress computed from measurements on three faults correlate with the theoretical distribution of stresses resulting from the bending of thin, circular, elastic plates. Bedding-plane slip and layer flexure were important components of the early deformation, as shown by field observations, by analysis of frictional driving stresses acting on horizontal planes above an opening-mode dislocation, and by paleostress analysis of the faulting. As the amplitude of doming increased, radial and circumferential stretching of the strata and rotation of the older faults in the steepening limbs of the domes increased the complexity of the fault patterns. Steeply dipping map-scale faults with dip-slip displacements indicate a late-stage jostling of major blocks over the central magma chamber. Radial dikes pierced the dome and accommodated some of the circumferential stretching.

At all three domes, porphyritic diorite sills are concordantly interleaved with the outward-dipping, arcuate beds of sedimentary host rock (fig. 2). More than 10 of these sills crop out at Mount Hillers, where they dip nearly vertically. Thermal demagnetization of cored specimens from five of these sills reveals that their partial thermoremanent magnetization has a broad range of blocking temperatures, ranging from 20°C to 590°C (Jackson and Champion, 1987). Figure 3 shows an example of the typical demagnetization data from one of the sills. When rotated to correct for the strike and dip of the beds, the high-temperature component of magnetization (450°C to 590°C) of these sills has about the same orientation as the expected Oligocene declination and inclination (358° and 56°, respectively (Irving and Irving, 1982)) This finding indicates that the sills were emplaced at nearly horizontal orientations and were later tilted. At intermediate blocking temperatures, between 377°C and 194°C, the paleomagnetic vectors recorded by the sample show a range of orientations, indicating that the sill was being rotated as it cooled, during growth of the central intrusion. At lower blocking temperatures, the stability and direction of the magnetization of the samples in their current position suggests the Oligocene magnetization rather than a recent viscous overprint. Apparently, the originally rotated low-temperature magnetization was reset by an *in situ* thermal remagnetization when the main intrusion at the center of the dome reheated the sills. The sills closest to the contact with the main intrusion show this reheating to a greater extent than sills higher in the section.

Whether the central intrusions underlying the domes are laccoliths or stocks has been the subject of controversy. According to G.K. Gilbert (1877), the central intrusions are direct analogs of the much smaller floored intrusions exposed on the flanks of the domes, which grew from sills by lifting and bending of a largely concordant overburden (fig. 4). Gilbert (1877) hypothesized that the intrusion of numerous sills preceded the inflation of an underlying laccolith, as shown by his cross section of Mount Hillers (fig. 4*B*). According to Hunt and others (1953), the central intrusions are cylindrical stocks, sheathed with a zone of shattered sedimentary rocks, and the small flanking sills and laccoliths grew laterally as tongue-shaped masses from the discordant sides of these stocks (fig. 5).

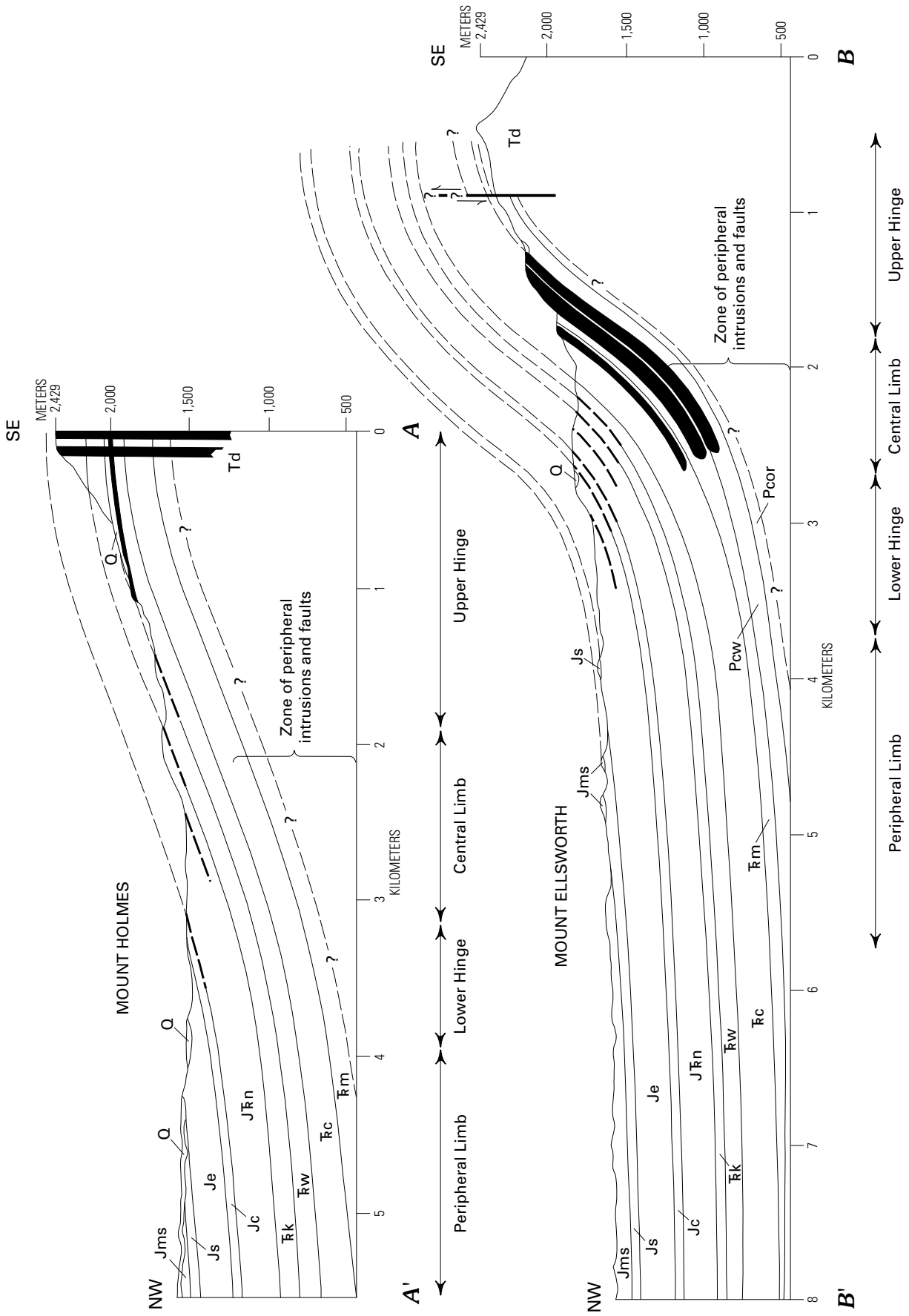
Although geologic cross sections and aeromagnetic data for the three domes are consistent with floored, laccolithic intrusions, these data do not rule out the possibility of a stock at depth (Jackson and Pollard, 1988). The paleomagnetic data from Mount Hillers (as in fig. 3, for example) indicate that the sills intruded during the first stages of doming, as Gilbert suggested. The sills cooled through their high blocking temperatures while horizontal and were then tilted with their host rock on the flanks of the growing dome. This sequence of events is not consistent with the emplacement of a stock and subsequent or contemporaneous lateral growth of sills and laccoliths. Growth in the diameter of a stock from about 300 m at Mount Holmes to nearly 3 km at Mount Hillers, as Hunt and others suggested (fig. 5), should have been accompanied by considerable radial shortening of the sedimentary strata and a style of folding that is not observed.

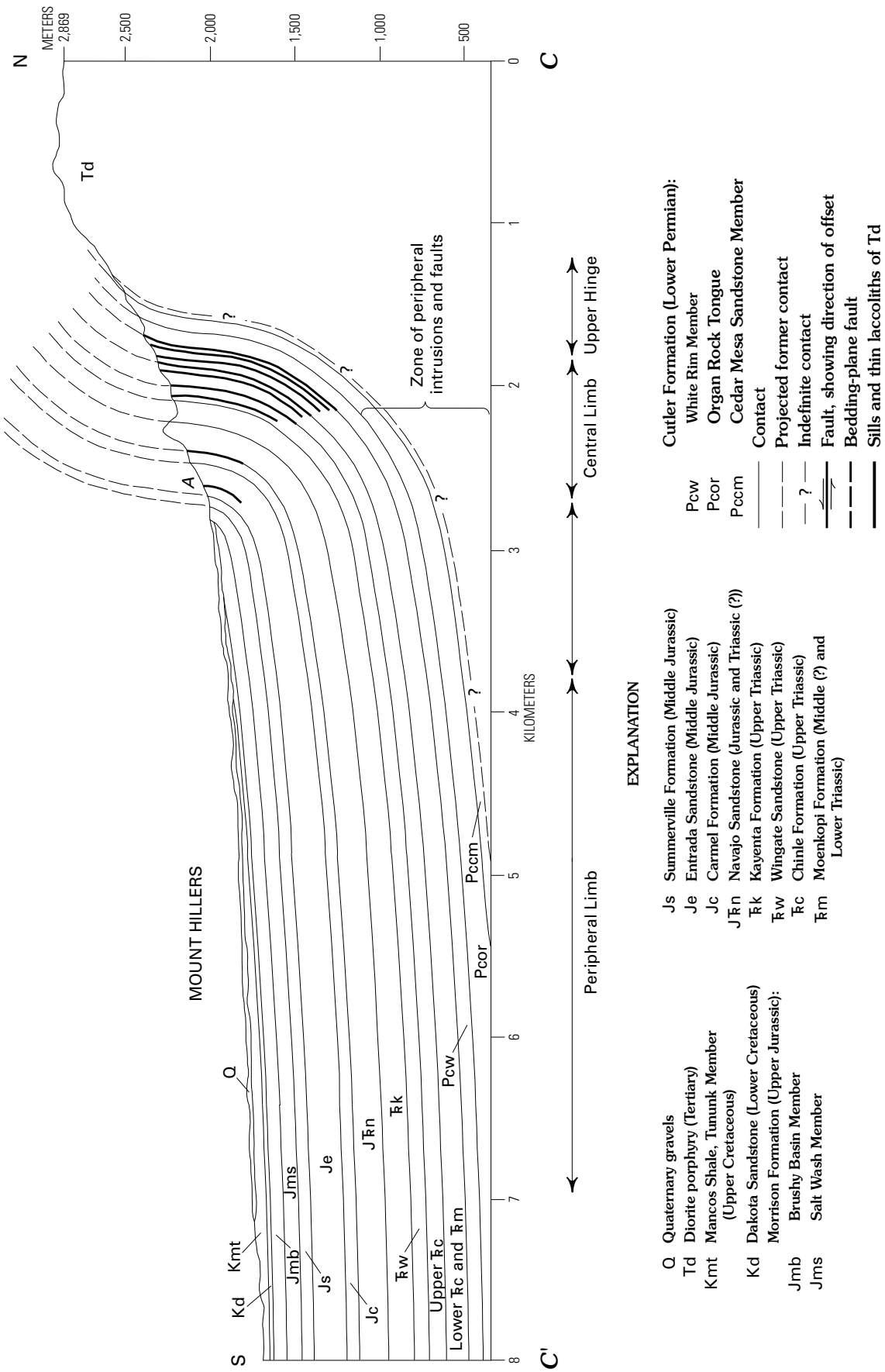
The following concepts define the difference between stocks and laccoliths (Jackson and Pollard, 1988, p. 117):

1. Laccoliths may be low in height relative to their horizontal dimensions, and they range from circular to tongue-shaped in plan form. Stocks have greater height relative to a roughly constant diameter, and they approximate a tall upright cylinder.

2. Laccoliths have a local feeder, such as a dike or stock, which has a very different size and mechanism of formation from those of the laccolith. Stocks do not have a

Figure 2 (following pages). Interpretive radially oriented cross sections through Mounts Holmes, Ellsworth, and Hillers. See figure 1 for lines of sections. Cross sections are based on a laccolithic model of the central intrusions. Roof-stock contacts are drawn at base of the Triassic section, the deepest rocks exposed on these mountains. True shapes of these contacts are probably much more complex than the concordant shapes we extrapolated from the surficial geology. The tapered peripheries of the central intrusions are zones where satellite diorite dikes, sills, and thin laccoliths are distributed through the stratigraphic section. Sill marked *A* (in cross section *C–C′*) was the source of the sample plotted in figure 3. From Jackson and Pollard (1988, fig. 10).


SE
METERS
2,429
2,000
1,500
1,000
500
0
Td
Q
?
Zone of peripheral intrusions and faults
MOUNT HOLMES
Jms
Js
Je
Jc
JTRn
TRk
TRw
TRc
TRm
NW
A
A'
Upper Hinge
Central Limb
Lower Hinge
Peripheral Limb
KILOMETERS
1
2
3
4
5
MOUNT ELLSWORTH
Pcor
Pcw
B
B'
6
7
8


N
METERS
2,869
2,500
2,000
1,500
1,000
500
0
C
Td
Zone of peripheral intrusions and faults
?
A
Central Limb
Upper Hinge
1
2
3
4
KILOMETERS
5
6
7
8
MOUNT HILLERS
Q
Kmt
Kd
Jms
Jmb
Js
Je
Jc
JTRn
TRk
TRw
Upper TRc
Lower TRc and TRm
Pcw
Pccm
Pcor
Peripheral Limb
S
C'
EXPLANATION
Q Quaternary gravels
Td Diorite porphyry (Tertiary)
Kmt Mancos Shale, Tununk Member (Upper Cretaceous)
Kd Dakota Sandstone (Lower Cretaceous)
Morrison Formation (Upper Jurassic):
Jmb Brushy Basin Member
Jms Salt Wash Member
Js Summerville Formation (Middle Jurassic)
Je Entrada Sandstone (Middle Jurassic)
Jc Carmel Formation (Middle Jurassic)
JTRn Navajo Sandstone (Jurassic and Triassic (?))
TRk Kayenta Formation (Upper Triassic)
TRw Wingate Sandstone (Upper Triassic)
TRc Chinle Formation (Upper Triassic)
TRm Moenkopi Formation (Middle (?) and Lower Triassic)
Cutler Formation (Lower Permian):
Pcw White Rim Member
Pcor Organ Rock Tongue
Pccm Cedar Mesa Sandstone Member
Contact
Projected former contact
? Indefinite contact
Fault, showing direction of offset
Bedding-plane fault
Sills and thin laccoliths of Td

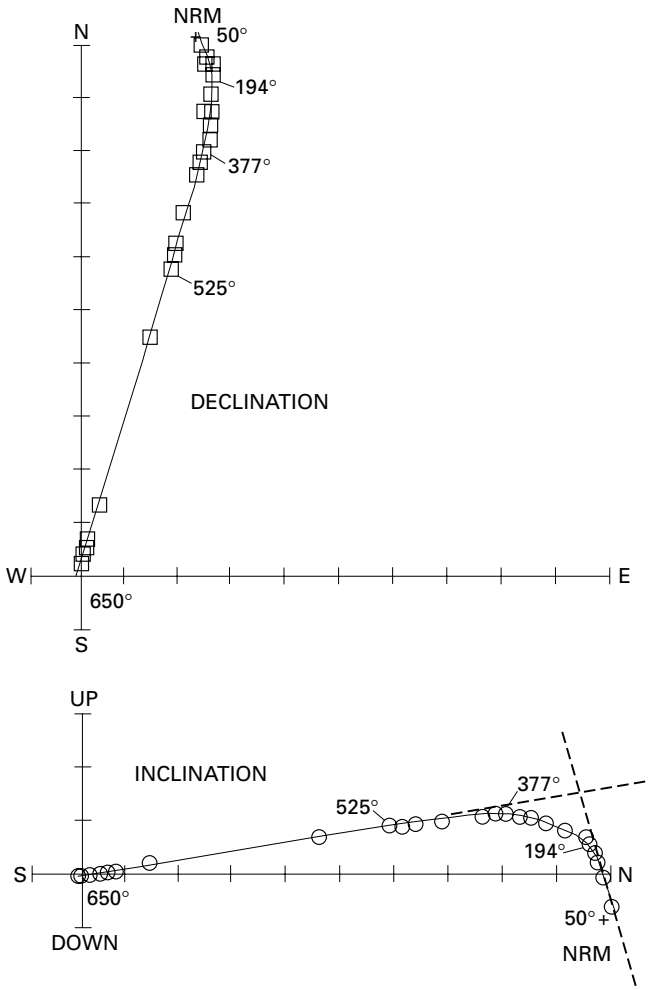


Figure 3. Zijderveldt plots showing the progressive demagnetization of a diorite porphyry sample from sill A in cross section C–C′ (fig. 2). Axis=2.36 emu/g. From the NRM (natural remanent magnetization) to the 194°C demagnetization step, the declination is 332°and the inclination is 70°. From 374°C to 600°C the declination is 17° and the inclination is –9°C. When corrected for strike and dip of adjacent beds, these components become 6° and 77°, respectively.

local feeder; they are continuous to great depth, perhaps extending to a deep magma reservoir.

3. Stocks grow upward, perhaps by stoping, zone melting, and (or) diapiric piercement, so they are not floored and may be largely discordant. Laccoliths grow from a thin sill that thickens into a floored body, and so they are largely concordant. Distinguishing between laccoliths and stocks is made more difficult because laccoliths can attain great height by peripheral faulting. This process produces bismaliths, bodies that have discordant sides but are floored.

Geologic and geophysical data and mechanical models suggest the following sequence of events for the formation of the domes (Jackson and Pollard, 1988). The first stage involved the intrusion of many horizontal diorite sills, some of which grew to be small laccoliths (fig. 6*A*). Many of these sills were elliptical or tongue shaped and formed a radiating pattern around the incipient dome. The feeders for the sills may have been radially oriented dikes that were distributed around the incipient dome much like the conspicuous minette dikes that form a radiating pattern around the Ship Rock volcanic neck in northwestern New Mexico (Delaney and Pollard, 1981). At some point, one such sill grew to sufficiently great radius, probably between 1 and 3 km, to thicken by bending the overburden. The growth of this laccolith was enhanced by its great radius, its circular plan shape, local heating of the host rock by the several older sills, and a continuing supply of magma.

As the central intrusion began to inflate (fig. 6*B*), host-rock flexure passed through an early bending stage of deformation, such as that observed at Mount Holmes (fig. 2, *A*–*A*′). The overburden behaved as a stack of layers that slipped over one another on bedding-plane faults, and the

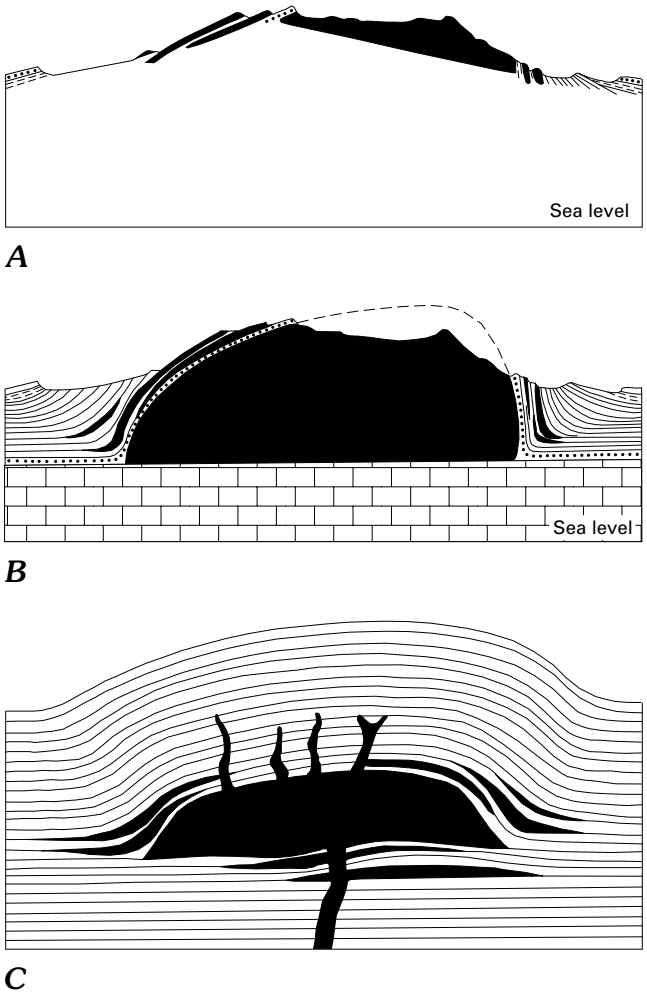


Figure 4. G.K. Gilbert's concept of laccoliths in Henry Mountains (modified from Gilbert, 1877). *A*, Geologic cross section of Mount Hillers, striking N. 35°W. Diorite in black. *B*, Gilbert's interpretation of subsurface structure of Mount Hillers. *C*, Idealized laccolithic intrusion with a narrow feeder at its base.

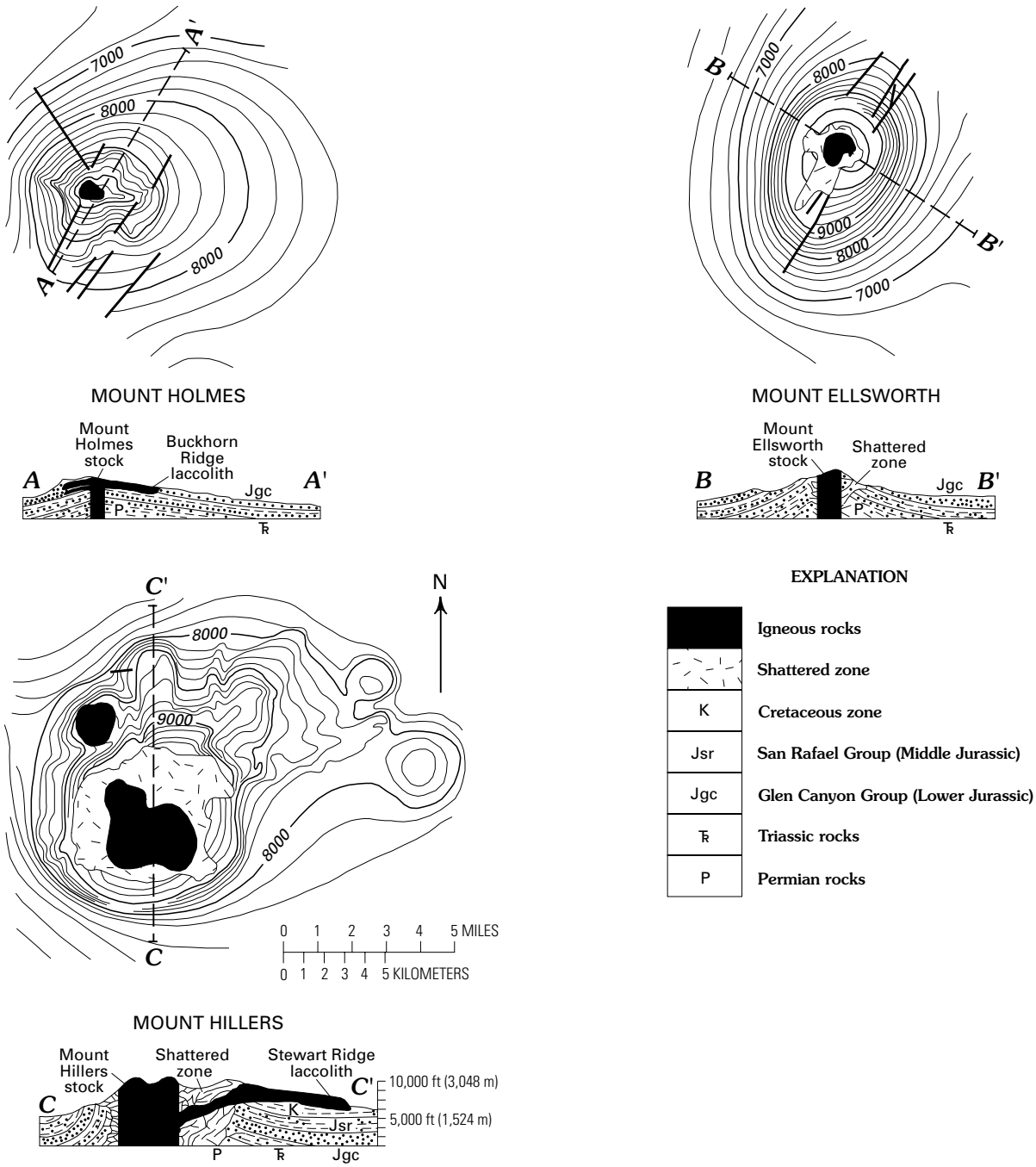
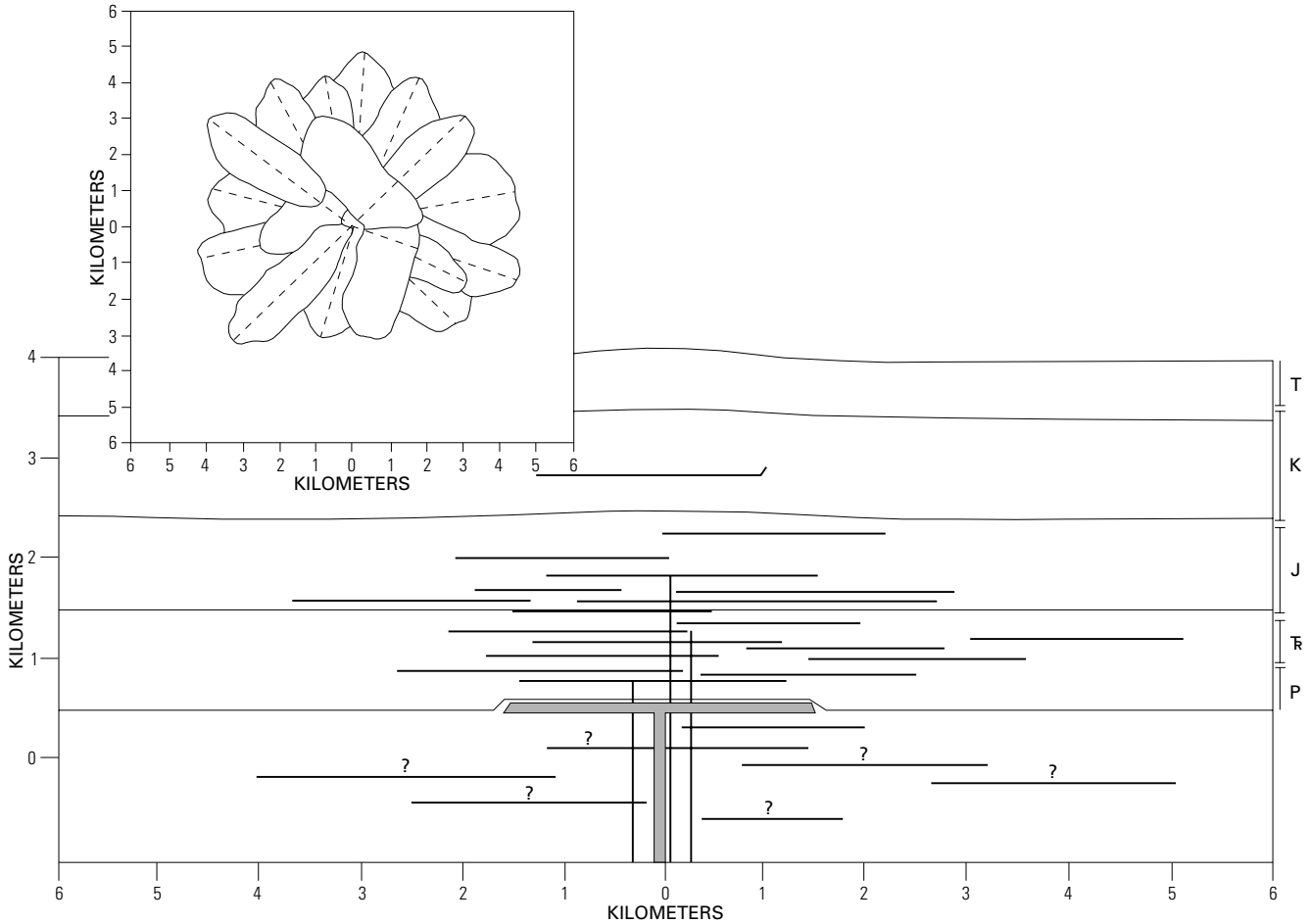


Figure 5. Structure contour maps and cross sections of Mounts Holmes, Ellsworth, and Hillers, illustrating C.B. Hunt's concept of relationships between the stocks and uplift of the beds (modified from Hunt and others, 1953). Contour interval 200 ft (≈60 m).

sills were gently rotated. In addition the layers of host rock were slightly stretched over the dome as the amplitude of deflection increased. Multiple injections of dikes and sills extended laterally beyond the sides of the central intrusion.

With continuing growth (fig. 6*C*), the hinges of the host-rock flexure tightened and the central limb steepened, as at Mount Ellsworth and Mount Hillers. Radial and circumferential stretching of the overlying layers became more important, relative to bending. Radial dikes cut across steeply dipping sills on the flanks of the dome. At the edge of the dome, the cumulative effect of continued intrusion of satellitic sills and laccoliths was to incline the overburden over the length of the long outer limb. During the entire intrusive episode, brecciation and disruption of the host rock were limited to a thin zone at the immediate contact with the central intrusion.



A

Figure 6 (above and facing page). Vertical cross sections showing states in growth of central intrusions and domes in the Henry Mountains. *A*, Emplacement of a stack of tongue-shaped sills and thin laccoliths fed by vertical dikes. Inset: plan view of early-formed intrusions, showing their tongue-like shape. The incipient major laccolith (stipple pattern) has a circular plan shape. *B*, Thickening of the major laccolith induces bedding-plane faulting, and the overlying intrusions are faulted. Peripheral dikes and faults form as lateral growth of the laccolith stops. Some sills and thin laccoliths intrude laterally under the peripheral limb of the dome. *C*, The major laccolith continues to thicken as dome grows in amplitude. Beds steepen and stretch on flanks of the dome, numerous faults lift the roof rock, zone of peripheral intrusion enlarges, and radial dikes cut upward through overburden. P, Tr, J, K, T: Permian, Triassic, Jurassic, Cretaceous, and Tertiary sedimentary host rocks. From Jackson and Pollard, 1988, figure 19.

REFERENCES CITED

Armstrong, R.L., 1969, K-Ar dating of laccolithic centers of the Colorado Plateau and vicinity: Geological Society of America Bulletin, v. 80, p. 2081–2086.

Delaney, P.T., and Pollard, D.D., 1981, Deformation of host rocks and flow of magma during growth of minette dikes and breccia-bearing intrusions near Ship Rock, New Mexico: U.S. Geological Survey Professional Paper 1201, 61 p.

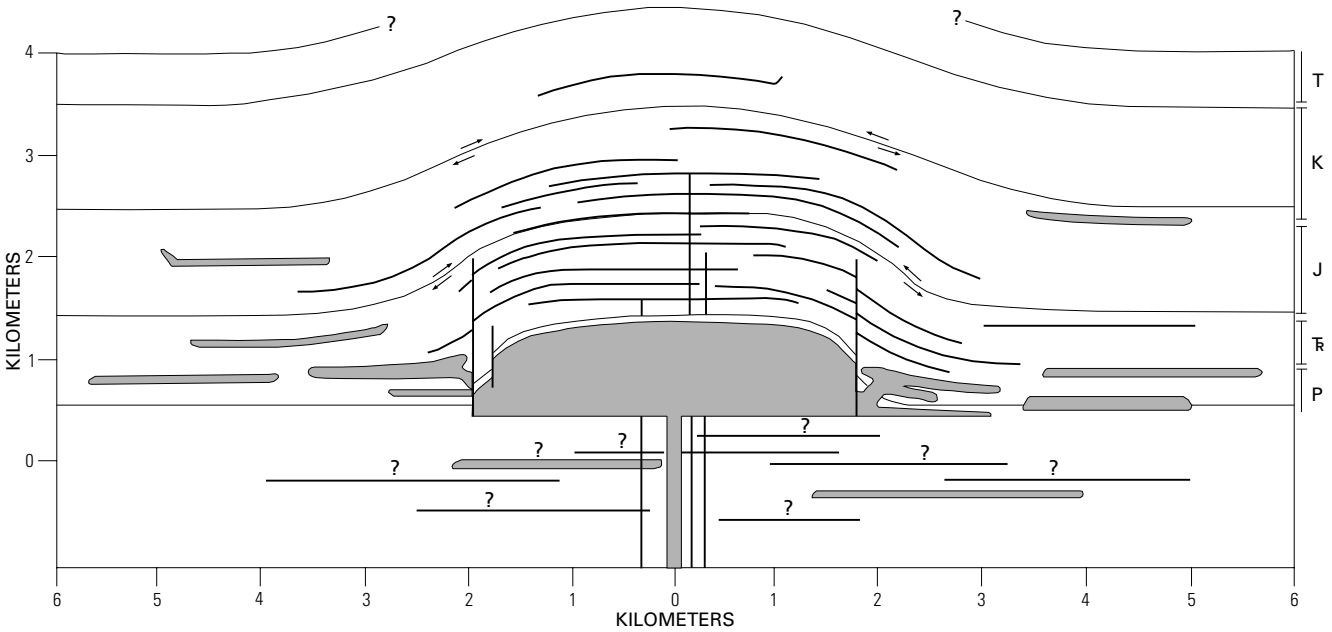
Gilbert, G.K., 1877, Report on the geology of the Henry Mountains: U.S. Geographical and Geological Survey of the Rocky Mountain Region (Powell), 160 p.

Hunt, C.B., Averitt, Paul, and Miller, R.L., 1953, Geology and geography of the Henry Mountains region, Utah: U.S. Geological Survey Professional Paper 228, 234 p., 22 pl.

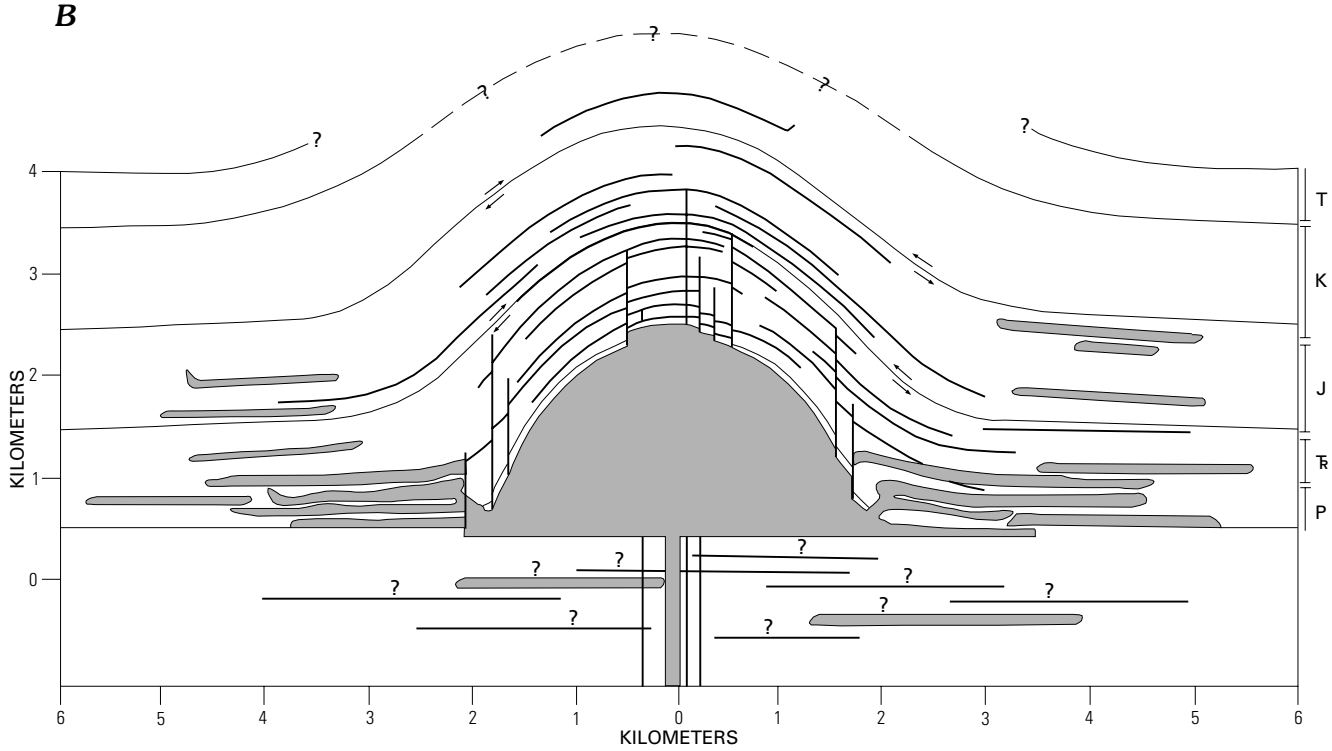
Irving, E., and Irving, G.A., 1982, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana: Geophysical Surveys, v. 5, p. 141–188.

Jackson, M.D., and Champion, D.E., 1987, Paleomagnetism of rotated sills at Mount Hillers, Henry Mountains, Utah—Implications for the early stages of growth of near surface igneous domes: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 391.

Jackson, M.D., and Pollard, D.D., 1988, The laccolith-stock controversy—New results from the southern Henry



B



C

Mountains, Utah: Geological Society of America Bulletin, v. 100, p 117–139.

———1990, Flexure and faulting of sedimentary host rocks during growth of igneous domes, Henry Mountains, Utah: Journal of Structural Geology, v. 12, p. 185–206.

Sullivan, K.R., 1987, Isotopic ages of igneous intrusions in southeastern Utah—Relation to space-time-composition patterns of Cenozoic igneous activity in Nevada, Utah, and Colorado: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 337.

Next section →