Stratigraphic Notes, 1989–90

Four short papers propose changes in stratigraphic nomenclature in Oregon, Vermont, Massachusetts, and southern Pakistan

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[Numbers designate notes]

The Salmon River Formation—a Lower Eocene Sequence in the Central Oregon Coast Range

By Parke D. Snavely, Jr.

Abstract

The Salmon River Formation, named in this report, crops out in the central part of the Oregon Coast Range, where it occurs in the lower part of a 6,000-m-thick Tertiary marine sequence. The Salmon River Formation consists predominantly of well-indurated, fine-grained basaltic and lithic sandstone and concretionary, tuffaceous siltstone. The formation includes minor interbeds of basalt pebble and cobble conglomerate, pillow basalt, breccia, and lapilli tuff. The thickness of the Salmon River Formation can only be estimated because it is folded and faulted and lacks lithologically distinctive beds that can be traced across structure. One homoclinally dipping sequence in the type section along the Salmon River is about 600 m thick. The Salmon River Formation unconformably overlies the lower Eocene Siletz River Volcanics and in most places is unconformably overlain by the middle Eocene Yamhill Formation. Coccolith floras typical of the lower Eocene *Discoaster lodoensis* Zone (CP11) occur at several localities in basaltic fine-grained sandstone and siltstone in the type section of the Salmon River Formation. Strata also assigned to the *D. lodoensis* Zone include the Umpqua Formation in the southern Oregon Coast Range and the Kings Valley Siltstone Member of the Siletz River Volcanics 15 km west of Corvallis on the east flank of the range. In the northern part of the Oregon Coast Range on the southeast side of the Tillamook Highlands, a sequence of siltstone and basaltic sandstone and pillow lava and breccia that crop out in the headwaters of the North Fork of the Trask River also contains a coccolith assemblage of Zone CP11.

INTRODUCTION

The Salmon River Formation (new name) is a lower Eocene sequence of basaltic sandstone and siltstone that contains minor interbeds of conglomerate and basalt flows, breccia, and tuff. This faulted and folded sequence is best exposed along the Salmon River and its tributaries between Otis and Rose Lodge on the west flank of the central Oregon Coast Range (fig. 1). Originally, these rocks were included in the Siletz River Volcanics as described by Snavely and Baldwin (1948) and mapped by Snavely and Vokes (1949) and Snavely and others (1976). In a report on coccolith zonation in Paleogene strata of the Oregon Coast Range, strata that now compose the Salmon River Formation were informally referred to as the basaltic siltstone of Neskowin Creek (Bukry and Snavely, 1988). Recent detailed mapping by P.D. Snavely, Jr., and N.S. MacLeod (unpub. data, 1983–88), however, shows that the Salmon River Formation unconformably overlies the Siletz River Volcanics and constitutes a younger mappable unit in the northwestern part of the Euchre Mountain 15-minute quadrangle and the southwestern part of the Hebo 15-minute quadrangle, Oreg. The Salmon River Formation is interpreted to represent aprons of clastic debris eroded from, and deposited adjacent to, oceanic islands or seamounts formed by extrusion of the Siletz River Volcanics.

Manuscript approved for publication, March 7, 1990.

TYPE SECTION

The type section for the Salmon River Formation is designated as the exposures in the riverbed and banks of the Salmon River (from which the unit takes its name) extending upstream from a point 0.8 km southeast of Otis (SE¼SW¼ sec. 29, T. 6 S., R. 10 W., Hebo quadrangle) to Rose Lodge (SW¼SE¼ sec. 26, T. 6 S., R. 10 W., Hebo quadrangle), a distance of about 8 km (sec. *A–A'*, fig. 1). The unit is particularly well exposed in a 30-m-high cutbank on the north side of the Salmon River near the confluence of Slick Rock Creek just west of Rose Lodge. The sequence is exposed adjacent to the type section in the riverbeds and roadcuts along lower reaches of several major tributaries to the Salmon River, including Deer Creek and Panther Creek north of the type section, and Bear Creek and Slick Rock Creek south of the type section (fig. 1).

Well-exposed, microfossil-bearing strata that crop out in the riverbed of Neskowin Creek, extending from near the confluence of Kingston Creek (NE¼NE¼ sec. 16, T. 6 S., R. 10 W., Hebo quadrangle) eastward for a

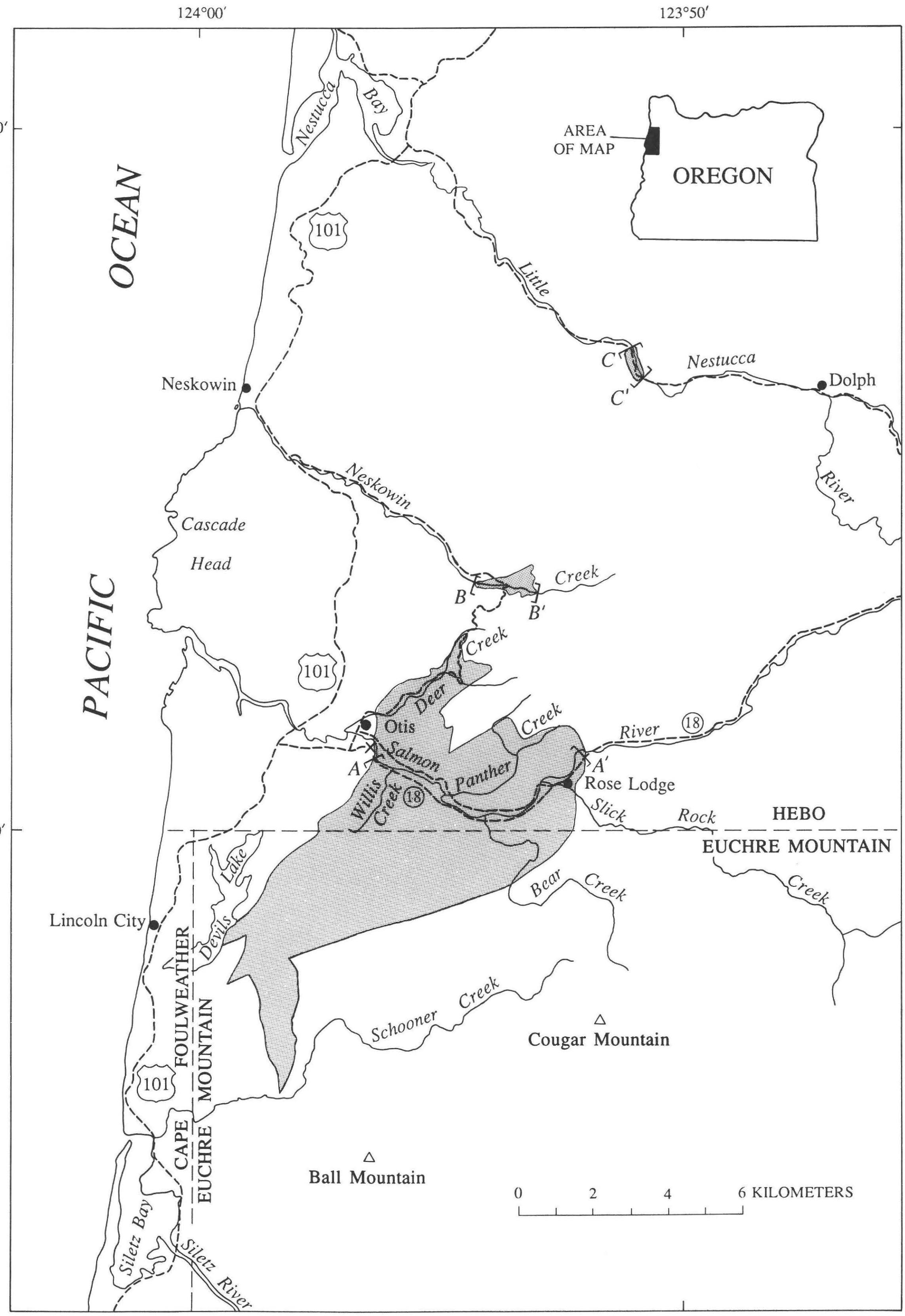

Figure 1. Index map of northwestern Oregon, showing distribution of the Salmon River Formation (shading) and locations of type section *A–A′* and reference sections *B–B′* and *C–C′*. ×, location of exposure of basaltic sandstone and siltstone of Otis.

distance of 1.5 km, are designated as a reference section (sec. *B–B'*, fig. 1), as are exposures of the basal part of the Salmon River Formation along the Little Nestucca River eastward for a distance of approximately 250 m from a point in the SW¼SW¼ sec. 24, T. 5 S., R. 10 W., Hebo quadrangle (sec. *C–C'*, fig. 1).

LITHOLOGIC CHARACTERISTICS

The Salmon River Formation consists predominantly of well-indurated, flaggy, thin- to medium-bedded, fine-grained basaltic and lithic sandstone and tuffaceous siltstone; locally, the strata are calcareous and carbonaceous. The formation includes minor interbeds of basalt pebble and cobble conglomerate, pillow basalt, breccia, and lapilli tuff (fig. 2). In places, the unit contains light-gray, discontinuous calcareous siltstone ledges (4–6 cm thick), beds of broken-shell material, feldspar-rich fine-grained sandstone, and glauconitic, medium-grained basaltic and lithic sandstone. Calcareous concretions, as much as ½ m long, occur in the siltstone and commonly contain small (5 mm diam) crystals of pyrite. Locally, the strata are penecontemporaneously deformed and cut by 0.5- to 1-m-thick vesicular basalt dikes that probably were feeders to the interbedded pillow lavas and breccia.

In the riverbed of the Little Nestucca River (sec. *C–C'*, fig. 1), conglomerate at the base of the Salmon River Formation consists of clasts of fine-grained amygdaloidal basalt, porphyritic olivine basalt, and rounded to subangular calcareous concretions containing abundant small crystals of pyrite; calcite veinlets cut the beds. The conglomerate is overlain by massive to thick-bedded basaltic sandstone containing rip-up blocks of pyrite-bearing calcareous siltstone and blocky, massive-appearing siltstone with disc-shaped pyrite-bearing calcareous concretions. A few 0.5-m-thick basaltic sandstone beds are graded and sole marked. Thin, irregularly bedded, well-indurated siltstone and gritty to fine-grained, flaggy basaltic sandstone are exposed at the top of this faulted and folded 60-m-thick sequence.

In weathered exposures, the basaltic sedimentary rocks of the Salmon River Formation are stained with iron and manganese oxides and weather spheroidally.

CONTACT RELATIONS AND THICKNESS

The Salmon River Formation unconformably overlies the Siletz River Volcanics, here of early Eocene age. A basal boulder to pebble conglomerate is present along the contact and is particularly well exposed in roadcuts along Slick Rock Creek just south of the junction of Oregon Highway 18. The conglomerate exhibits imbricate structure and is composed of clasts derived from basalt flows and gabbroic intrusive rocks of the Siletz River Volcanics. The base of the Salmon River Formation also is exposed in the creekbed of the Little Nestucca River near the SW. cor. sec. 24, T. 5 S., R. 10 W. (sec. *C–C'*, fig. 1), where it overlies massive basalt-flow breccia of the Siletz River Volcanics. At this exposure, about 20 m of gritty basaltic sandstone and pebble to cobble conglomerate in a matrix of calcareous cemented sandstone is present at the base of the Salmon River Formation.

The Salmon River Formation is unconformably overlain in most places by the middle Eocene Yamhill Formation; however, in its westernmost exposures along

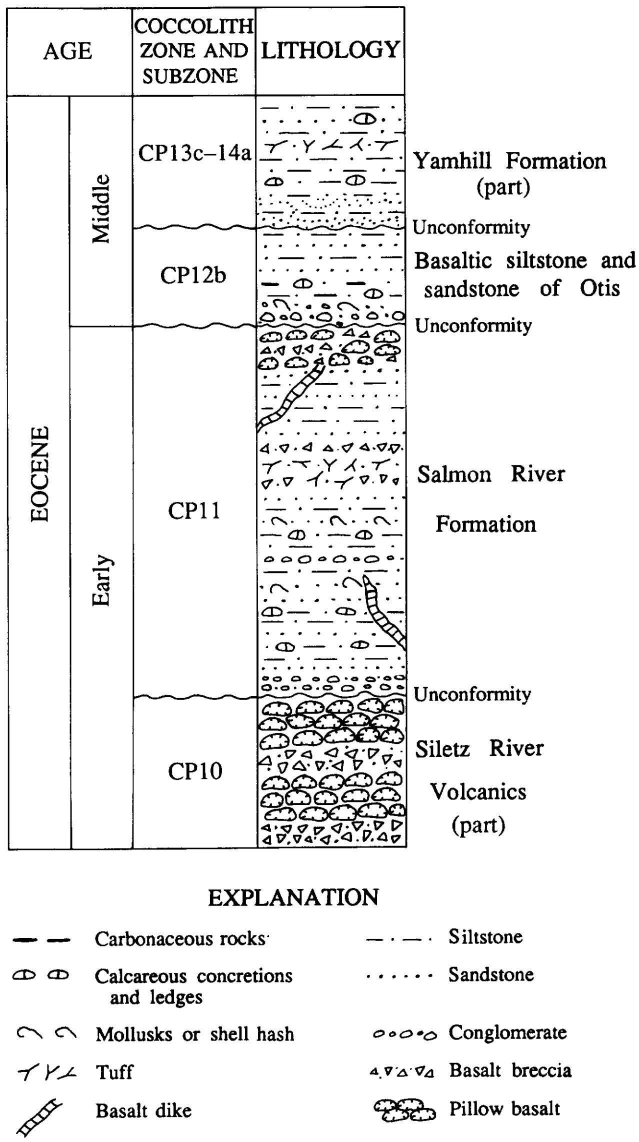

Figure 2. Generalized stratigraphic section of the Salmon River Formation in its type section. Zonal assignments based on Bukry (1973), Okada and Bukry (1980), and Bukry and Snavely (1988). No scale indicated.

the Salmon River, 0.7 km southeast of Otis (×, fig. 1), it is unconformably overlain by lower middle Eocene strata that contain a coccolith assemblage assigned to the lower middle Eocene *Rhabdosphaera inflata* Subzone (CP12b) (Bukry and Snavely, 1988). This younger unit, informally referred to as the basaltic sandstone and siltstone of Otis (Bukry and Snavely, 1988), consists of approximately 150 m of shallow-water, thin- to medium-bedded, platy, carbonaceous basaltic siltstone and calcareous fossiliferous sandstone. The Otis beds are areally restricted and cannot be mapped north of the Salmon River because the unit is unconformably overlain by the Yamhill Formation that overlaps these beds and rests directly on the Salmon River Formation. South of the Salmon River, these lower middle Eocene strata are poorly exposed and are known to occur only in the upper part of Willis Creek.

The thickness of the Salmon River Formation can only be estimated because the unit is folded and faulted and lacks lithologically distinctive beds that can be traced across structure. One homoclinally dipping sequence within an apparent single fault block is about 600 m thick. In Neskowin Creek, the formation is approximately 300 m thick where it unconformably underlies the Yamhill Formation. In the streambed of the Little Nestucca River, only 60 m of strata unconformably overlies the Siletz River Volcanics because the upper part of the Salmon River Formation is cut out by a fault.

AGE

A coccolith assemblage assigned to the lower Eocene *Discoaster lodoensis* Zone (CP11) occurs at several localities in basaltic fine-grained sandstone and siltstone in the type section of the Salmon River Formation (Bukry and Snavely, 1988). Coccoliths typical of Zone CP11 also occur in strata of the Neskowin Creek and Little Nestucca River reference sections. Studies of foraminifers by W.W. Rau (written communs., 1965–85) place most samples from the Salmon River Formation in the middle Eocene Ulatisian Stage of Mallory (1959); however, Rau assigned a few samples to the lower Ulatisian or Penutian Stage. In his biostratigraphic studies of Eocene strata exposed along Neskowin Creek, Callender (1977) assigned strata included in the reference section of the Salmon River Formation to the Ulatisian Stage. I believe that the early Eocene (CP11) age based on planktonic coccoliths for the Salmon River Formation is more precise than that based on benthonic foraminifers. Strata also assigned to the *D. lodoensis* Zone include the Umpqua Formation in the southern Oregon Coast Range and the Kings Valley Siltstone Member of the Siletz River Volcanics 15 km west of Corvallis on the east flank of the range (Bukry and Snavely, 1988). In the northern part of the Oregon Coast Range on the southeast side of the Tillamook Highlands, a sequence of siltstone and basaltic sandstone and pillow lava and breccia that crop out in the headwaters of the Trask River contains a coccolith assemblage of Zone CP11 (Bukry and Snavely, 1988).

A few mollusks collected from basaltic sandstone beds of the Salmon River Formation were correlated with the Capay Formation (or Shale) of California and with the Umpqua Formation in the southern Oregon Coast Range (Snavely and Vokes, 1949).

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Revisions to the Stratigraphy of the Connecticut Valley Trough, Eastern Vermont

By Norman L. Hatch, Jr.

Abstract

Proposed changes to the stratigraphy of the Connecticut Valley trough sequence in east-central and northeastern Vermont include moving the Northfield Formation from the base to the top of the sequence and changing it to a more distal member of the Gile Mountain Formation, and moving the Meetinghouse Slate Member from the base to the top of the Gile Mountain Formation.

INTRODUCTION

The nomenclature and sequence of stratigraphic units in the Connecticut Valley-Gaspe synclinorium (Cady, 1960) in northeastern and east-central Vermont have recently been modified (Hatch, 1987, 1988b) from those followed by Doll and others (1961). The purpose of this note is to formally propose those changes for U.S. Geological Survey usage, as well as to suggest that, because the structure of the belt is more of a faulted anticline (see Hatch, 1988b, fig. 9), its name be changed from "synclinorium" to "sedimentary trough."

PROPOSED CHANGES

In their map explanation, Doll and others (1961) arranged the Northfield Formation, the Waits River Formation and its Standing Pond Volcanic Member, and the Gile Mountain Formation and its Meetinghouse Slate Member essentially as shown in figure 1. In most of their cross sections, however, they clearly show the Gile Mountain Formation stratigraphically above the Waits River Formation, except in the easternmost few miles of their cross sections *A–A′*, *B–B′*, and *C–C′*, where they show the Waits River pinching out abruptly eastward beneath the Gile Mountain. Although I do not believe that the Waits River Formation pinches out stratigraphically as shown on their cross sections, I agree that the Gile Mountain Formation is stratigraphically above the Waits River (Fisher and Karabinos, 1980; Hatch, 1988b).

The points on which I disagree with Doll and others (1961) and herein propose formal changes chiefly concern the stratigraphic positions of the Northfield Formation and the Meetinghouse Slate Member of the Gile Mountain Formation. Both of these units, which form narrow, locally discontinuous belts along the western and eastern margins, respectively, of the trough, are primarily dark-gray carbonaceous slate or phyllite. Doll and others (1961) interpreted both units as resting depositionally on older rocks to the west and east. Thus, Doll and others believed that both units form the base of the Connecticut Valley sequence resting unconformably on their respective sides of the synclinorium.

Recent restudy of the rocks of the trough, however, has revealed several relations that argue against the Northfield and (or) Meetinghouse being basal units in the Connecticut Valley sequence. First, having the finest grained sediment (presumably originally mud; now represented by the Northfield and Meetinghouse) as the base of an unconformable stratigraphic sequence is somewhat unusual. Second, at many localities, the Northfield contains graded beds virtually identical (compare figs. 4B and 7 of Hatch, 1988b) to the graded beds in the western belt (Townshend-Brownington syncline) of the Gile Mountain Formation. These beds are generally 10 to 30 cm thick and grade from light-gray, slightly micaceous quartzite to dark-gray aluminous metapelite. Third, nearly all of these graded beds in the Northfield at or near the contact with the Waits River Formation indicate that the Northfield is *above*, rather than below, the Waits River.

Furthermore, in at least one well-exposed section near the Gile Mountain-Meetinghouse contact, graded beds consistently indicate stratigraphic tops to the east, placing the Meetinghouse *above* the rest of the Gile Mountain. Finally, evidence has recently been presented that both the "Monroe line" at the eastern margin of the trough (Hatch, 1988a) and the west boundary of the trough (Westerman, 1987; Hatch, 1988b) are faults. All of the above relations either eliminate the necessity for placing the Northfield and Meetinghouse at the base of the Connecticut Valley trough sequence, or indicate that the Northfield or Meetinghouse is at the top of the stratigraphic sequence.

CONCLUSIONS

I therefore propose that the arrangement of stratigraphic units portrayed by Doll and others (1961), as shown in figure 1, be formally revised for U.S. Geological Survey usage to that shown in figure 2. In figure 2, the Northfield Formation is reassigned as the Northfield Member of the Gile Mountain Formation, as a western, more distal facies at or near the top of the formation, rather than being a separate formation below the Waits River-Gile Mountain package.

The Meetinghouse Slate is retained as a formal member of the Gile Mountain Formation but is considered to form the top rather than the bottom of the formation along the eastern margin of the trough.

The Standing Pond Volcanic Member of the Waits River Formation of Doll and others (1961) is retained as the Standing Pond Volcanic Member of the Waits River Formation. However, I would restrict the use of the name "Standing Pond Volcanic Member" to the narrow belt of rocks that passes through Standing Pond (type locality of Doll, 1944) and is essentially at or within about 100 m of the Waits River-Gile Mountain contact. Furthermore, I would not extend the use of this name to the metavolcanic rocks at St. Johnsbury, Vt. (Hall, 1959), or to the metavolcanic rocks southwest of Island Pond, Vt. (Goodwin, 1963). Both correlations have been made, but the great distance (100 km in the case of the Island Pond rocks) separating them from rocks continuous with the type Standing Pond makes such correlations quite uncertain. These other metavolcanic rocks should be mapped, along with the many other narrow lenses in the trough, simply as unnamed lenses of metavolcanic rocks.

The age of the Waits River and Gile Mountain Formations has long been controversial, ranging from Middle Ordovician to Early Devonian. Recently, however (Hueber and others, 1990), the discovery of Early Devonian plant fossils appears to have resolved the question, at least for the Gile Mountain Formation. In the belief (discussed by Hatch, 1988b) that all of the rocks in the Waits River and Gile Mountain Formations represent parts of one essentially continuously deposited package of sediment, the recent determination (Hueber and others, in press) of an Early Devonian age for the Gile Mountain Formation effectively dates the whole Connecticut Valley trough sequence. Therefore, for this reason and my placement of the Northfield at the top rather than the bottom of the sequence (fig. 1), I propose to modify the age of all the trough rocks, including the Northfield, to Early Devonian.

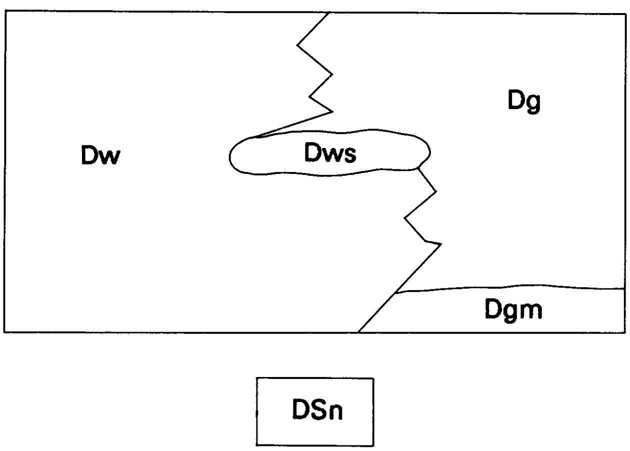

Figure 1. Correlation of map units in the Connecticut Valley trough (simplified from Doll and others, 1961). Dg, Gile Mountain Formation; Dgm, Meetinghouse Slate Member of the Gile Mountain Formation; DSn, Northfield Formation; Dw, Waits River Formation; Dws, Standing Pond Member of the Waits River Formation.

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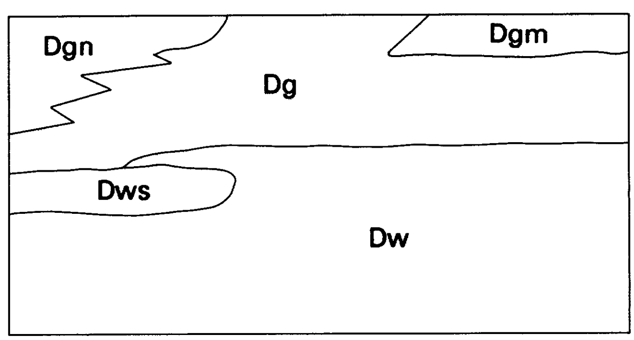

Figure 2. Revised correlation of map units in the Connecticut Valley trough. Dg, Gile Mountain Formation; Dgn, Northfield Member of the Gile Mountain Formation; Dgm, Meetinghouse Slate Member of the Gile Mountain Formation; Dw, Waits River Formation; Dws, Standing Pond Volcanic Member of the Waits River Formation.

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Revisions to the Nomenclature of Some Middle Proterozoic Granitic Rocks in the Northern Berkshire Massif, Massachusetts, and the Southern Green Mountains, Vermont and Massachusetts

By Nicholas M. Ratcliffe

Abstract

The Mount Holly Complex of Middle Proterozoic age in Vermont and northern Massachusetts consists of metavolcanic rocks, paragneiss, and highly deformed granitoids, all of which were involved in high-grade dynamothermal metamorphism before about 950 Ga. The Mount Holly Complex is proposed to include all the gneisses and gneissic granites exposed in the Green Mountain massif and the Lincoln massif, as well as in ancillary eastern domes in Vermont and immediately adjacent Massachusetts that have been affected by Grenvillian deformation.

One newly recognized, syntectonic, highly deformed granite, the College Hill Granite Gneiss exposed in the central part of the Green Mountain massif, is typical of the deformed and unnamed granitoids considered to be part of the Mount Holly Complex.

Nongneissic, rapakivi biotite granite, younger than the Middle Proterozoic deformation of the Mount Holly, forms intrusive masses in the eastern and southern Green Mountains and in the northern Berkshire massif. Paleozoic deformed correlatives of this granite occur in the domes to the east. These posttectonic granites, which are herein assigned to the Cardinal Brook Intrusive Suite, include (1) the Stamford Granite, (2) the Somerset Reservoir Granite, (3) the Harriman Reservoir Granite, and (4) the Bull Hill Gneiss. I recommend that the name "Bull Hill Gneiss" be confined to exposures in or near the type locality within the Chester-Athens dome. As used here, the igneous rocks of the Cardinal Brook Intrusive Suite postdate the Mount Holly Complex and establish a minimum or upper age limit for Grenvillian deformation of the Mount Holly Complex.

INTRODUCTION

Middle Proterozoic gneiss of the Green Mountain massif, the Lincoln massif, the Chester-Athens dome, and the Rayponda-Sadawga dome,[1] all in Vermont (fig. 1), was referred to as the Mount Holly Complex by Doll and others (1961). In all areas, the rocks assigned to the Mount Holly unconformably underlie Late Proterozoic and (or) Lower Cambrian clastic rocks along a profound metamorphic and structural discontinuity. Gneisses of the Mount Holly contain high-grade-mineral assemblages and have a tectonite fabric indicative of upper amphibolite- or higher-grade dynamothermal metamorphism of Middle Proterozoic age (Doll and others, 1961; Ratcliffe and others, 1988). Problematic biotite granite, including the Stamford Granite, either intrudes the Mount Holly Complex (Doll and others, 1961) or is interbedded in it (Skehan, 1961), or entirely postdates the basement gneiss, as believed by Doll and others (1961) for the Bull Hill Gneiss of Richardson (1929–30). Other granitic gneisses within the Mount Holly Complex are highly deformed and share high-grade dynamothermal metamorphic fabrics and structures with the Mount Holly; these gneisses clearly predate Proterozoic deformation of the Mount Holly Complex.

Rocks correlative with the Mount Holly Complex of Vermont, as well as granites or granite gneisses similar to the problematic granites of Vermont, are exposed in the Berkshire massif of Massachusetts (Ratcliffe and others, 1988). In this massif, a largely unnamed sequence of Middle Proterozoic paragneiss, metavolcanic rocks, and intrusive gneissic granite constitutes the basement rocks, which all underwent high-grade Middle Proterozoic dynamothermal metamorphism before the intrusion of late posttectonic granite represented by the Stamford Granite of Emerson (1917). Some of the previous usages for the Mount Holly Complex and related rocks of Vermont and Massachusetts are shown in figure 2.

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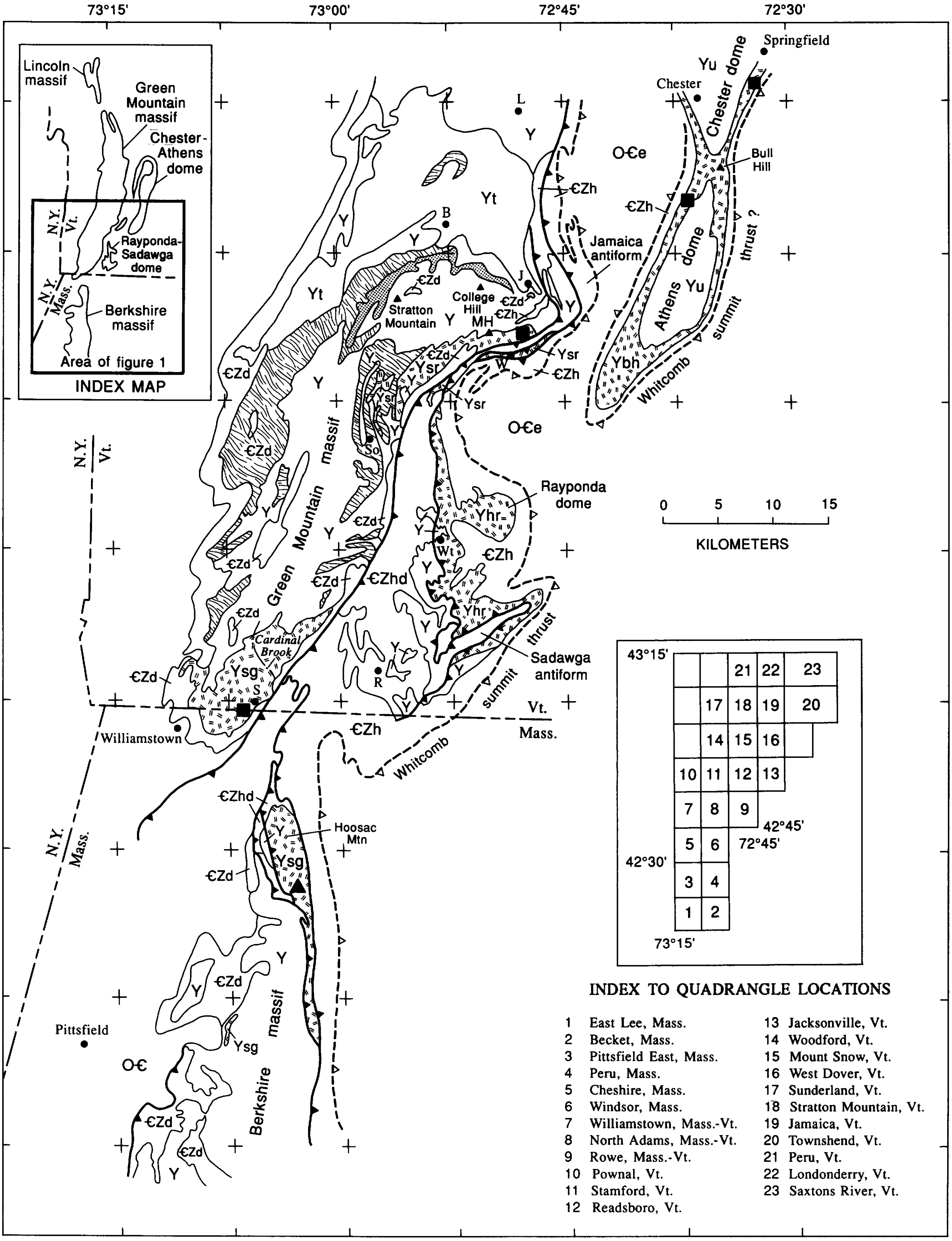
[1]The name "Rayponda-Sadawga dome" is ingrained in the literature and is here used throughout, although structural studies (Ratcliffe and others, 1988) indicate that it is not a simple dome but a highly thrust faulted and refolded antiformal structure.



73°15'
73°00'
72°45'
72°30'
43° 15'
43° 00'
42° 45'
42° 30'
INDEX MAP
Lincoln massif
Green Mountain massif
Chester-Athens dome
Rayponda-Sadawga dome
Berkshire massif
Area of figure 1
N.Y.
Vt.
Mass.
Springfield
Chester
Chester dome
Yu
Bull Hill
Athens dome
Whitcomb summit thrust ?
Ybh
O€e
€Zh
Jamaica antiform
Yt
Y
L
B
J
€Zd
Stratton Mountain
College Hill
MH
Ysr
W
So
Green Mountain massif
Rayponda dome
Yhr
Wt
€Zhd
Cardinal Brook
Ysg
S
R
Sadawga antiform
Whitcomb summit thrust
Williamstown
Hoosac Mtn
Berkshire massif
Pittsfield
O€
0 5 10 15
KILOMETERS
43°15'
42°45'
72°45'
42°30'
73°15'
INDEX TO QUADRANGLE LOCATIONS
1 East Lee, Mass.
2 Becket, Mass.
3 Pittsfield East, Mass.
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5 Cheshire, Mass.
6 Windsor, Mass.
7 Williamstown, Mass.-Vt.
8 North Adams, Mass.-Vt.
9 Rowe, Mass.-Vt.
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11 Stamford, Vt.
12 Readsboro, Vt.
13 Jacksonville, Vt.
14 Woodford, Vt.
15 Mount Snow, Vt.
16 West Dover, Vt.
17 Sunderland, Vt.
18 Stratton Mountain, Vt.
19 Jamaica, Vt.
20 Townshend, Vt.
21 Peru, Vt.
22 Londonderry, Vt.
23 Saxtons River, Vt.

EXPLANATION

ORDOVICIAN, CAMBRIAN, AND UPPER PROTEROZOIC

O€ — Ordovician and Cambrian miogeoclinal rocks

O€e — Ordovician and Cambrian eugeoclinal rocks

€Zd, €Zd-€c — Dalton Formation or Dalton and Cheshire Formations, combined

€Zhd — Transitional Hoosac-Dalton Formations

€Zh — Hoosac Formation

unconformity

MIDDLE PROTEROZOIC

Cardinal Brook Intrusive Suite

Ysg — Stamford Granite

Ysr — Somerset Reservoir Granite

Yhr — Harriman Reservoir Granite

Ybh — Bull Hill Gneiss of Richardson (1929–30)

Mount Holly Complex

College Hill Granite Gneiss

Unnamed biotite granite gneiss

Y — Well-layered biotite paragneiss, metavolcanic rocks, and migmatitic biotite granite gneiss; Yu, undifferentiated gneiss in eastern domes

Yt — Biotite trondhjemitic gneiss, metatonalite, metadacitic volcanic rocks, and associated mafic metavolcanic rocks

Contact

Inferred thrust fault—Teeth on upper plate

Taconic or Acadian thrust fault—Teeth on upper plate

■ **Zircon sample site of Karabinos and Aleinikoff (1988, 1990)**

▲ **Zircon sample site of Beth Harding and Samuel Mukasa (written commun., 1988)**

Geographic locations

B **Bondville, Vt.**

J **Jamaica, Vt.**

L **Londonderry, Vt.**

MH **Mundell Hill**

R **Readsboro, Vt.**

S **Stamford, Vt.**

So **Somerset, Vt.**

W **Wardsboro, Vt.**

Wt **Wilmington, Vt.**

Figure 1. Generalized geologic map of northern Berkshire massif, southern Green Mountains, and Rayponda-Sadawga dome, western Vermont and Massachusetts. Geology based on mapping since 1986 by N.M. Ratcliffe and W.C. Burton in quadrangles 10, 11, 17–19, 21, and 22; by W.C. Burton in quadrangles 14 and 17; and by N.M. Ratcliffe in quadrangles 12, 13, and 15. Quadrangles 1, 3, 5, 7, and 8 mapped before 1979 by N.M. Ratcliffe. Data in quadrangle 2 from Norton (1974), in quadrangle 6 from Norton (1969), and in quadrangle 16 from Skehan (1961); data in area just east of quadrangle 19 from Karabinos (1984); data in Chester-Adams dome from Doll and others (1961). For a more detailed map of the Green Mountains, see Ratcliffe and others (1988, trip B-1, fig. 15), and of the Athens dome, see figure 6.

The purpose of this note is to define the Mount Holly Complex on the basis of exposures in the southern part of the Green Mountain massif and to clarify the relation of the granitic gneisses and granites found within the Mount Holly Complex to other rocks within it. A suite of Proterozoic granites, herein referred to as the Cardinal Brook Intrusive Suite, that postdate deformation of the Mount Holly are herein excluded from the Mount Holly Complex on the basis of their crosscutting relations to structures and metamorphic fabrics within the Mount Holly.

The highly deformed Middle Proterozoic gneisses of the Green Mountains of Vermont belonging to the Mount Holly Complex (fig. 1) are overlain unconformably by Late Proterozoic(?) and Lower Cambrian clastic sedimentary rocks of the Dalton Formation and Cheshire Quartzite. The Cheshire contains the Early Cambrian *Olenellus* fauna (Walcott, 1888). Gneisses of the Mount Holly Complex in the Lincoln and Green Mountain massifs are crosscut by less deformed, nongneissic metadiabase dikes of inferred latest Proterozoic age. In addition, relict high-grade metamorphic rocks, such as sillimanite-garnet-biotite quartzite, diopside-bearing calc-silicate rocks, and hypersthene-K-feldspar-brown hornblende-garnet-plagioclase amphibolite, are found in the Mount Holly Complex. These rocks are clearly of higher metamorphic rank than the biotite-zone metasedimentary rocks that overlie the Mount Holly Complex along the northwest and south border of the Green Mountains. All workers (see Doll and others, 1961) have long recognized evidence for Proterozoic high-grade metamorphism and deformation in the basement rocks of the Green Mountains and in the Berkshire massif of Massachusetts to the south (Ratcliffe and Zartman, 1976). Recent studies in Vermont (Ratcliffe and others, 1988) have confirmed the presence of pre-Paleozoic complex structures formed at high metamorphic grade throughout the Mount Holly Complex of southern Vermont.

The Mount Holly Complex as defined herein consists of a 10- to 15-km-thick sequence of metavolcanic, metasedimentary, and metagranitoid rocks that are distributed in outcrop belts trending northeast to east-west across the massif. These belts contain Proterozoic folds with generally subvertical axial surfaces (Ratcliffe and others, 1988). The presumed base of the exposed section of the Mount Holly Complex is a sequence of quartz-plagioclase gneisses, chemically defined as metatrond-

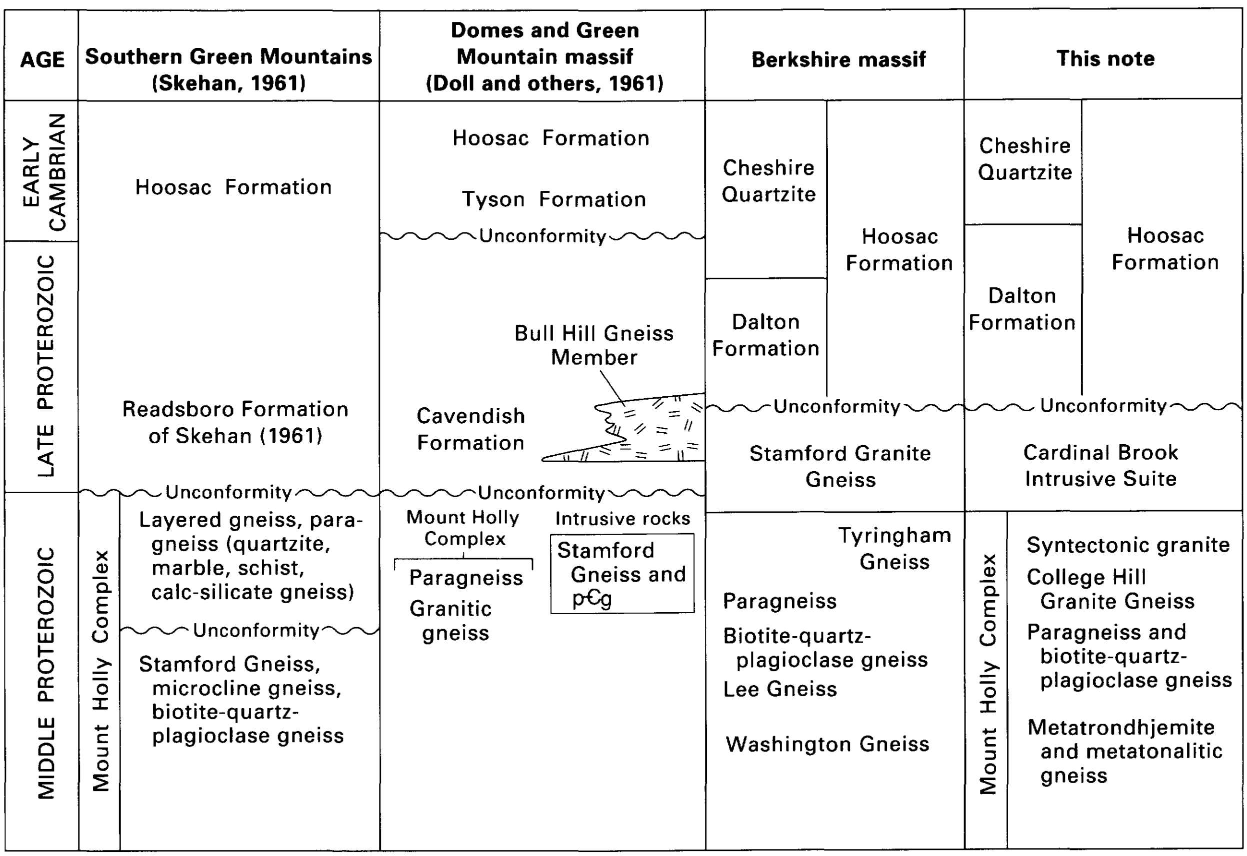


Figure 2. Correlation chart of Middle and Late Proterozoic rocks of the Green Mountains, eastern domes, and Berkshire massif, showing interpretation used in this report.

hjemite, metatonalite, and dacitic to basaltic metavolcanic rocks (unit Yt, fig. 1; Ratcliffe and others, 1988), that underlie well-layered paragneiss and are well exposed in the area north of Bondville, Vt. These trondhjemitic gneisses contain the same structures as the granitic orthogneiss and the paragneiss, and so this sequence is collectively assigned to the Mount Holly Complex.

Granitic rocks composing two textural groups are found in contact with gneisses of the Mount Holly Complex: (1) highly deformed and migmatitic granite gneiss, and (2) coarse-grained, nongneissic rapakivi biotite granite. These two groups were classified as syntectonic, late to posttectonic intrusive rocks by Ratcliffe and others (1988).

Another purpose of this note is to call attention to the location and significance of these two types of granite, to clarify the relation of both types to the Mount Holly Complex, and to revise the nomenclature. I propose that those gneissic granites which were deformed with their country rocks during the pre-Paleozoic, high-grade "Grenvillian" orogeny be considered parts of the Mount Holly Complex. In contrast, the late to posttectonic granites are assigned to a younger intrusive suite to stress their geologic and tectonic setting. The name "Cardinal Brook Intrusive Suite" is proposed for these younger intrusive rocks.

Included in the Cardinal Brook Intrusive Suite are (1) the Stamford Granite type locality, Stamford, Vt., also occurring on Hoosac Mountain, Mass.; (2) the Somerset Reservoir Granite type locality, at and around the Somerset Reservoir in the Mount Snow quadrangle, extending northeastward to near Wardsboro and Jamaica, Vt.; (3) the Harriman Reservoir Granite type locality, on the east shore of the Harriman Reservoir in the Readsboro and Jacksonville quadrangles, Vt.; and (4) the Bull Hill Gneiss of Richardson (1929–30) type locality, on Bull Hill between the Chester and Athens domes.

Recent geologic mapping and U-Pb zircon geochronology by Karabinos and Aleinikoff (1988, 1990), and the zircon data of Beth Harding and Samuel Mukasa (unpub. data, 1988), have done much to clarify the age of these granitic rocks. Field studies have established their intrusive relation to Middle Proterozoic gneisses of the Mount Holly Complex, and their nonconformable relation to adjacent cover rocks (Ratcliffe and others, 1988).

Two important facts emerge from these studies: (1) The western, least deformed granites intruded highly deformed gneissic rocks of the Mount Holly Complex (at Stamford, Vt.; at the Somerset Reservoir in the Mount Snow, Stratton Mountain, and Jamaica quadrangles of Vermont; and on Hoosac Mountain in Massachusetts); (2) zircons from the type Stamford Granite in the Green Mountains, the Stamford Granite on Hoosac Mountain, the Somerset Reservoir Granite at Wardsboro, Vt., and the Bull Hill Gneiss of the Chester and Athens domes all have comparable 965- to 945-Ma U-Pb upper-intercept ages (Beth Harding and Samuel Mukasa, written commun., 1988; Karabinos and Aleinikoff, 1988, 1990).

The structural setting, petrography, and zircon ages of these late to posttectonic granites are all so similar and uniquely different from those of other granitic gneisses in the Mount Holly Complex that these granites should be distinguished from the Mount Holly Complex.

SYNTECTONIC GRANITIC ORTHOGNEISS OF THE MOUNT HOLLY COMPLEX

Medium- to coarse-grained, thoroughly gneissic granitic gneiss (fig. 1) is abundant within the Mount Holly Complex. These rocks intrude or are in contact with metasedimentary and metavolcanic units. A preliminary map of the Mount Holly Complex south of lat 43°15' N. shows the distribution of the granitic gneisses recognized in mapping conducted since 1986 (Ratcliffe and others, 1988, fig. 5). One distinctive unit is a coarse-grained, microcline-megacrystic granitic gneiss exposed in the Stratton Mountain, Peru, and Jamaica quadrangles, where it is excellently exposed on College Hill (fig. 1; Ratcliffe and Burton, 1989). The name "College Hill Granite Gneiss" is proposed for this unit. The College Hill Granite Gneiss forms a northeast- to east-west-trending, arcuate outcrop belt, 20 km long and as much as 1½ km wide. On College Hill, abundantly outcropping, very coarse grained (2–3 cm) microcline-megacrystic biotite granite gneiss and deformed gneissic granite form a central belt of rocks mantled to the north and south by light-pinkish-green to gray biotite-microcline-migmatitic granitic gneiss. This sheath of migmatitic gneiss (not included in the College Hill Granite Gneiss as defined here) is widest where the College Hill Granite Gneiss is widest, and narrows near the tapering ends of the granite. Contact relations with the migmatite are gradational through an increase in the size and abundance of microcline megacrysts.

The College Hill Granite Gneiss (unit Ych, fig. 1) is a coarsely porphyritic microcline-perthite granite that differs from the other granitic gneisses of the Mount Holly Complex in southern Vermont by its much coarser grain size and the absence of the ghostlike inherited fabric present in the other unnamed units. The granite, however, is deformed into a gneissic rock containing K-feldspar augen, minor folds, and a Proterozoic tectonite lineation. Small irregular pods, stringers, and segregations of pegmatitic granite that crosscut the deformed granite gneiss indicate that high-grade dynamothermal metamorphism postdated intrusion of the College Hill Granite Gneiss.

On the north and south slopes of College Hill, the granite grades outward into migmatite over a distance of approximately 100 m. In this zone, both the size and abundance of microcline-perthite phenocrysts decrease along with the overall grain size of the matrix.

The College Hill Granite Gneiss is interpreted as an intrusive granite. It formed early enough in the Proterozoic tectonic history to have become a gneissic granite during Middle Proterozoic deformation but before formation of the late-stage pegmatite associated with the migmatization of the other granitic gneiss units. The College Hill Granite Gneiss resembles the widespread Tyringham Gneiss of the Berkshire massif of Massachusetts (Ratcliffe and Zartman, 1976) in texture and occurrence.

Other granitic gneiss units defined preliminarily by Ratcliffe and others (1988) have not been formally named, pending further study, and are here designated by lithic symbols; but inasmuch as these granitic gneisses all share the same strong Proterozoic structure and gneissosity, they are considered parts of the Mount Holly Complex.

POSTTECTONIC GRANITES INTRUDING THE MOUNT HOLLY COMPLEX

Distinctive coarse-grained biotite-microcline-perthite granite and locally well foliated, deformed granite crop out within the core of the Green Mountains, in the Chester-Athens and Rayponda-Sadawga domes in southern Vermont, and in the northern part of the Berkshire massif. These granitic rocks in the Green Mountains and Berkshire massif have been referred to as the Stamford Granite (Hitchcock and others, 1861) or the Stamford Granite Gneiss (Wolff, 1894; Emerson, 1917). Similar highly deformed, coarse-grained granites, were referred as the Bull Hill Gneiss in the Chester-Athens dome (Richardson, 1929–30) or as unnamed granites contained within the Wilmington Gneiss of Skehan (1961) in the Sadawga dome, or were locally recognized, as in the southern part of the Sadawga dome (Sadawga antiform, fig. 1), by Doll and others (1961). In southeastern Vermont, Thompson (1952) included the Bull Hill Gneiss as a member of the Hoosac Formation; Doll and others (1961) included it as a member of the Cavendish Formation and interpreted the microcline-rich gneiss as metamorphosed rhyolite younger than the Middle Proterozoic Mount Holly Complex. Norton (1969) also followed this interpretation for the Stamford Granite Gneiss on Hoosac Mountain, Mass., although Herz (1961) showed the Hoosac Formation to unconformably overlie the Stamford Granite Gneiss.

All of these granites, however, are so similar in chemistry, mineralogy, geologic setting, and age that they should be considered parts of the same intrusive suite. Recent geologic mapping in the southern Green Mountains of Vermont and Massachusetts has confirmed that the coarse-grained biotite granites intrude Middle Proterozoic gneiss of the Mount Holly Complex and similar gneiss in the Berkshire massif. In addition, these granites are unconformably overlain at many localities in the Green Mountains, in the Sadawga dome, and on Hoosac Mountain by metasedimentary rocks of the Hoosac or Dalton Formation. At certain localities in the Chester-Athens dome, mapping by J.B. Thompson, Jr., and J.L. Rosenfeld (see Doll and others, 1961) showed that the Bull Hill Gneiss occurs above a thin layer of dolomitic marble or albitic schist which structurally overlies undifferentiated Mount Holly Complex (unit Yu, fig. 1) and underlies additional cover rocks assigned to the Hoosac Formation.

CARDINAL BROOK INTRUSIVE SUITE

The Cardinal Brook Intrusive Suite is herein named for Cardinal Brook, which cuts through the core of the type Stamford Granite in the Stamford quadrangle, Vt., one of the most accurately dated units (Karabinos and Aleinikoff, 1990) least affected by Paleozoic deformation in the suite. The Cardinal Brook Intrusive Suite includes the Stamford Granite, the Somerset Reservoir Granite, the Harriman Reservoir Granite, and the Bull Hill Gneiss.

The type Stamford Granite (Hitchcock and others, 1861) is found on the hills immediately west of Stamford, Vt. Excellent, readily visitable exposures were described by Ratcliffe and others (1988, stop 6). The rock is a very coarse grained biotite-microcline-perthite granite, containing ovoidal to euhedral phenocrysts, as much as 6 cm in longest dimension. Representative samples showing typical textures (fig. 3) illustrate the coarse-grained, undeformed texture of the core rocks of the pluton. A U-Pb upper-intercept zircon age of 960±6 Ma was obtained from samples at this locality. This nearly concordant age (Karabinos and Aleinikoff, 1990) is exceptionally important because it best dates the entire suite. Mapping of the Stamford here and on Hoosac Mountain indicates that it crosscuts Grenvillian sillimanite-grade (hornblende-granulite facies) rocks but was not deformed in the Grenville orogeny; that is, it lacks the gneissic fabric characteristic of other Middle Proterozoic granitic rocks, such as the Tyringham Gneiss of the Berkshire massif and the granitic gneiss of the Green Mountains. Chemical characteristics of the Stamford are listed in table 1 and plotted in figure 7. Mafic to intermediate dikes and irregular masses within the granite suggest that gabbroic to monzonitic rocks are associated with the coarse-grained rapakivi granite, which is a K-feldspar cumulate. A strongly positive Eu anomaly characterizes the Stamford

Granite here and on Hoosac Mountain. Where mafic dikes crosscut or are in contact with the coarser grained granite, K-feldspar megacrysts, quartz, and plagioclase have resorption features, and a new generation of K-feldspar with rapakivi structure has formed in the matrix. The mafic rocks crystallized from comagmatic liquids that intruded and reacted with the feldspar cumulates.

STAMFORD GRANITE ON HOOSAC MOUNTAIN

On Hoosac Mountain in the North Adams and Windsor quadrangles, Mass., coarse-grained biotite granite gneiss occurs in the core of an anticlinal structure and intrudes Middle Proterozoic gneiss (Herz, 1961;

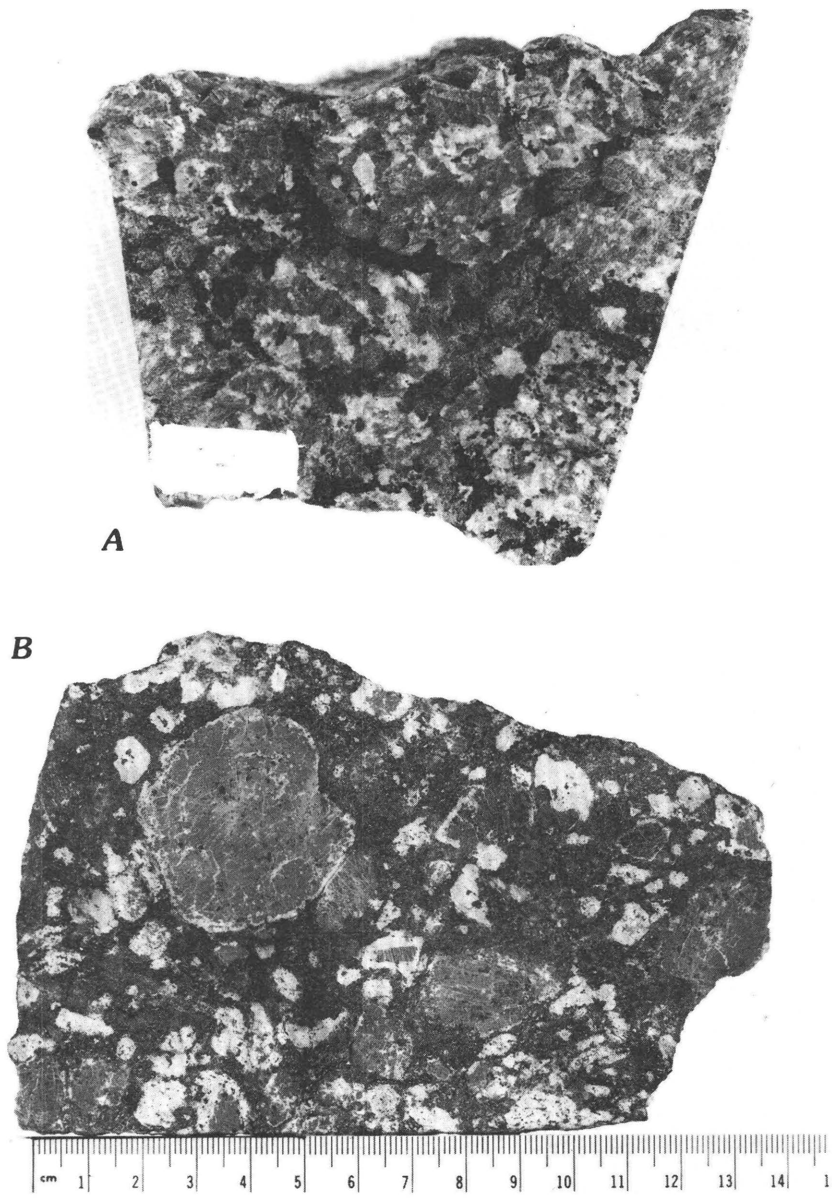


Figure 3. Typical hand specimens of Stamford Granite from near the Cardinal Brook Intrusive Suite type locality. *A*, Coarse-grained, glomeroporphyritic granite containing ovoidal microcline (gray) phenocrysts, 3 cm in diameter, with inclusions of quartz and plagioclase (white) surrounded by iron-rich interstitial matrix showing partial resorption of K-feldspar. *B*, Ovoidal microcline-perthite phenocrysts float in a matrix of fine-grained biotite, plagioclase, and quartz; several grains exhibit rapakivi rims of plagioclase (white), partially enclosing darker (stained) microcline.

Table 1. Representative analyses of samples of the Stamford Granite from the Green Mountains and Hoosac Mountain.

[Chemical analyses and Cross, Iddings, Pirsson, and Washington (CIPW) norms in weight percent, using rapid rock techniques of Shapiro (1975); analysts, N. Rait and H. Smith]

	Stamford Granite					Hoosac Mountain	
	Rapakivi granite			Border dike			
Sample	170	171	173	6	172	102–32	176
Chemical analyses							
SiO_2	67.6	69.2	70.7	64.5	50.5	68.0	69.4
TiO_2	.29	.23	.24	1.1	2.5	.39	.42
Al_2O_3	16.0	16.4	14.9	14.8	14.9	15.4	14.0
Fe_2O_3	1.5	1.1	.90	1.8	2.6	2.0	1.9
FeO	1.7	1.2	1.7	4.8	8.5	2.2	2.6
MnO	.04	.03	.04	.07	.15	.06	.04
MgO	.17	.12	.20	1.1	3.5	.36	.82
CaO_2	.4	2.2	2.1	3.1	7.7	2.0	.83
Na_2O	3.5	3.5	3.2	3.2	2.2	3.6	2.8
K_2O	5.9	6.4	5.8	4.2	3.7	5.4	5.8
P_2O_5	.15	.14	.14	.45	1.0	.19	.18
H_2O^+	.55	.32	.37	.62	1.0	.16	.04
H_2O^-	.02	.02	.08	.03	.06	.04	.03
CO_2	.01	.08	.03	.07	1.5	.01	.03
Total	99.83	100.94	100.40	99.84	99.81	99.81	98.89
S	.12	.09	.077	.093	.97	.027	.14
CIPW norms							
Q	18.43	18.58	24.3	20.0	20.78	27.10	25.61
or	35.0	37.40	34.6	25.05	31.9	34.5	35.2
ab	29.9	29.4	27.3	27.06	30.5	23.9	26.5
an	10.5	10.3	9.1	13.8	9.8	3.87	6.40
C	.0	.0	.0	.0	.03	1.72	.9
di	1.14	.43	.0	1.11	.0	.0	.0
hy	1.80	1.52	2.8	7.26	2.70	4.6	.86
mt	2.2	1.59	1.02	2.64	2.9	2.75	3.08
il	.56	.44	.45	2.09	.74	.80	.65
ap	.36	.34	.34	1.08	.43	.44	.44
Total	99.89	100.00	99.91	100.09	99.78	99.68	99.64

Ratcliffe, 1979b). Both the country rocks and the granite are unconformably overlain by basal conglomerate of the Hoosac Formation of Late Proterozoic or Early Cambrian age (Herz, 1961). In the core of the granite body, relict coarse-grained rapakivi microcline-perthite like that of the type Stamford is found. Deformation of the granite is more severe near the flanks of the anticline, where intense Paleozoic deformation transforms the original igneous porphyritic textures into a mylonitic augen gneiss. As in the type Stamford, the original, pre-Paleozoic texture of the rock appears to have been that of a very coarse grained granite lacking the strong gneissic structure present in the surrounding Middle Proterozoic country rocks. A U-Pb upper-intercept zircon age of approximately 965 Ma was obtained for the granite on Hoosac Mountain in the Windsor quadrangle by Beth Harding and Samuel Mukasa (written commun., 1988). Chemical analyses of the Stamford Granite on Hoosac Mountain are listed in table 1.

Coarse-grained quartz-pebble conglomerate of the Dalton Formation of Late Proterozoic or Early Cambrian age unconformably overlies the type Stamford Granite. Chemical data show that the outcrops of the Stamford Granite on Hoosac Mountain and at the type locality differ in major-element and rare-earth-element (REE) contents, and so they could be considered separate plutons, of approximately 960-Ma granite. Note that the east boundary of each pluton is obscured by cover rocks or by thrust sheets, and so the original contacts and shape of the plutons are not known.

SOMERSET RESERVOIR GRANITE

The Somerset Reservoir Granite is herein named for an exposure of very coarse grained rapakivi biotite granite at and around the Somerset Reservoir in the Mount Snow, Stratton Mountain, and Jamaica quadrangles, Vt. The distribution of this granite in the Stratton Mountain quadrangle was reported by Ratcliffe and Burton (1989). The granite locally has an extremely coarse grained pegmatitic phase, as well as a fine-grained aplitic phase. Locally, rapakivi granite (fig. 4*A*) and coarse-grained ferromonzonite (fig. 4*B*), with complexly zoned and inclusion-rich cores, are found; both rock types are abundant near intrusive contacts with country rocks. In the Jamaica quadrangle, the Somerset Reservoir Granite is unconformably overlain by dark biotite schist and conglomerate of the Dalton Formation or by albitic schist and granofels of the Hoosac Formation, both of Late Proterozoic or Early Cambrian age (Ratcliffe and others, 1988). Rocks of the Somerset Reservoir Granite extend eastward into the Jamaica quadrangle to exposures in the bed of Wardsboro Brook at a point east of Mundal Hill (MH, fig. 1) in the Jamaica antiform, where they were assigned by Doll and others (1961) to the Bull Hill Gneiss Member of the Cavendish Formation. Recent mapping (Ratcliffe and others, 1988; N.M. Ratcliffe, unpub. data, 1988), however, shows that the Somerset Reservoir Granite intrudes Middle Proterozoic gneiss of the Green Mountains and is not intercalated with cover rocks, as shown by Doll and others (1961), and so it is regarded as part of the basement rocks in this area. Therefore, the name "Bull Hill Gneiss" is not recommended for these occurrences. Chemical analyses of the Somerset Reservoir Granite are listed in table 2. A U-Pb upper-intercept zircon age of approximately 965±4 Ma was obtained on exposures of the Somerset Reservoir Granite in Wardsboro Brook (Karabinos and Aleinikoff, 1990). At or near the locality sampled by Karabinos and Aleinikoff, the Somerset Reservoir Granite exhibits a relict rapakivi texture (fig. 5*A*) but is transformed by Paleozoic mylonitization into augen gneiss and fine-grained ultramylonite (fig. 5*B*). The retrogressive fabrics have transformed the otherwise-coarse-grained granite into a pseudolayered rock (mylonite gneiss-augen gneiss-ultramylonite) at or near thrust faults along the eastern margin of the Green Mountain massif. A small area of biotite granite at the north border of the Mount Snow quadrangle exposed in the core of a south-plunging antiform is also assigned to the Somerset Reservoir Granite.

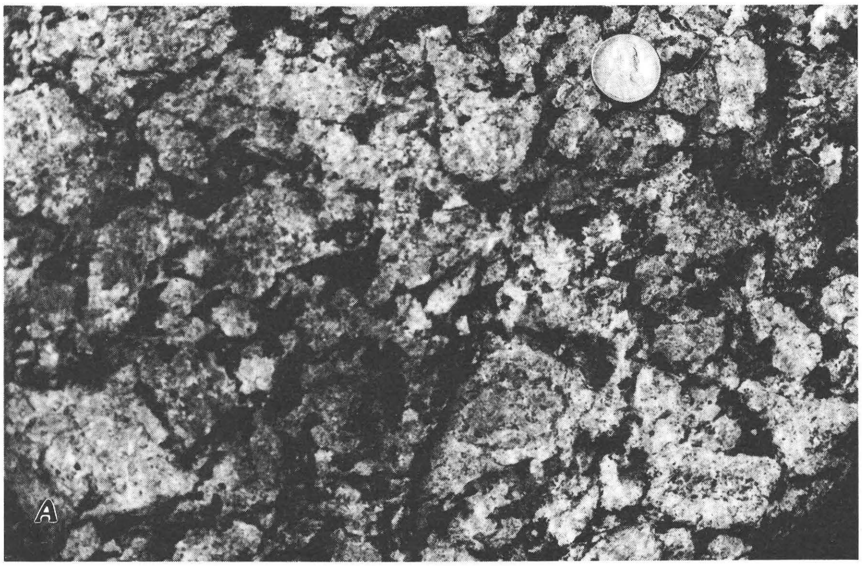
HARRIMAN RESERVOIR GRANITE

Megacrystic, mylonitic biotite granite gneiss occurs in the Wilmington, Vt., area in the hanging wall of the Wilmington fault (Ratcliffe and others, 1988). The east half of the Rayponda-Sadawga dome consists of the folded hanging wall of this thrust and its presumably unconformably overlying cover of Hoosac and younger units. Core rocks of the Rayponda-Sadawga dome were referred to as the Wilmington Gneiss by Skehan (1961, 1972), who regarded the entire succession of gneisses as Middle Proterozoic and correlative with the Mount Holly Complex (Doll and others, 1961). Skehan recognized the presence of a megacrystic biotite granite gneiss like the Bull Hill Gneiss within the Wilmington Gneiss but did not differentiate the outcrop belts of this material. As mapped by Ratcliffe (Ratcliffe and others, 1988, fig. 6), the Bull Hill-like gneiss of the Rayponda-Sadawga dome is largely restricted to the east half of the "dome" in the hanging wall of the Wilmington thrust. In figure 1, these rocks are shown separated from layered gneisses assigned to the Mount Holly Complex. The west half of the basement rocks of the "dome" contains units identical to gneiss of the Mount Holly Complex in the Green Mountain massif to the west (Ratcliffe and others, 1988, fig. 5). The Wilmington Gneiss of Skehan (1961) as used here refers only to the Mount Holly Complex in the Rayponda-Sadawga dome.

The Bull Hill-like gneiss of the Rayponda-Sadawga dome is highly mylonitic, strongly lineated, and deformed to the degree that original igneous mineralogy and textures are absent. Transposition structures, mylonitic layering, dark ultramylonite layers, and lighter mylonite gneiss layers impart a regular layering to the gneiss that parallels very intense second-generation mylonitic foliation in schists overlying and underlying the gneiss above and below the Wilmington thrust, and so the tectonic layering is Paleozoic in age.

The grain-size variation in the mylonitic gneiss makes the internal structures of the Bull Hill-like rock look deceptively simple and produces an internal layering that could be interpreted as layering in rhyolitic volcanic rocks. Chemical analyses (table 2) and plots (fig. 7) show that the Harriman Reservoir Granite closely resembles the Somerset Reservoir and Stamford Granites, although its SiO_2 content is lower and its K_2O/Na_2O ratio varies more widely.

The Wilmington thrust fault separates Middle Proterozoic basement and cover rocks from the overlying Harriman Reservoir Granite, but, locally, slivers of Hoosac Formation are found along the contact. The Wilmington fault may resurface in the Chester-Athens dome to form the contact between the Bull Hill Gneiss and core gneisses, as shown by Ratcliffe and others (1988, p. 4, fig. 2).



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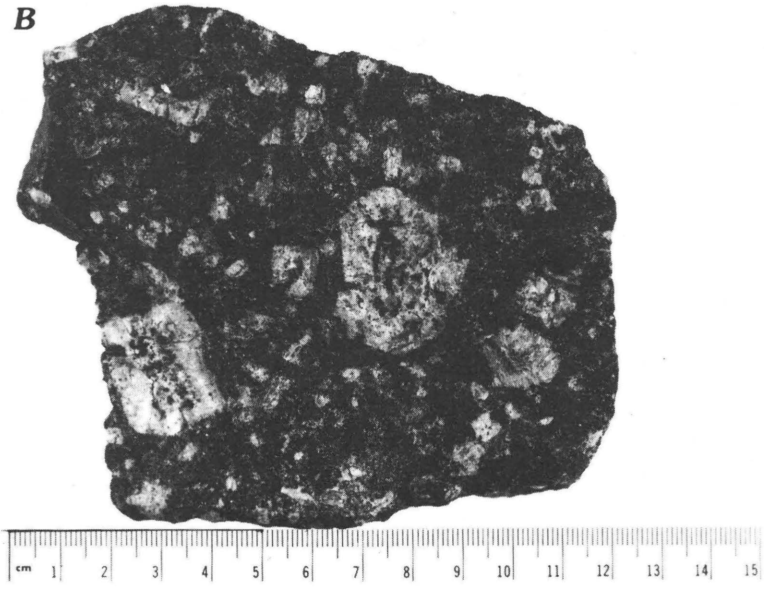

Figure 4. Typical hand specimens of Somerset Reservoir Granite. *A*, Rapakivi microcline phenocrysts, as much as 3 cm in diameter, in a matrix of biotite, quartz, and feldspar. *B*, Ferromonzonitic dike from southwestern part of the Somerset Reservoir in the Mount Snow quadrangle. Large aggregates of biotite-K-feldspar-quartz are rimmed by euhedral plagioclase overgrowths, set in a dark, iron-rich, ferromonzonitic matrix.

Table 2. Representative analyses of samples of the Somerset Reservoir Granite, Harriman Reservoir Granite, and Bull Hill Gneiss.

[Chemical analyses and Cross, Iddings, Pirsson, and Washington (CIPW) norms in weight percent, using X-ray-fluorescence and atomic-absorption techniques; analysts, J. Taggart, A. Bartel, and D. Siems]

	Somerset Reservoir Granite						Harriman Reservoir Granite					Bull Hill Gneiss
Sample	1439	1377	1375	1443	1374	1372	397	398	372	373	1838	BH–1
Chemical analyses												
SiO_2	70.20	74.50	74.50	70.20	70.70	74.00	62.30	62.50	64.90	63.50	68.5	72.30
TiO_2	.35	.09	.18	.31	.27	.23	1.02	.83	.76	1.01	.37	.28
Al_2O_3	14.20	13.70	12.40	14.50	14.00	12.40	15.40	15.50	15.00	14.20	15.1	13.20
Fe_2O_3	2.69	.83	.99	.94	1.81	1.16	3.16	1.38	1.30	2.19	.67	1.38
FeO	1.00	.20	1.30	2.30	1.20	1.60	3.90	4.60	3.80	5.50	2.4	1.30
MnO	.02	.02	.02	.04	.02	.02	.07	.08	.05	.08	.04	.02
MgO	.19	.45	.49	.18	.72	.72	.77	.79	.77	1.50	.31	.24
CaO	1.79	.59	.59	2.43	.74	.62	2.78	2.12	2.38	2.39	1.13	1.39
Na_2O	2.63	3.73	2.99	3.42	2.86	2.70	3.98	4.88	4.07	2.89	5.06	3.15
K_2O	5.24	4.09	5.25	4.01	5.95	5.06	4.60	4.72	4.65	4.73	4.79	5.47
P_2O_5	.08	.05	.05	.10	.05	.05	.39	.30	.33	.35	.09	.08
H_2O^+	.51	.63	.44	.45	.54	.51	.70	.73	1.00	1.80	.22	.30
H_2O^-	.02	.05	.05	.08	.16	.14	.26	.22	.16	.08	.30	.10
CO_2	.00	.41	.02	.01	.01	.13	.00	.55	.58	.01	.52	.01
Total	98.92	99.34	99.27	98.97	99.03	99.34	99.33	99.20	99.75	100.23	99.50	99.22
F	.02	.02	.03	.03	.03	.05	--	--	--	--	--	--
S	.00	.00	.03	.00	.00	.00	--	--	--	--	--	--
CIPW norms												
Q	31.5	37.2	35.1	28.9	29.2	36.9	14.6	10.2	17.9	19.5	18.0	30.1
or	31.6	24.6	31.5	24.1	35.8	30.4	27.7	28.6	28.1	28.5	28.3	32.8
ab	22.7	32.1	25.6	29.4	24.7	23.2	34.4	42.3	35.2	24.9	42.8	27.0
an	8.5	.0	2.5	11.5	3.3	2.0	10.8	5.2	6.1	9.7	1.7	5.8
C	1.2	3.2	.9	.4	1.7	1.8	.0	.5	1.1	.9	1.0	.0
di	.5	1.1	2.6	3.5	2.1	3.5	.6	.0	.0	.0	4.1	.5
hy	2.3	.5	1.5	1.4	2.7	1.7	4.7	8.3	6.8	10.7	1.0	1.2
mt	.7	.2	.3	.6	.5	.4	4.7	2.0	1.9	3.2	.7	2.0
il	1.1	.5	.0	.0	.0	.0	2.0	1.6	1.5	2.0	.2	.5
ap	.2	.1	.1	.2	.1	.1	.9	.7	.8	.8	1.2	.2
cc	.0	.9	.1	.0	.0	.3	.0	1.3	1.3	.0	1.2	.0
Total	100.3	100.4	100.2	100.0	100.1	100.3	100.4	100.7	100.7	100.2	100.2	100.1

BULL HILL GNEISS OF RICHARDSON (1929–30) IN THE CHESTER-ATHENS DOME

The Bull Hill Gneiss was named by Richardson (1929–30, p. 230–231) for exposures of coarsely porphyritic biotite granite gneiss on Bull Hill northeast of the village of Grafton, Vt., and extending at least as far northward as the southeast corner of the Chester township, Vt. He interpreted the unit as an orthogneiss. At the type locality, it is described as a belt, ¾ km wide, separated from biotite and hornblende schist and gneiss on the west and east by a thin zone of sericite schist. The Bull Hill at the type locality ranges in composition from a very coarse grained biotite-plagioclase-quartz microcline granite (fig. 8*A*) to a mylonitic and porphyroclastic augen gneiss (fig. 8*B*). Microcline phenocrysts form ovoidal to euhedral crystals, as much as 5 cm long, with rapakivi rims. The coarsest grained Bull Hill contains large epitaxial growths of microcline involving three or more individual phenocrysts sharing similar prism facies. Near the margins of the Bull Hill, a medium-grained, white, biotite-poor border facies can be mapped locally. In chemical composition, relict igneous textures, and mylonitic texture, the type Bull Hill closely resembles the Somerset Reservoir Granite and Stamford Granite. Zircons from two samples of Bull Hill Gneiss of the Chester-Athens dome have U-Pb upper-intercept ages of 945±7 and 955±5 Ma (Karabinos and Aleinikoff, 1990) (see fig. 1 for sample localities).

Subsequent studies by Thompson (1952) assigned the Bull Hill Gneiss of the Chester-Athens dome to the Hoosac Formation and interpreted the unit as a metamorphosed rhyolite intercalated within the cover rocks, structurally and stratigraphically above the Mount Holly Complex of the dome. Doll and others (1961) showed the Bull Hill Gneiss to be a member of the Cavendish Formation, a reportedly older sequence lying unconformably beneath the Hoosac Formation. The term "Cavendish Formation" has never been adopted by the U.S. Geological Survey and is now considered obsolete. Schists previously assigned to the Cavendish Formation by Doll and others (1961) in the Chester dome have been

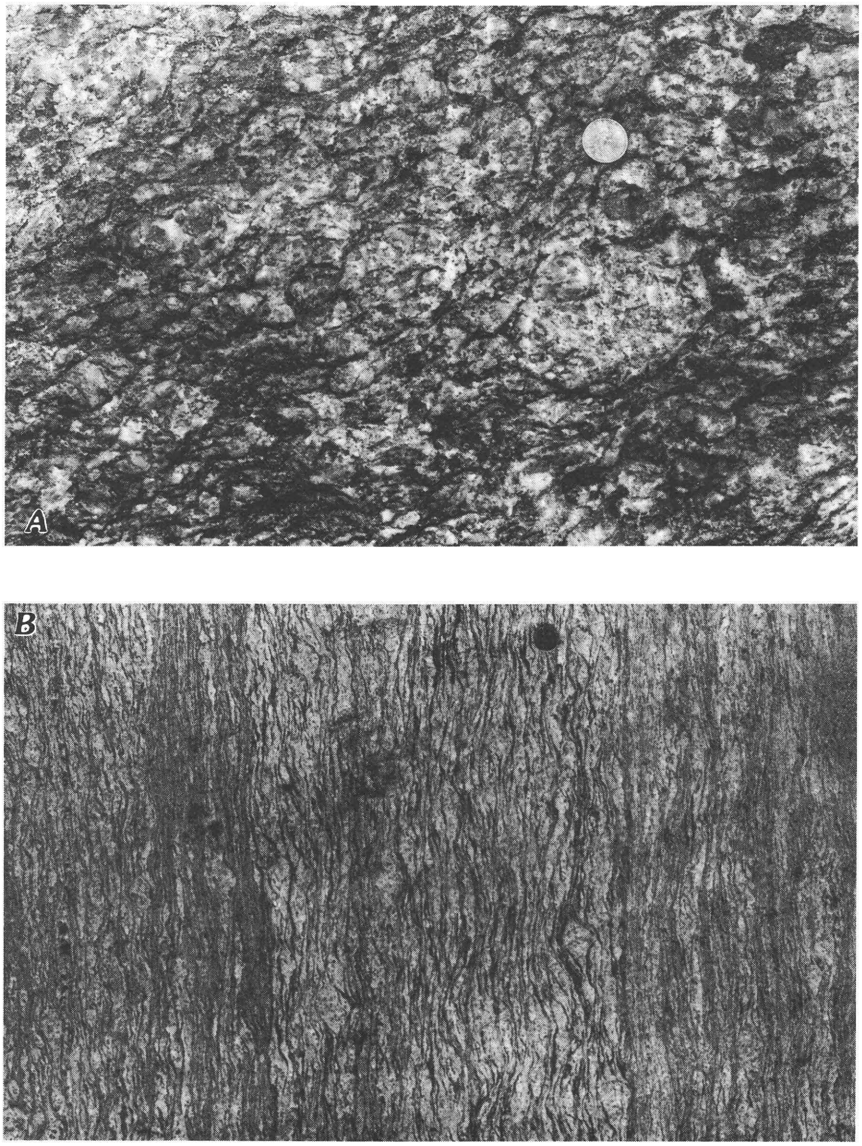

Figure 5. Somerset Reservoir Gneiss at and near zircon-sample site of Karabinos and Aleinikoff (1988) in Wardsboro Brook, showing relict rapakivi texture and intense Paleozoic mylonitization. *A*, Large relict rapakivi K-feldspar (near penny) preserved in otherwise-mylonitic augen gneiss. *B*, Well-foliated ultramylonite and augen gneiss from Wardsboro Brook at Wardsboro, Vt., showing nearly complete transformation of Somerset Reservoir Granite into a tectonically layered rock.

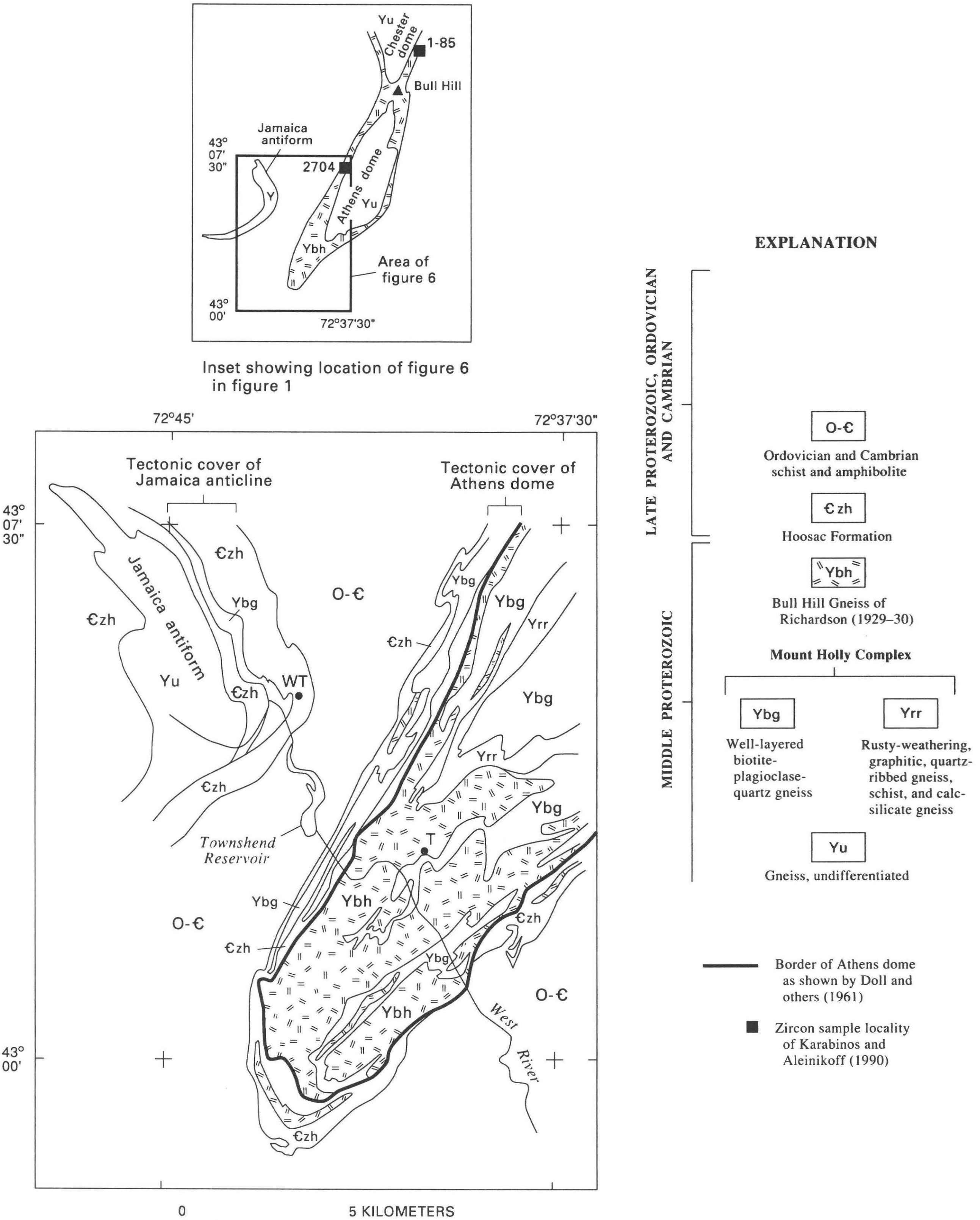

Figure 6. Generalized geologic map of southern part of the Athens dome, showing the Bull Hill Gneiss in relation to other gneisses in core of the dome, with a revision to geologic relations of Doll and others (1961) shown in figure 1. Geology based on mapping in 1989 at 1:25,000 scale. T, Townshend; WT, West Townshend.

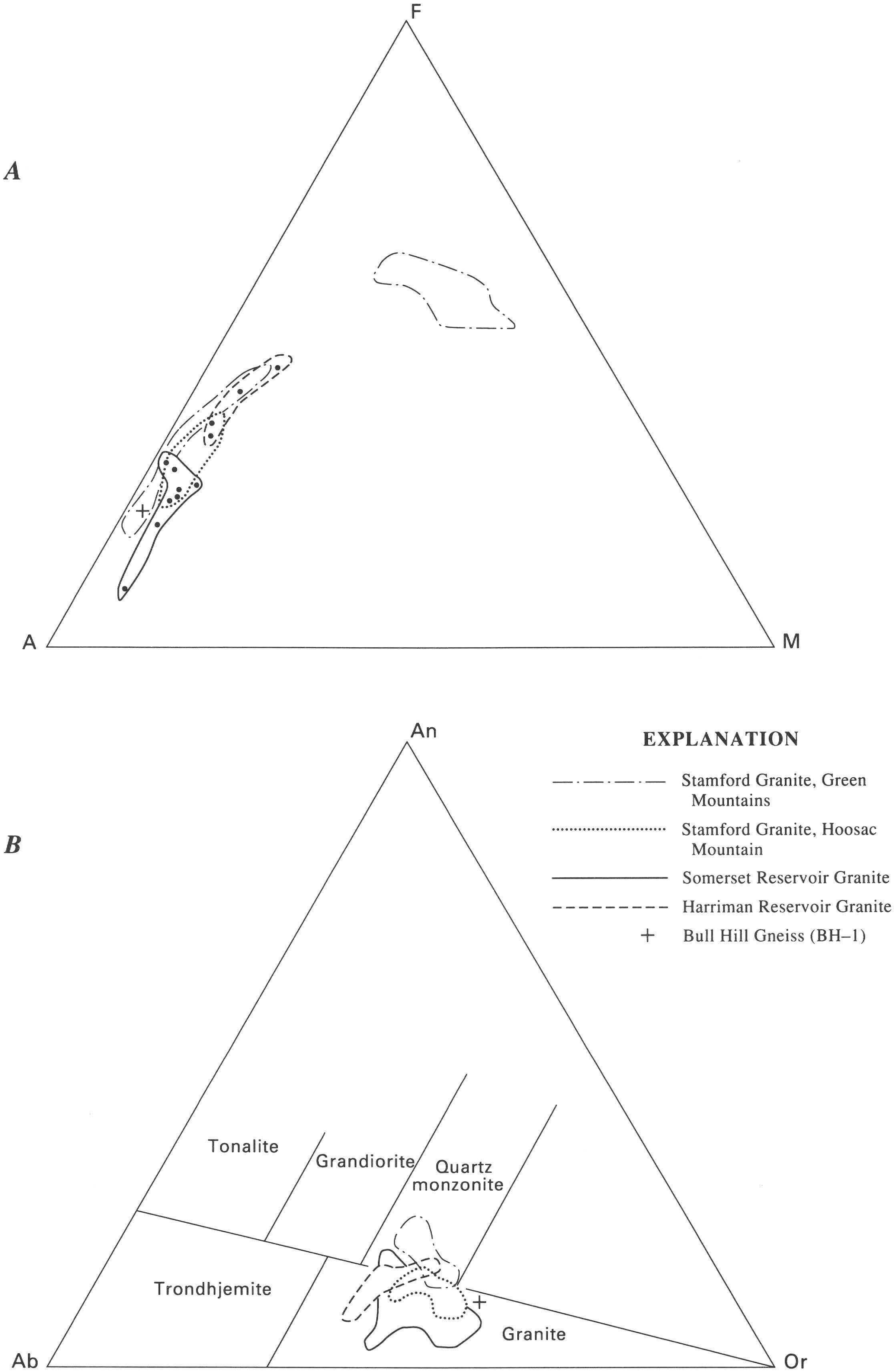

Figure 7. AFM (*A*) and An-Ab-Or (*B*) diagrams showing distinctions among the Stamford, Somerset Reservoir, and Harriman Reservoir Granites and one sample of the Bull Hill Gneiss, using classification scheme of O'Connor (1965).

correlated with rocks mapped as the Hoosac and Tyson Formations elsewhere (Thompson and others, 1977, p. 1124), whereas similar occurrences mapped by Skehan (1961) in the Wilmington, Vt., area have been mapped as the type Hoosac Formation on Hoosac Mountain, Mass. (Ratcliffe, 1979a, b).

Thompson (1952) described the Bull Hill Member of the Hoosac Formation as a microcline augen gneiss that occurs near the base of the Hoosac Formation in the Chester dome and on the eastern limb of the Green Mountain anticlinorium from Jamaica southward. Therefore, he specifically regarded the coarse gneiss at

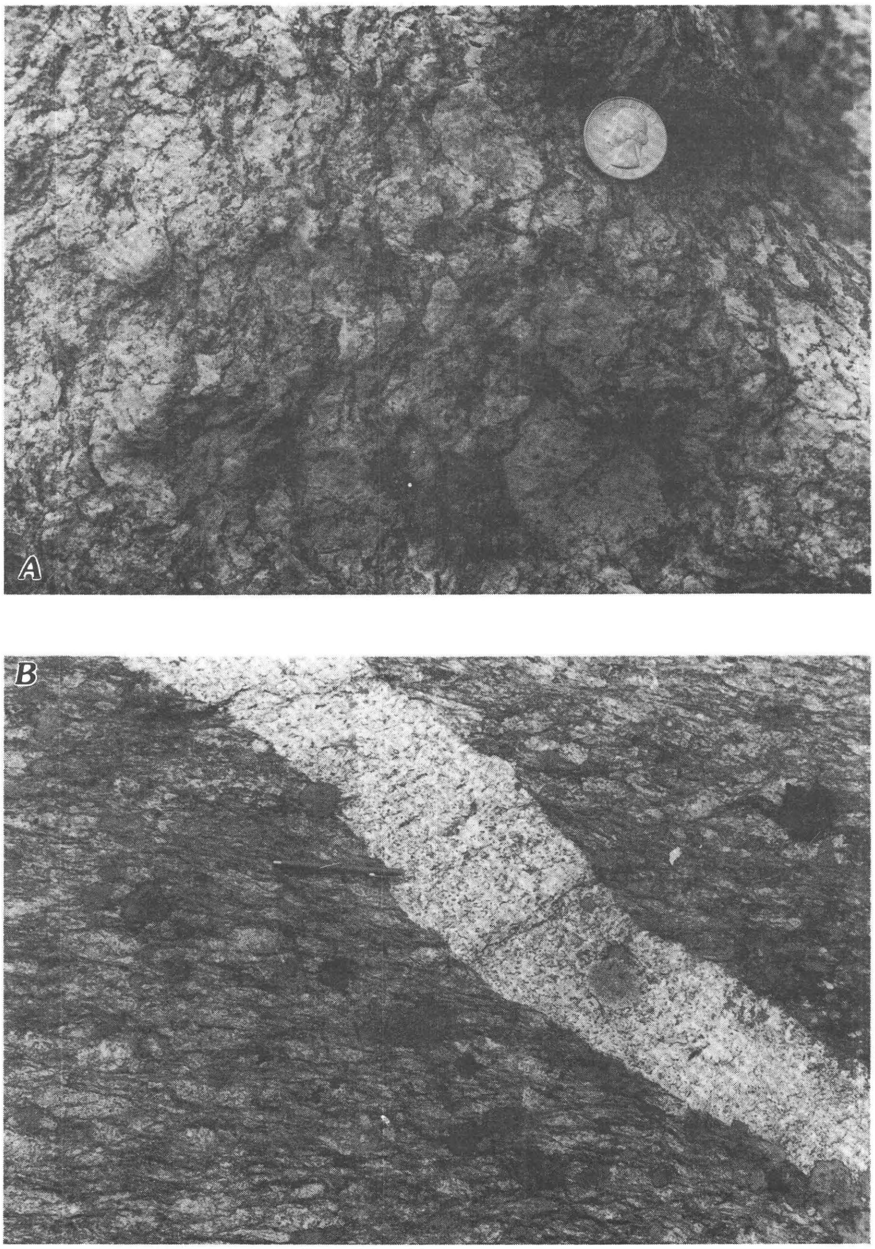

Figure 8. Typical Bull Hill Gneiss from type locality on Bull Hill in the Saxtons River quadrangle, Vt. A, Coarse-grained ovoidal facies, showing partial rapakivi rim on large microcline phenocryst (immediately to left of coin). *B*, Mylonitic Bull Hill Gneiss, showing augen structure produced by penetrative Paleozoic foliation (parallel to pen) in same outcrop as in figure 8*A*. Nonfoliated posttectonic muscovite-biotite granite dike of probable Devonian age crosscuts mylonitic fabric. Pen is 13 cm long.

Wardsboro as the Bull Hill and implied that the gneiss overlies albitic rocks assigned to the Hoosac Formation. In this note, however, that usage is not followed.

Critical map relations in the Jamaica, Vt., area (Ratcliffe and others, 1988), however, indicate that the Bull Hill Gneiss shown by Doll and others (1961) south of Jamaica (here mapped as the Somerset Reservoir Granite) is not intercalated within the cover rocks but is an integral part of the basement rocks (Somerset Reservoir Granite) everywhere lying stratigraphically beneath the Hoosac Formation. Where the granite's "lower" contact is exposed, it intrudes Middle Proterozoic gneiss of the Green Mountain massif, for example, near Mundal Hill in the Jamaica quadrangle. The newly recognized occurrences of Bull Hill-like gneiss in the Rayponda-Sadawga dome are now referred to as the Harriman Reservoir Granite.

In the Chester-Athens dome, Doll and others (1961) showed discontinuous belts of albitic granofels or schist (Readsboro Member), or calcitic marble (marble member) of the Cavendish, separating the Bull Hill Gneiss from core gneisses of presumed Middle Proterozoic age. In particular, Doll and others (1961) showed a continuous belt of marble separating an outer belt of the Bull Hill from core rocks of the Chester dome from Springfield to a point 6 km south of Chester, Vt. In all the outcrop areas, the Bull Hill Gneiss is portrayed as part of the cover rocks lying beneath the Hoosac Formation.

Recent maps of the Chester-Athens dome (for references, see Rosenfeld and others, 1988) show these minor belts as cover rocks of the Hoosac Formation but do not distinguish the Bull Hill Gneiss from the core gneisses. Rosenfeld (1972) and Rosenfeld and others (1988, p. 236) stated that attempts to separate the Bull Hill Gneiss from Proterozoic gneisses in the core of the Athens dome had not been successful, and the distribution of the Bull Hill and core gneisses shown by Doll and others (1961) is not shown by Rosenfeld and others (1988, p. 226, fig. 2). From these remarks, I conclude that the distribution of the Bull Hill Gneiss shown by Doll and others has not been verified by their more recent studies.

Recent mapping by the author in the Athens dome south of lat. 43°07'30" N. (fig. 6), shows that the Bull Hill Gneiss is not distributed as a continuous cover above older core gneiss as depicted in figure 1, which is based on the map of Doll and others (1961). Instead, the Bull Hill Gneiss in the dome contains septa of Mount Holly Complex consisting of two major rock types. The bulk of the Mount Holly is a well-layered biotite-plagioclase-quartz gneiss (unit Ybg, fig. 6). A distinctive rusty-weathering, graphitic, sulfidic, quartz-ribbed gneiss, schist, and calc-silicate forms a second, easily distinguished unit (Yrr, fig. 6). The mapping shows the Bull Hill Gneiss to be in contact with both units, and in an area 2 km north of Townshend it truncates the contact between the two units. In this area, cliff exposures show dikes of the Bull Hill Gneiss intruding the second unit and the Bull Hill Gneiss enclosing xenoliths of gneiss. From map relations and field observations, the Bull Hill Gneiss in the southern part of the Athens dome is regarded as intrusive into the Mount Holly Complex. Furthermore, map relations (fig. 6) do not confirm depiction of the Bull Hill Gneiss as interlayed within the cover rocks. Instead, the immediately overlying cover rocks, previously shown as the Hoosac Formation, actually include significant amounts of Mount Holly Complex gneiss and Bull Hill Gneiss. This zone, as much as 1 km wide, contains numerous repeats of the stratigraphic section and highly mylonitic gneisses intercalated within the Hoosac; the intercalation is caused both by repetition by folding and by faulting (Ratcliffe, 1990). Thus, although the Bull Hill locally appears to be interlayed within the cover rocks above the dome, both its age of approximately 950 Ma and the intrusive relations preserved in the core of the dome argue against this intercalation being either intrusive or stratigraphic.

Until the map relations of the Bull Hill Gneiss in the Chester-Athens dome are more clearly defined, little meaningful can be said about the structural position of the Bull Hill Gneiss. If the interpretation by Doll and others (1961) is locally correct, then the position of the approximately 950-Ma Bull Hill Gneiss above marble and albitic rocks of the Hoosac Formation (formerly the Cavendish Formation) requires a major thrust fault between the Bull Hill and core gneisses of the Chester-Athens dome, as suggested by Ratcliffe and others (1988, 1990). Much more geologic mapping needs to be completed, however, before this question can be resolved. Because of the uncertainty regarding the geologic position of the Bull Hill Gneiss of Richardson (1929–30), I recommend that his original definition be retained and applied only to those gneisses mappable into the type locality at Bull Hill. This usage restricts the name "Bull Hill Gneiss" to the Chester-Athens dome and does not follow the broader usage of Doll and others (1961).

Chemical data from the various exposures of granite defined in tables 1 and 2 and illustrated in figure 7 suggest that each exposure is somewhat compositionally distinct. REE analyses further confirm that the type Stamford Granite in the Green Mountains and on Hoosac Mountain have similar but distinctive patterns and that the Somerset Reservoir and Harriman Reservoir Granites have parallel but nonoverlapping REE envelopes (Ratcliffe and others, 1988). These data suggest that the individual exposures may represent separate intrusions rather than a continuous, sheetlike body repeated by faulting and folding.

SUMMARY

The Mount Holly Complex of Vermont and northernmost Massachusetts is herein defined as a collection of metavolcanic, metasedimentary, and metagranitoid rocks that underwent high-grade dynamothermal metamorphism during the Middle Proterozoic. Gneissic granites within the Mount Holly Complex, such as the herein-named College Hill Granite Gneiss, are defined as integral parts of the Mount Holly Complex.

A group of posttectonic biotite granites and rapakivi granite intruded the Mount Holly Complex and correlative rocks after Middle Proterozoic deformation. These posttectonic granites, which occur within the Green Mountain massif, along its eastern margin, in the cores of the Chester-Athens and Rayponda-Sadawga domes, and in the northern part of the Berkshire massif, are herein defined as the Cardinal Brook Intrusive Suite. Therefore, the 960- to 950-Ma age of the suite, as defined by Karabinos and Aleinikoff (1988, 1990) and Beth Harding and Samuel Mukasa (unpub. data, 1988), establishes a minimum date for the Grenville orogeny in the Green Mountains and Berkshire massifs.

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The Sohnari Formation in Southern Pakistan

By William F. Outerbridge, Norman O. Frederiksen, Mohammed Riaz Khan, Rafiq Ahmed Khan, Mohammed Jaffar Qureshi, Muhammad Zameer Khan, Niamatullah, *and* Shafiq Ahmed Khan

Abstract

The late Paleocene Basal Laki Laterite of Nuttall (1925) in Sindh Province, Pakistan, has been termed the Sohnari Member of the Laki Formation by other workers. New subsurface information provided by coal exploration in southern Sindh Province, however, indicates that the carbonaceous Sohnari is lithologically distinct from the underlying shelly Lakhra Formation and from overlying rubbly limestone of the Laki Formation. The Sohnari is lithologically nearly identical to the Bara Formation that underlies the Lakhra: Both the Sohnari and the Bara are mainly nonmarine to brackish-water deposits. Therefore, the Sohnari Member of the Laki Formation is herein excluded from the Laki Formation and renamed the Sohnari Formation.

INTRODUCTION

Extensive core drilling in the course of coal exploration by the Geological Survey of Pakistan and the U.S. Geological Survey near Hyderabad, Sindh, Pakistan (fig. 1), has provided a wealth of stratigraphic data and has made a reinterpretation of the lower Tertiary stratigraphy of the region both possible and necessary. The Paleocene Basal Laki Laterite (fig. 2) has been one of the most controversial stratigraphic units in the region in regard to its sedimentary origin and stratigraphic nomenclature. This note provides new information about the lithology and origin of the unit and redefines the Sohnari as a formation.

HISTORY

Noetling (1905) observed that the Kirthar Group as recognized by Blanford (1879) in the Laki Range predates the Kirthar Group of the Kirthar Range, and renamed the strata in the Laki Range the Laki Series. Nuttall (1925) subdivided the Laki Series of Noetling (1905) (Laki Formation, figs. 2, 3) and included within it a distinctive red to reddish-brown and yellow unit he called the Basal Laki Laterite. The name has been in use ever since. Nuttall considered the Basal Laki Laterite to form the base of the Laki Series and to rest on an unconformity at the top of the underlying Ranikot Formation. He considered the Basal Laki Laterite to be a weathered zone that originated from a phase of uplift during which weathering and erosion of the Ranikot took place; that is, Nuttall (1925) did not consider the "laterite" to be a depositional unit. Nuttall reported the age of the Basal Laki Laterite as Eocene on the basis of its content of the large foraminifer *Assilina granulosa*, its position as the basal member of an Eocene formation dated by larger foraminifers, and its separation from Paleocene rocks by an unconformity. Nuttall's explanation of the geologic structure and stratigraphy of the Meting-Lakhra area (fig. 1) has powerfully influenced geologic thought in the region.

In contrast to the view of Nuttall (1925, 1932) that the Basal Laki Laterite is a zone of weathering, Jones and others (1960, p. 186, 433) considered the "Basal Laki laterite or the Sohnari beds" to represent a discrete depositional unit "laid down on an old erosion surface."

Ghani and others (1973) made extensive observations and collections of Basal Laki Laterite around the Lakhra coal field (at the head of Lakhra Nala, fig. 1). They realized that the Sohnari is not a pre-Eocene laterite because they observed that the unweathered Sohnari consists of dark-gray to light-gray, pyritic claystone and siltstone. Ghani and others commented that similar red units also appear within sequences cropping out much lower stratigraphically than the "Basal Laki Laterite." The John T. Boyd Co. (1986, p. 3–13) noted that the lateritic appearance of the Sohnari is due at least in part to Quaternary weathering because the depth of weathering depends "* * * on the thickness of the overlying limestone, the amount of sandstone and other permeable strata in the upper part of the formation, and the current drainage patterns."

Cheema and others (1977) and M.Z. Farshori (unpub. data, undated) described the Basal Laki Laterite or Sohnari Member of the Laki Formation from outcrops extending from the head of Lakhra Nala to Kalri Lake (fig. 1). The Sohnari Member of the Laki Formation derives its name from thick and extensive outcrops near Sunahri Dhand (southwest corner, fig. 1), and was adopted for use by the Geological Survey of Pakistan by

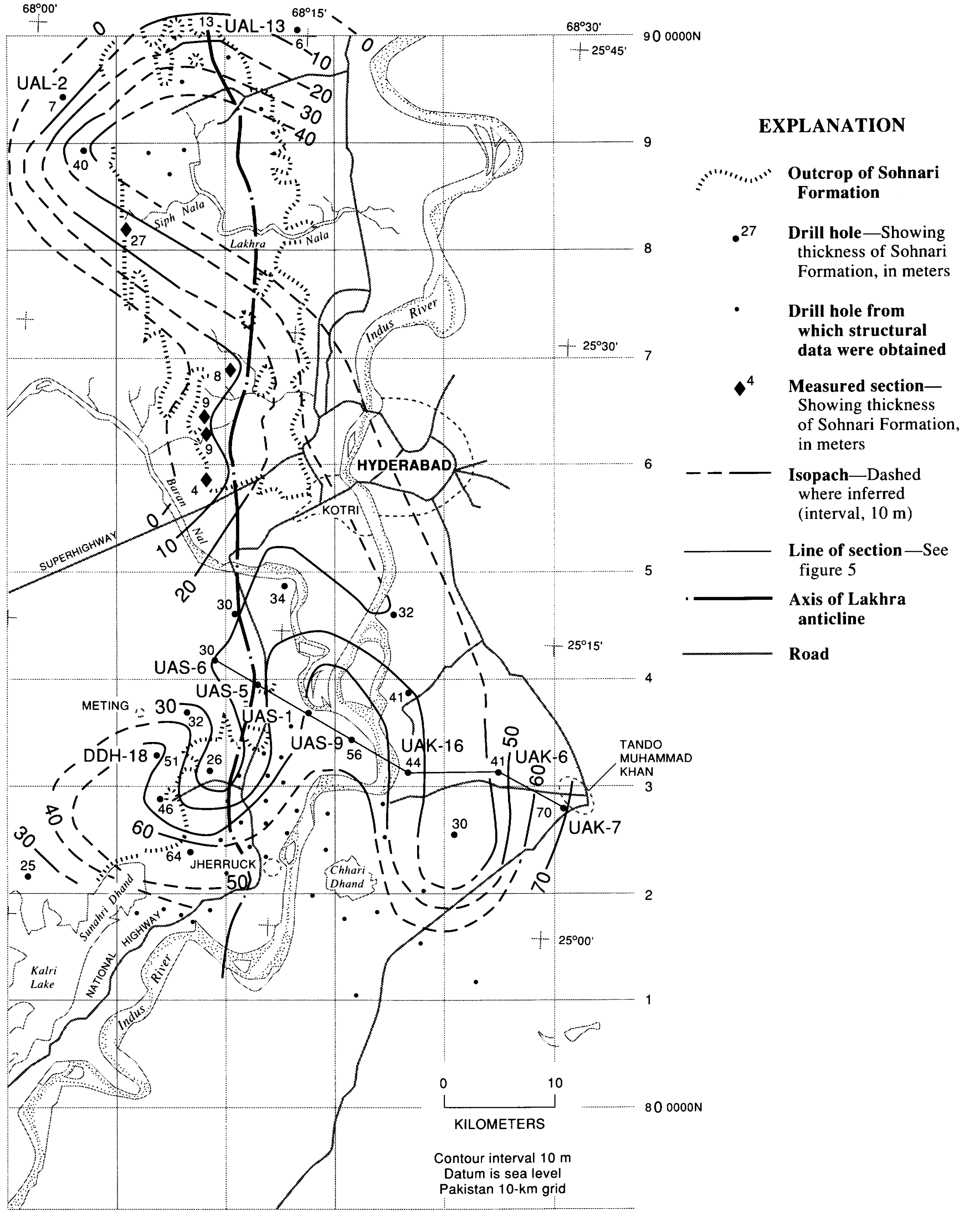

Figure 1. Hyderabad, Pakistan, area, showing locations of outcrop areas, drill holes, and places where thickness of the Sohnari Formation was measured. Stippled areas, sand deposits.

Cheema and others (1977). Because of difficulties in transliterating names from Urdu to English, some authors use the spelling "Sohnari" (for example, Jones and others, 1960; Cheema and others, 1977; Outerbridge and Khan, 1988), whereas others use "Sonhari" (for example, Shah, 1977, fig. 8; Husain, 1986; Frederiksen, 1988), and at the type locality on the Survey of Pakistan's topographic map it is spelled "Sunahri." The Urdu spelling of the name is سنہری.

Usmani (1983) studied smaller foraminifers from two drill cores furnished by the Pakistan Oil and Gas Development Corp. and concluded that the Sohnari Member is of middle to late Paleocene rather than early Eocene (Ypresian) age, as reported by Nuttall (1925). Frederiksen (1988) found that pollen assemblages in the Sohnari are more similar to Paleocene than to Eocene assemblages of southwestern India.

DESCRIPTION

Lithology

The idea that the Sohnari is a laterite is deeply embedded in the geologic literature on the area but is based on field observations of outcrops. Therefore, we present detailed logs (see section below entitled "Supplementary Data * * *" and fig. 4) of representative drill cores through the Sohnari.

The Sohnari Formation, as herein defined, consists of sandstone, siltstone, shale, claystone, coal, underclay, and conglomerate. The sandstone is medium to light gray and weathers yellowish gray to dark reddish brown and moderate red. It is very fine to coarse grained and even bedded or crossbedded. In drill cores, the sandstone is friable to completely unconsolidated, except where it contains calcite cement. The sand grains are angular to subangular, and most are composed of quartz. Locally abundant pyrite makes up as much as 10 percent of the rock; a minor amount of glauconite is also present. Sand in the Ranikot Group is thought to have been derived from low-lying crystalline rocks of Peninsular India (Jones and others, 1960).

The siltstone and shale are medium light gray to dark gray and weather yellowish gray, dusky yellow, moderate red, and very dark red. Fresh siltstone and shale is well compacted but when wet becomes soft and easily molded. In outcrops, the rocks are case hardened and commonly impregnated with iron oxides.

Coal is reported to crop out near Sunahri Dhand (Jones and others, 1960), but we have not seen it in outcrops. In cores, it is generally less than 1 m thick, black-

<table>
<tr><th colspan="2">AGE</th><th>Blanford (1879)</th><th>Noetling (1905)</th><th colspan="2">Nuttall (1925)</th><th colspan="2">Jones and others (1960)</th><th colspan="2">Shah (1977)</th><th colspan="2">This note</th></tr>
<tr><td rowspan="9">CENOZOIC</td><td rowspan="4">EOCENE</td><td rowspan="4">Kirthar Group</td><td rowspan="4">Laki Series</td><td rowspan="4">Laki Group</td><td>Laki Limestone</td><td rowspan="4">Laki Group</td><td rowspan="4">Basal Laki Laterite (Sohnari beds)</td><td rowspan="4">Laki Formation</td><td>Unnamed member</td><td rowspan="5">Laki Formation</td><td>Laki Limestone Member</td></tr>
<tr><td>Meting Shale</td><td rowspan="2">Meting Limestone and Shale Member</td><td>Meting Shale Member</td></tr>
<tr><td>Meting Limestone</td><td rowspan="3">Meting Limestone Member</td></tr>
<tr><td>Basal Laki Laterite</td><td>Sonhari Member</td></tr>
<tr><td rowspan="5">PALEOCENE</td><td rowspan="5">Ranikot Group</td><td rowspan="5">Ranikot Group</td><td colspan="2" rowspan="3">Upper Ranikot</td><td rowspan="5">Ranikot Group</td><td rowspan="3">Upper Ranikot</td><td rowspan="5">Ranikot Group</td><td rowspan="3">Lakhra Formation</td></tr>
<tr><td rowspan="4">Ranikot Group</td><td>Sohnari Formation</td></tr>
<tr><td>Lakhra Formation</td></tr>
<tr><td colspan="2" rowspan="2">Lower Ranikot</td><td>Lower Ranikot</td><td>Bara Formation</td><td>Bara Formation</td></tr>
<tr><td>Cardita beaumonti beds</td><td>Khadro Formation</td><td>Khadro Formation</td></tr>
</table>

Figure 2. Nomenclatural diagram for beds near the Sohnari Formation.

ish brown to black, laminated, and resinous. Every drill core through the Sohnari has cut one or more coal beds, generally within the middle part of the unit, but correlation of individual coal beds is uncertain; on the basis of cores from the area south of Sunahri Dhand, Husain (1986) reported that the coal beds within the Sohnari are lenticular.

The underclay or seat earth is commonly about 1 m thick. It may be a clay-pebble conglomerate, sand, silt, or claystone. It is light to medium gray and weathers yellowish gray to dark red. The underclay is characteristically rooted and compression slickensided. It is soft when fresh but becomes case hardened in outcrops.

The clay-pebble conglomerate is gray and contains brown sideritic claystone pebbles; it weathers yellowish gray to reddish brown. The sideritic claystone pebbles, as much as 3 cm across, are supported by a clay matrix. Clay-pebble conglomerate has been found in drill holes UAL–2 and UAL–13, as well as in widely scattered outcrops and mine exposures. It occurs at several stratigraphic positions in the Sohnari Formation and resembles the clay-pebble conglomerate found in the lowest part of channel-fill sandstone bodies in the Appalachian coal field (U.S.A.), but here it may represent local beach or tidal-channel lag deposits.

The deep red color that characterizes some outcrops of the Sohnari is caused by impregnation of the clastic sediment by hematite (Ghani and others, 1973). Our observations and those of Ghani and others (1973) and the John T. Boyd Co. (1986) indicate that the red color does not occur below the weathered zone, where the Sohnari is gray and locally contains abundant pyrite. We believe that the color is a result of Quaternary weathering.

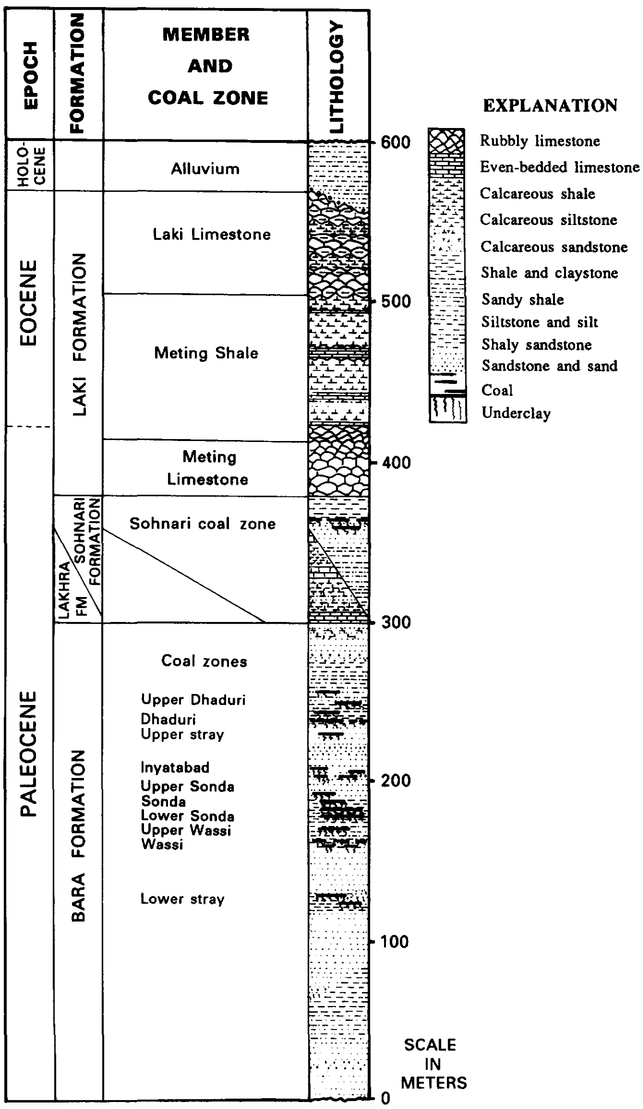

Figure 3. Stratigraphic column illustrating general stratigraphy of Hyderabad, Pakistan, area.

Lower Contact of the Sohnari Formation

The lower contact of the Sohnari Formation is normally placed at the top of the highest limestone bed of the underlying Lakhra Formation. However, limestone beds of the Lakhra Formation grade eastward into calcareous shale; where the topmost limestone bed of the Lakhra Formation grades laterally into shale, the base of the Sohnari Tongue is placed at the top of the next lower limestone bed.

Contacts at the top of the Lakhra limestone beds are abrupt, but at any individual locality there is no convincing physical stratigraphic evidence of an unconformity at the base of the Sohnari. Nevertheless, most authors who discussed the Basal Laki Laterite or the Sohnari Member of the Laki Formation considered the contact of this unit with the underlying Lakhra Formation to be an unconformity. Nuttall (1925) observed that the marine fauna of the upper part of his Ranikot Series (that is, fauna of the Lakhra Formation of present usage) differed considerably from that of the Meting Limestone member of the Laki Formation, which overlies the Sohnari; he ascribed this difference to the existence of an unconformity between the Ranikot and the Meting.

Nuttall (1932) and Ghani and others (1973) suggested that an angular unconformity exists between the Ranikot Series and the Laki Series, which includes the Basal Laki Laterite. Evidence for its presence was that progressively older Ranikot strata underlie the Basal Laki Laterite from south of Jherruck in the south to the Laki Range (west of the area of fig. 1) in the north, suggesting gentle tilting and erosion of the Ranikot strata before subsidence and deposition of the Laki limestone beds. Palynologic data (Frederiksen, 1988) also suggest the presence of a distinct unconformity between the

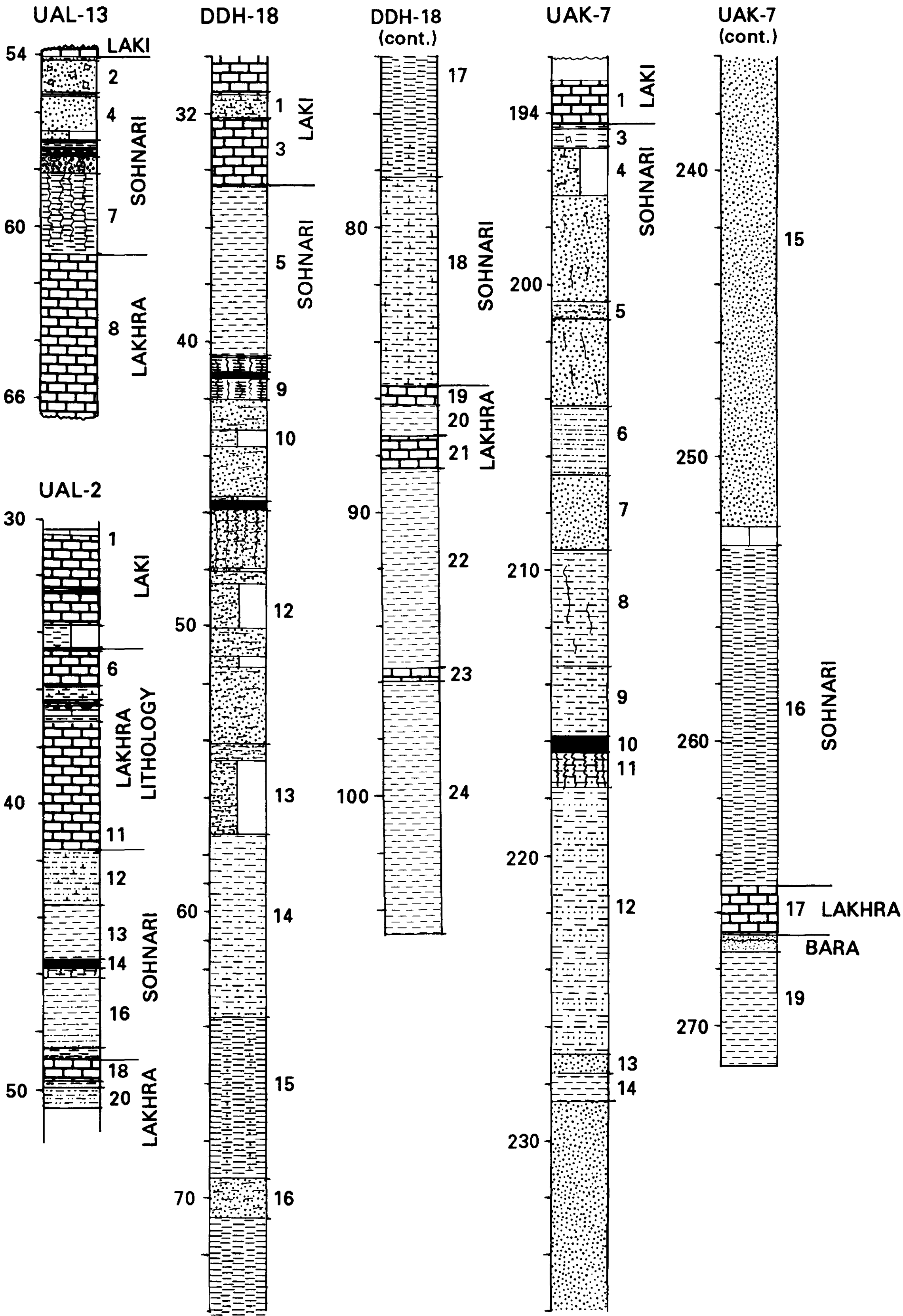

Figure 4. Graphic logs of the Sohnari Formation in drill holes UAL–13, UAL–2, DDH–18, and UAK–7 (see fig. 1 for locations). Lithologies are described in text section entitled "Supplementary Data * * *." Depth scale, on left side of columns, in meters; numbers on right sides of columns are bed numbers related to core logs. Same symbols as in figure 3.

Sohnari and the Lakhra, at least in some areas (for example, in drill hole UAL–2).

Jones and others (1960) indicated that pre-Laki erosion of the Ranikot Group was caused by minor uplift of the Hyderabad arch. Alternatively, Jones and others (1960) suggested that the absence of upper Ranikot strata in the Laki Range may be due to nondeposition during a phase of gentle uplift of the Hyderabad arch.

Upper Contact of the Sohnari Formation

The Laki Formation apparently overlies the Sohnari Formation with a lithologically transitional contact; Ghani and others (1973) considered this contact to be conformable between the "Basal Laki Laterite" and limestone of the overlying Laki Formation. In the ordinary stratigraphic sequence, the upper part of the Sohnari Formation is a dark-gray to black claystone that becomes intensely burrowed upward. The uppermost part of the Sohnari is generally calcareous, containing fossils of thin-shelled clams and snails, and is commonly burrowed. The burrows are filled with sand and comminuted shells. The claystone commonly is pale and highly calcareous at the top and is immediately overlain by nearly white limestone of the Laki Formation; the lowermost limestone of the Laki is even bedded in at least some drill cores but generally is rubbly bedded in outcrops. The section in drill hole UAL–2 (fig. 4) is unusual in that a Lakhra-like set of beds occurs between the base of rubbly bedded limestone of the Meting Member and sandstone, shale, and coal of the Sohnari. At drill hole UAL–2, the Sohnari may be thinning westward, owing to interfingering with the Lakhra.

Nuttall (1925), however, concluded that an unconformity exists between the Laki Formation and the Sohnari Formation (of our usage) in at least part of the lower Indus Basin because he believed that the Meting Limestone and Meting Shale Members of the Laki (fig. 2) are missing owing to nondeposition in the northern part of our study area (fig. 1). That is, he thought that the Laki Formation (of our usage) was deposited in an onlapping fashion by a northward-transgressing sea over an erosional surface represented by the top of the Sohnari Formation. Since Nuttall's study, no paleontologic investigations have been published that would prove or disprove the existence of a distinct unconformity between the Sohnari Formation and the Laki Formation in the northern part of our study area.

Comparison with the Bara Formation

The Bara Formation underlies the Lakhra Formation (fig. 2). In the subsurface, rock types found in the Bara are nearly identical to those found in the Sohnari Formation. The only way to distinguish between these units lithologically is to find them separated by the Lakhra Formation; as pointed out by Ghani and others (1973), the red to yellow colors of the Sohnari in outcrop are not a definitive criterion for recognizing that unit. However, the Bara and Sohnari Formations contain different pollen assemblages and can be differentiated in this way (Frederiksen, 1988).

Thickness and Distribution

The known thickness and distribution of the Sohnari Formation are shown in figures 1 and 5. In general, the Sohnari thins westward and northward but has a thick salient extending westward and northward from

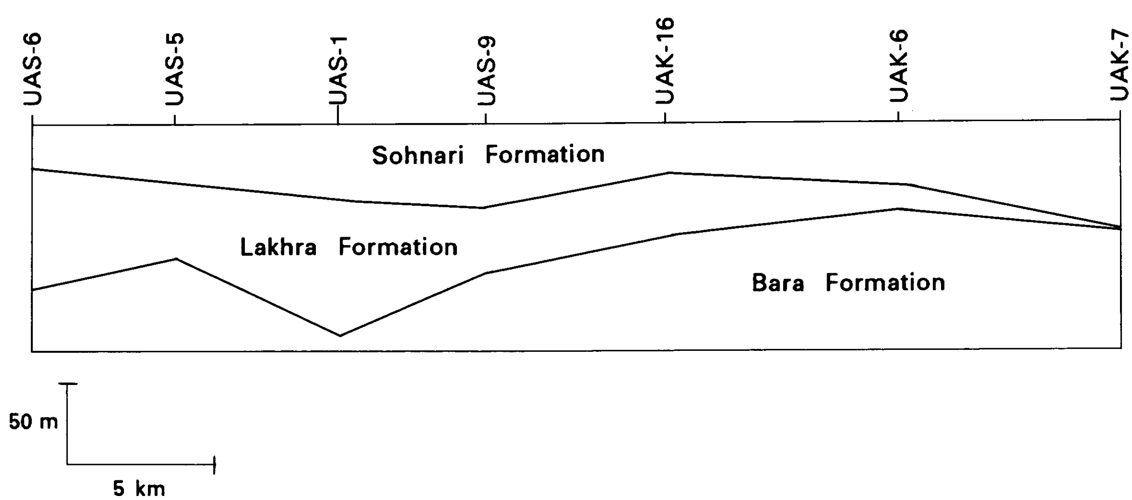

Figure 5. Schematic cross section illustrating thickness relations between the Sohnari Formation and the Lakhra Formation. Datum is top of Sohnari Formation. Symbols, drill holes. See figure 1 for explanation.

near Jherruck to Meting. It thickens as the Lakhra Formation thins from Meting to Tando Muhammad Khan (fig. 1), where, in drill hole UAK–7 (figs. 1, 4), the Sohnari is 70 m thick and the Lakhra is a single shaly limestone bed, 2 m thick. Because the limestone beds of the Lakhra grade eastward to shale, only slightly farther east the Lakhra limestone may be absent, and the Sohnari may rest directly on the Bara. The Sohnari and the Lakhra both thin toward the northwest edge of the area of figure 1.

Environment of Deposition

Data bearing on the environments of deposition of the Bara, Lakhra, Sohnari, and Laki Formations, as well as interpretations of these data, have appeared in many reports (for example, Nuttall, 1932; Jones and others, 1960; Ghani and others, 1973; Cheema and others, 1977; Usmani and Ahmed, 1986; Warwick and others, 1987; Frederiksen, 1988; see section below entitled "Supplementary Data * * *"). The Sohnari Formation appears to represent mainly nonmarine to brackish-water deposition, as shown by the presence of coal, underclay, abundant carbonaceous material in the detrital sedimentary rocks, and some brackish-water pollen.

Fossil and lithologic indicators of open-marine conditions are of subordinate abundance in the Sohnari, but the presence of limestone, shells, foraminifers, and glauconite at some horizons indicates that the Sohnari also includes shallow-marine sediment, and so the entire formation was probably deposited in coastal and near-coastal environments. The coal-bearing Bara Formation is also considered to be mainly of nonmarine to brackish-water origin, but it, too, contains fossils indicating marine deposition of some strata. Although the Sohnari Formation is lithologically similar to the Bara Formation (fig. 3), the two units contain somewhat different palynomorph assemblages and thus differ somewhat ecologically and, possibly, paleoclimatically; for example, the Sohnari Formation appears to have been deposited under less marine influence, on the average, than the Bara (Frederiksen, 1988). In contrast to the Bara and Sohnari Formations, the Lakhra and Laki Formations (as here restricted) are abundantly fossiliferous and mainly of marine origin.

CONCLUSIONS

The Sohnari Formation is a wedge of clastic sedimentary rocks derived from the east and deposited between the marine Lakhra and Laki Formations. The Lakhra Formation apparently pinches out eastward near Tando Muhammad Khan, and in that area the Sohnari Formation and the Bara Formation may be in direct contact. The Sohnari Formation pinches out to the west, and in that area the Lakhra Formation immediately underlies the Laki Formation. The Lakhra and Laki Formations are lithologically distinct from each other, although both units represent mainly marine deposition; however, the Bara Formation and the Sohnari Formation lithologically are nearly identical.

The Sohnari, originally known as the Basal Laki Laterite, represents a very slight marine regression, possibly a reduction in the rate of sinking of the continental shelf of the Indian plate, while clastic sediment and peat accumulated very close to sea level. The Sohnari does not represent an early Tertiary zone of weathering, as Nuttall (1925) and other authors have claimed, and so it should not be considered a basal member of the Laki Limestone, because it clearly is not related to that formation, except that it underlies the Laki.

Much more work needs to be done to improve our understanding of this controversial unit. In particular, more biostratigraphic work is needed to clarify stratigraphic and paleoenvironmental relations of the Paleocene and Eocene strata in southern Sindh and their relation to similar-age deposits elsewhere in Pakistan.

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Supplementary data. Logs of drill holes UAL–13, UAL–2, DDH–18, and UAK–7

Bed	*Top*	*Interval thickness (m)*	*Base*	*Description*
				UAL–13; lat 25°45′50″ N., long 68°13′53″ E.; elev 115 m
				Top of the Sohnari Formation
1	54.06	0.12	54.18	Silt, calcareous, very light gray (N7), sharply contacting overlying rubbly limestone; contains abundant shell fragments, echinoids, and foraminifers (*Assilina*, *Alveolina*).
2	54.18	1.13	55.31	Sandstone, clayey, dark-greenish-gray (5GY 4/1), containing abundant pyrite in cubes, octahedrons, and nodules as much as 3 cm across; very poorly laminated, with sharp upper contact, containing clamshell fragments; sandier downward. Green color may be pyrite coating on quartz grains.
3	55.31	0.12	55.43	Limestone, very light gray (N7), calc-siltite, containing black chert nodules. Upper contact is sharp, lower contact gradational. Contains shell fragments and sparse carbonaceous fragments.
4	55.43	1.21	56.64	Sand, gray (N5), consisting of very fine to fine angular grains, mostly of quartz, and a few dark grains; extremely bioturbated, with sharp lower contact. Contains concentrations of oyster shell and clamshell fragments.
	56.64	0.34	56.98	(Lost; probably sand.)
5	56.98	0.51	57.49	Coal and coaly clay, black to brownish-black (N1 to 5YR 2/1), containing flecks of amber resin, more clayey at top and bottom. Lower contact is gradational with clay-pebble conglomerate. Sampled for pollen.
6	57.49	0.59	58.08	Conglomerate, clay-pebble; matrix gray (N5 to N7), lighter downward, containing pebbles, brown (5YR 6/4 to 10YR 8/2), generally 1 to rarely 3 cm in diameter at top, grading to 3 mm in base, composed of clay. Conglomerate is well-rooted seat earth; base is gradational.
7	58.08	2.73	60.81	Claystone, gray (N5), massive; abundantly rooted underclay; permeable, softens when wet, contains abundant pyrite cubes. Bottom 0.5 m is calcareous, containing sparse foraminifers (*Discocyclina*).
				Base of the Sohnari Formation
				Top of the Lakhra Formation
	60.81	0.13	60.94	(Lost; probably clay.)
8	60.94	5.65	66.59	Limestone, light gray (N7), calc-siltite, containing 10 to 15 volume percent siliceous material; pyritic, with local heavy concentrations of foraminifers, some containing glauconite.
Sohnari thickness is 6.88 m.				
				UAL–2; lat 25°41′35″ N., long 68°01′58″ E.; elev 111 m
1	30.49	2.01	32.50	Limestone, very pale orange to yellowish-brown (10YR 8/2 to 10YR 6/2), compact, massive, hard, fossiliferous, becoming sandy at base, with very thin gypsum veins.

Bed	*Top*	*Interval thickness (m)*	*Base*	*Description*
				UAL–2; lat 25°41′35″ N., long 68°01′58″ E.; elev 111 m—Continued
2	32.50	1.28	33.78	Limestone, sandy, yellowish-brown (10YR 6/2), fine- to medium-grained, hard, massive, compact, highly foraminiferal. Core lost at 32.79 to 32.83 and 33.42 to 33.48 m.
3	33.78	0.73	34.51	(Lost; probably claystone, silty.)
4	34.51	0.05	34.56	Limestone, sandy, yellowish-brown (10YR 6/2), fine- to medium-grained, hard, massive, compact, highly foraminiferal.
				Base of the Laki Formation
				Top of Lakhra lithology
5	34.56	0.04	34.60	Clay, silty, gray (N5).
6	34.60	1.28	35.88	Limestone, silty to sandy, light-gray to gray (N7 to N5), micritic, massive, compact, containing a few foraminifers.
	35.88	0.04	35.92	(Lost.)
7	35.92	0.40	36.32	Claystone, calcareous, light-gray (N7).
8	36.32	0.16	36.48	Limestone, very light gray (N8), calc-siltite.
9	36.48	0.25	36.73	Shale, medium-light-gray (N6), containing limestone nodules and a sea urchin. Shale is chewed up.
	36.73	0.17	36.90	(Lost.)
10	36.90	0.22	37.12	Shale, medium-light-gray (N6), slightly silty, burrowed, containing plant trash.
11	37.12	4.52	41.64	Limestone, light-gray (N7), calc-siltite, grading to siltstone, containing foraminifers, clams, and carbonaceous material.
				Top of the Sohnari Formation
12	41.64	1.93	43.57	Siltstone to sandstone, medium-light gray (N6), fine-grained, calcareous, friable.
13	43.57	1.91	45.48	Shale, dark-gray (N3), carbonaceous.
14	45.48	0.25	45.73	Coal, missing.
15	45.73	0.43	46.16	Claystone, dark-gray (N3), carbonaceous, rooted, containing plant trash; underclay.
16	46.16	2.38	48.54	Claystone to sandstone, dark-gray (N3), interbedded, carbonaceous, highly pyritic.
17	48.54	0.33	48.87	Claystone, pale- to moderate-brown (5YR 5/2 to 5YR 4/4), stained by pyrite oxidation, clearly visible in core. Clay-pebble conglomerate at base.
				Base of the Sohnari Formation

Bed	*Top*	*Interval thickness (m)*	*Base*	*Description*
				UAL–2; lat 25°41′35″ N., long 68°01′58″ E.; elev 111 m—Continued
				Top of the Lakhra Formation
18	48.87	0.82	49.69	Limestone, greenish-gray (5G 6/1), micritic, pyritic, slightly glauconitic or chloritic, with some calcite filling in fossils. Hard and dense, highly fossiliferous at top, becoming silty and less fossiliferous near base. Fossils are mostly fragments of and whole clams and snails and foraminifers.
19	49.69	0.22	49.91	Claystone, light-gray to gray (N7 to N5), sandy and silty, pyritic.
20	49.91	0.69	50.60	Siltstone, sandy, gray (N5), containing disseminated carbonaceous material, pyrite, shell fragments, and shell impressions. Highly fossiliferous in lower 5 cm.
Sohnari thickness is 7.23 m				
				DDH–18; lat 25°06′43.8″ N., long 68°08′42.6″ E.; elev 60 m
1	31.34	0.82	32.21	Sandstone, silty, light gray (N7), very fine grained to fine-grained, calcareous.
2	32.21	0.03	32.25	Shale, sandy, containing fragmental fossils.
3	32.25	2.28	34.53	Limestone, silty to clayey, very light gray (N8) containing a large clam, snails, and abundant foraminifers. Coal fragments and pyrite lenses occur at base.
				Base of the Laki Formation
				Top of the Sohnari Formation
4	34.53	0.06	34.59	Clay, calcareous, containing small clams.
	34.59	0.21	34.81	(Lost.)
5	34.81	5.73	40.54	Shale, dark-gray to medium-dark-gray, (N3 to N4), noncalcareous. Burrowed; filling is sandstone, richly fossiliferous (foraminiferal hash) and calcareous. Rooted, containing some coaly particles. Richly fossiliferous between 36.99 and 37.19 m, slightly sideritic and pyritic from 37.19 to 40.54 m. Core lost at 35.66 to 35.84 and 38.71 to 38.89 m.
6	40.54	0.03	40.57	Shale, dark-gray (N3), coaly, containing some resin.
7	40.57	0.58	41.15	Clay, medium-dark-gray (N4), rooted, slickensided; underclay. At base is 3 cm of dark-gray (N3) shale with light-gray (N7) blotches, possibly sulfate.
8	41.15	0.15	41.30	Coal, removed for analysis.
	41.30	0.09	41.39	(Lost.)
9	41.39	0.67	42.06	Clay, dark-gray (N3) in top 0.15 m, light-gray (N7) below. Rooted, slickensided; underclay.
10	42.06	3.54	45.60	Sandstone, silty, dark-gray (N3) at top to light-gray (N7) at base, very fine grained to fine-grained, massive, rooted, carbonaceous, friable in lower 3.29 m, muddy at base. Core lost at 43.13 to 43.63 and 45.44 to 45.60 m.

Bed	Top	Interval thickness (m)	Base	Description
				DDH-18; lat 25°06′43.8″ N., long 68°08′42.6″ E.; elev 60 m—Continued
11	45.60	0.30	45.90	Coal, removed for analysis.
12	45.90	8.23	54.13	Sandstone, muddy to clayey, medium-dark- to medium-light-gray (N4 to N6), very fine grained to medium-grained, quartzose, containing sparse mica flakes, massive to laminated, fining downward. Top 2.06 m is seat earth, rooted, containing abundant coaly particles. At 48.44 to 48.49 m is quartzite containing calcite, a sulfide (pyrite, marcasite, or chalcopyrite), and hematite, possibly a vein, certainly a very heavy piece of core. Core lost at 47.96 to 48.03, 48.49 to 50.08, and 51.08 to 51.42 m.
13	54.13	0.55	54.68	Mudstone, medium-gray (N5), massive, containing sparse fragmental fossils.
	54.68	2.59	57.27	(Lost.)
14	57.27	6.43	63.70	Siltstone, medium-gray (N5), containing some mudstone, fining downward; snail at 58.95 m, compaction slickensided in lowest 1 m. Core lost at 58.83 to 58.95 and 63.25 to 63.70 m.
15	63.70	5.67	69.37	Claystone, silty, medium-gray (N5), massive, containing abundant snails, compression slickensided. Sampled at 66.54 to 66.65 m; core lost at 65.47 to 65.53 m.
16	69.37	1.01	70.38	Sandstone, muddy, medium-gray (N5), fine- to medium-grained, massive, friable, sagging to shape of core box when wet, containing abundant carbonaceous material.
17	70.38	7.83	78.21	Claystone, medium-dark-gray (N4), brownish-gray (5YR 4/1) in lower 2 m, calcareous from 76.81 to 78.21 m, fossiliferous, massive, compression slickensided. Separation of core segments has added 27 cm to its length.
18	78.21	18.63	85.50	Siltstone, greenish-gray (5G 6/1), massive, calcareous, locally clayey, with fossil content decreasing toward base, absent in lowest 1 m.
				Base of the Sohnari Formation
				Top of the Lakhra Formation
19	85.50	0.71	86.21	Limestone, medium-light-gray (N6), composed of fossil hash with micritic matrix, massive.
20	86.21	1.10	87.31	Claystone, calcareous, greenish-gray (5GY 6/1), massive, richly fossiliferous, composed of fossil hash in clay, grading into unit 19.
21	87.31	1.22	88.53	Limestone, silty, medium-light-gray (N6), containing abundant foraminifers in a calc-siltite matrix.
22	88.53	7.04	95.57	Claystone, calcareous, greenish-gray to medium-gray (5GY 6/7 to N5), massive to poorly bedded, ranging in composition from about 90 volume percent clay and 10 volume percent fossil hash to 50 volume percent clay and 50 volume percent fossil hash, large foraminifers common.
23	95.57	0.45	96.02	Limestone, clayey, medium-light-gray (N6), massive, micritic, containing abundant fossils and some pyrite.

Bed	Top	Interval thickness (m)	Base	Description
				DDH–18; lat 25°06′43.8″ N., long 68°08′42.6″ E.; elev 60 m—Continued
24	96.02	8.92	104.94	Claystone, silty, from medium-gray (N5) through medium-dark-gray (N4) to greenish-gray (5GY 6/1), calcareous except in basal 1.65 m, where it is brownish-gray (5YR 4/1). Massive, silty to clayey, composed of about half clay and half foraminiferal hash and some large thin-shelled clams; foraminifers are mostly discoid forms. Limestone below.
Sohnari thickness is 50.97 m.				
				UAK–7; lat 25°07′00″ N., long 68°31′15″ E.; elev 12.5 m
1	193.00	1.55	194.55	Limestone, white, rubbly.
				Base of the Meting Limestone
				Top of the Sohnari Formation
2	194.55	0.15	194.70	Clay, calcareous, medium-greenish-gray (5GY 5/1), containing chalky fossils (clams and foraminifers). Fault plane at 30° to axis of hole near base, probably intraformational.
3	194.70	0.70	195.40	Claystone, carbonaceous, olive-gray (5Y 3/2), pyritic, burrowed, containing pyritized plant trash and shell fragments.
4	195.40	1.65	197.05	Most of core lost, ground up at top. Sandstone, calcareous.
5	197.05	7.35	204.40	Sandstone, medium-gray (N5), very fine grained; grains angular, quartz with pyrite and carbonaceous material. Planar-bedded, rooted; silty between 200.38 and 201.35 m, light-olive-gray (5Y 6/1) below 203.6 m.
6	204.40	2.42	206.82	Mudstone, sandy, greenish-gray (5GY 6/1), calcareous, fossiliferous (shell fragments and ostracods); structure destroyed during drilling.
7	206.82	2.63	209.45	Sandstone, medium-gray (N5), interlaminated with shale, carbonaceous and silty, even-laminated, grading to siltstone at 209.45 m.
8	209.45	4.10	213.55	Siltstone, medium-light-gray (N6), massive, rooted, burrowed, medium-greenish-gray (5G 5/1) in glauconitic sandstone in burrows.
9	213.55	2.45	216.00	Siltstone, medium-brownish-gray (5YR 5/1), laminated, rooted, containing pyritic plant trash and some white mica; sandy from 215.3 to 216 m, with siderite nodules, rooted.
10	216.00	0.60	216.60	Coal, removed for analysis.
11	216.60	1.20	217.80	Siltstone, seat earth, medium-gray (N5), rooted, slickensided.
12	217.80	9.35	227.15	Siltstone, medium-dark- and light-gray (N4 and N7), interlaminated with claystone and fine-grained sandstone, even-laminated, burrowed. The rock is carbonaceous and resinous; the sand is quartz, subangular to subrounded, decreasing in abundance downward.
13	227.15	0.65	227.80	Sandstone, light-gray (N7), fine- to medium-grained, subangular to subrounded, laminated with siltstone.
14	227.80	1.00	228.80	Shale, dark-gray (N3), burrowed, rooted, resinous, carbonaceous, containing some white mica.

Supplementary data. Logs of drill holes UAL-13, UAL-2, DDH-18, and UAK-7—Continued

Bed	*Top*	*Interval thickness (m)*	*Base*	*Description*
				UAK-7; lat 25°07′00″ N., long 68°31′15″ E.; elev 12.5 m—Continued
15	228.80	23.65	252.45	Sandstone, medium-light-gray (N6), fine- to medium- grained, poorly sorted, clayey; grains subangular to subrounded, loose to friable, pyritic. Bedding destroyed during drilling. Quartz sand is clean and clear from 252.45 to 253.15 m.
	252.45	0.70	253.15	(Lost.)
16	253.15	11.88	265.03	Claystone, medium-gray (N5), light-bluish-gray (5B 7/1) in top 0.2 m, locally sandy to silty, massive to poorly laminated, burrowed. Small broken fossils concentrated in burrows. More calcareous downward, heavily burrowed in base. Siderite nodules concentrated between 254.34 and 255.30 m, but interval badly disrupted in drilling.
				Base of the Sohnari Formation
				Lakhra Formation
17	265.03	1.77	266.80	Limestone, sandy to clayey, very light gray to light-gray (N8 to N7), calc-siltite, locally pyritic, even-bedded, burrowed, with sharp upper and lower contacts. Richly fossiliferous, but shells are broken and comminuted.
				Top of the Bara Formation
18	266.80	0.60	267.40	Sandstone, dark-greenish-gray to dark-gray (5GY 4/1 to N3), containing fine subrounded grains, poorly sorted, clayey at base, with some carbonaceous fragments.
19	267.40	3.99	271.39	Claystone, from dark-gray (N3) through olive-black (5Y 2/1) to dark-greenish-gray (5GY 4/1), interlaminated with fine-grained sandstone in upper 2 m, locally silty, containing shell fragments in lower part, with some burrows. Locally pyritic.

Sohnari thickness is 70.48 m.

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