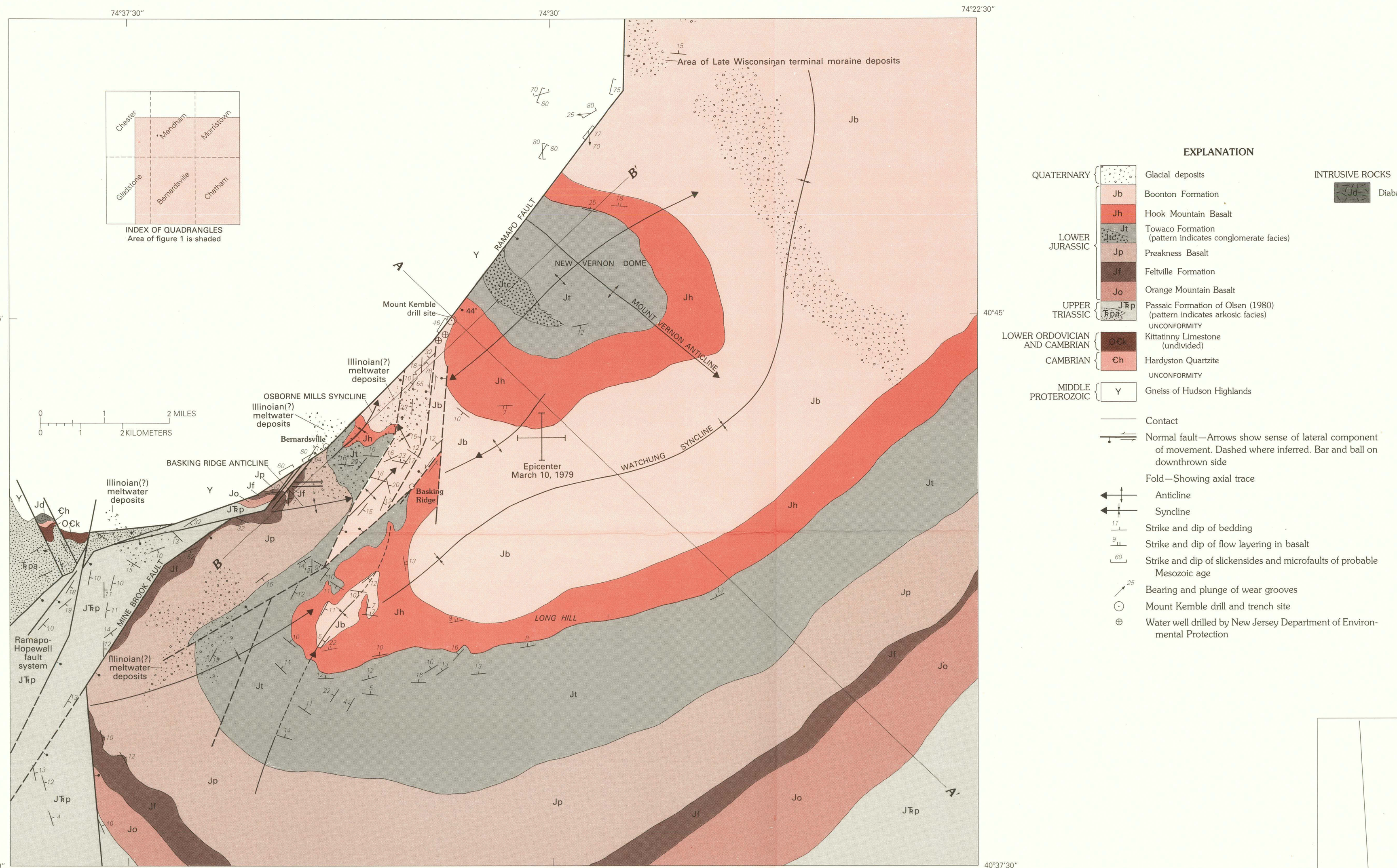


Figure 1A.—Regional geologic map of the southern end of the Watchung syncline in the Newark Basin in New Jersey, showing the location of the Mount Kemble drill site near Bernardsville, N.J.

Geology by H.B. Kümmel (New Jersey Geological Survey, unpub. data), N.M. Ratcliffe (1978, 1979, unpub. data), Olsen (1980), and N.M. Ratcliffe and W.C. Burton (1984, unpub. data)

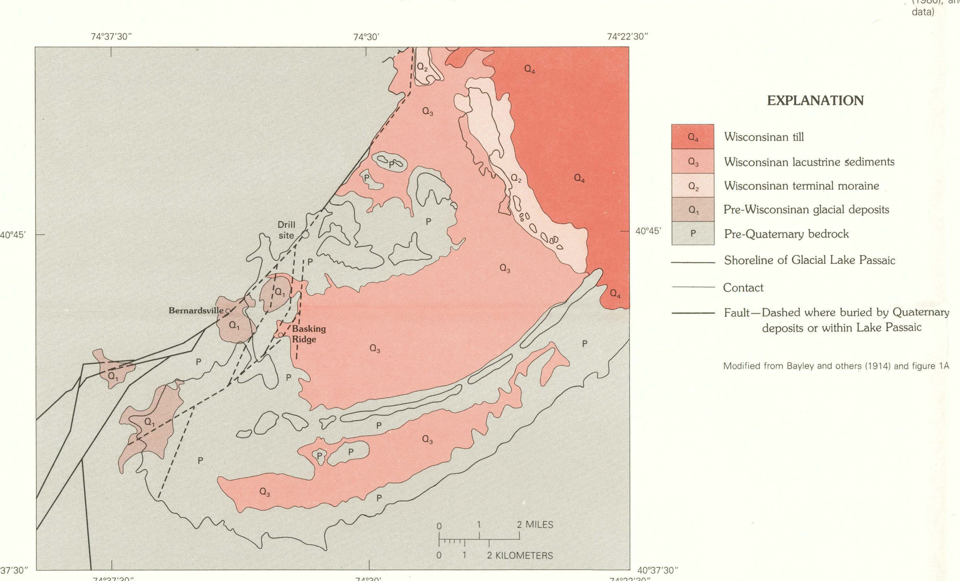
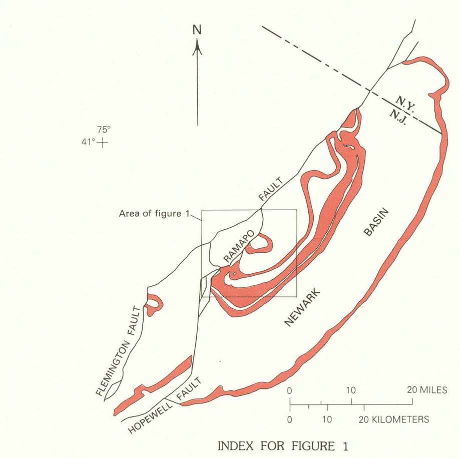


Figure 1B.—Map of Quaternary deposits in the southern end of the Watchung syncline.



INDEX FOR FIGURE 1

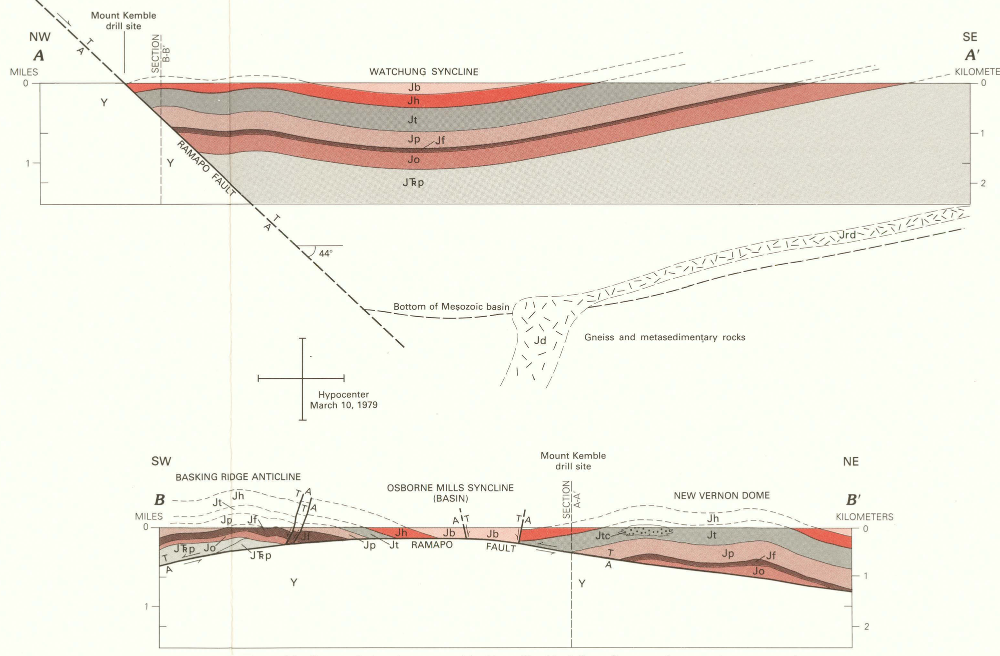


Figure 2.—Cross sections of the Ramapo fault in the vicinity of the Mount Kemble drill site. For an explanation of map units and symbols, see figure 1.

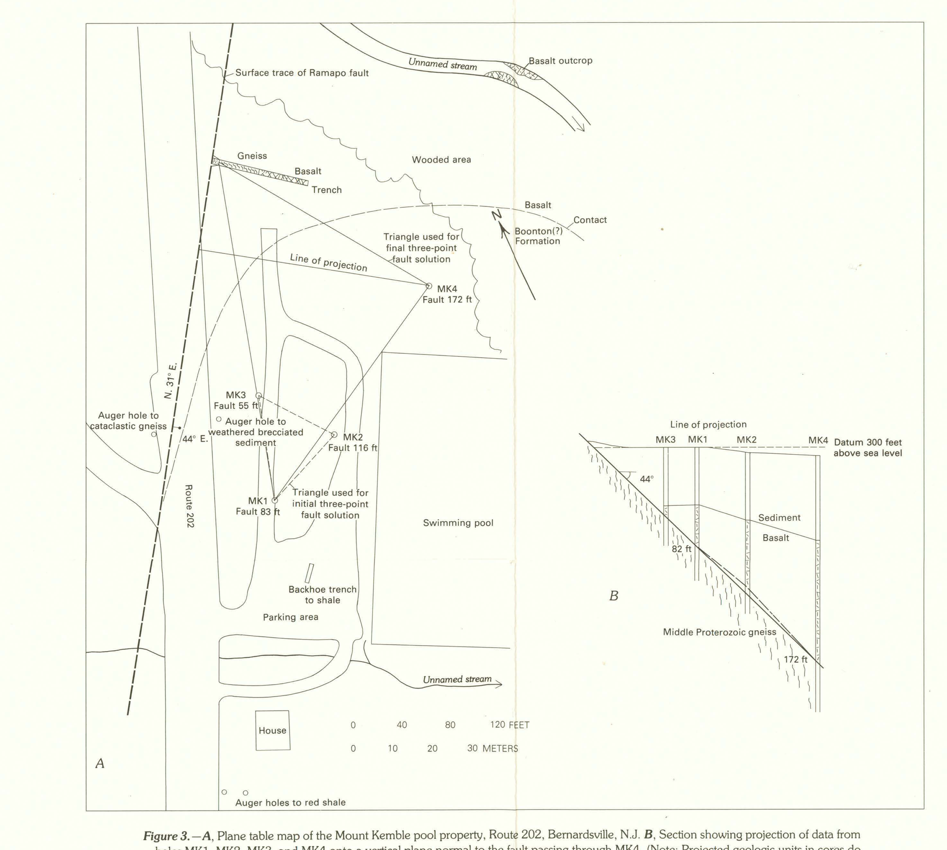


Figure 3.—*A*, Plane table map of the Mount Kemble pool property, Route 202, Bernardsville, N.J. *B*, Section showing projection of data from holes MK1, MK2, MK3, and MK4 onto a vertical plane normal to the fault passing through MK4. (Note: Projected geologic units in cores do not reflect actual geology in line of section; hence, this is not a geologic cross section.)

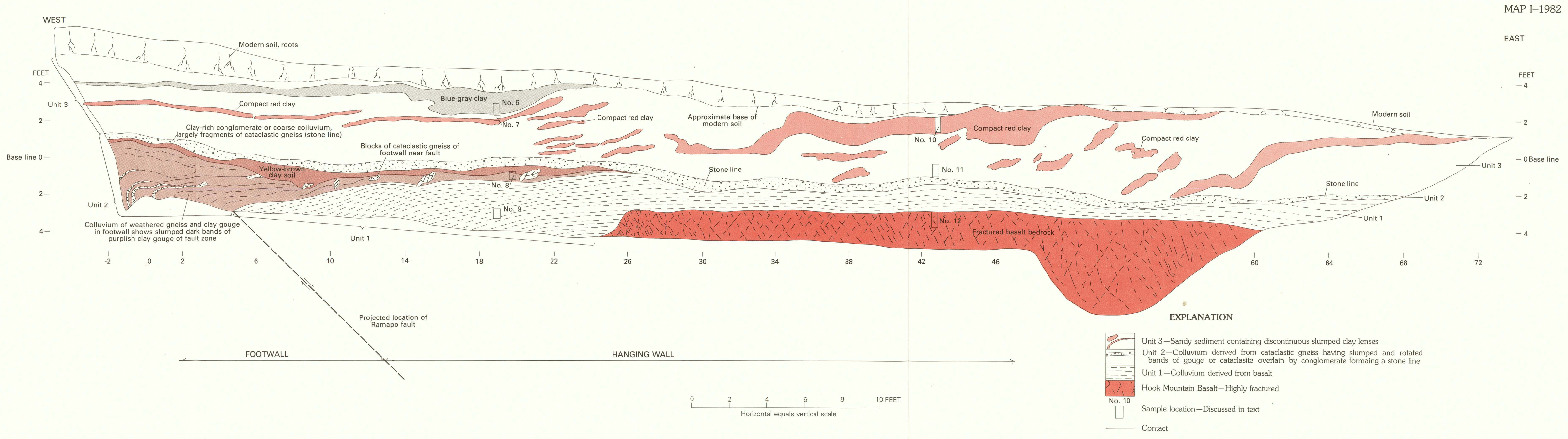


Figure 4.—Schematic diagram of trench in alluvium and clay over the Ramapo fault, Mount Kemble drill site, Route 202, Bernardsville, N.J.

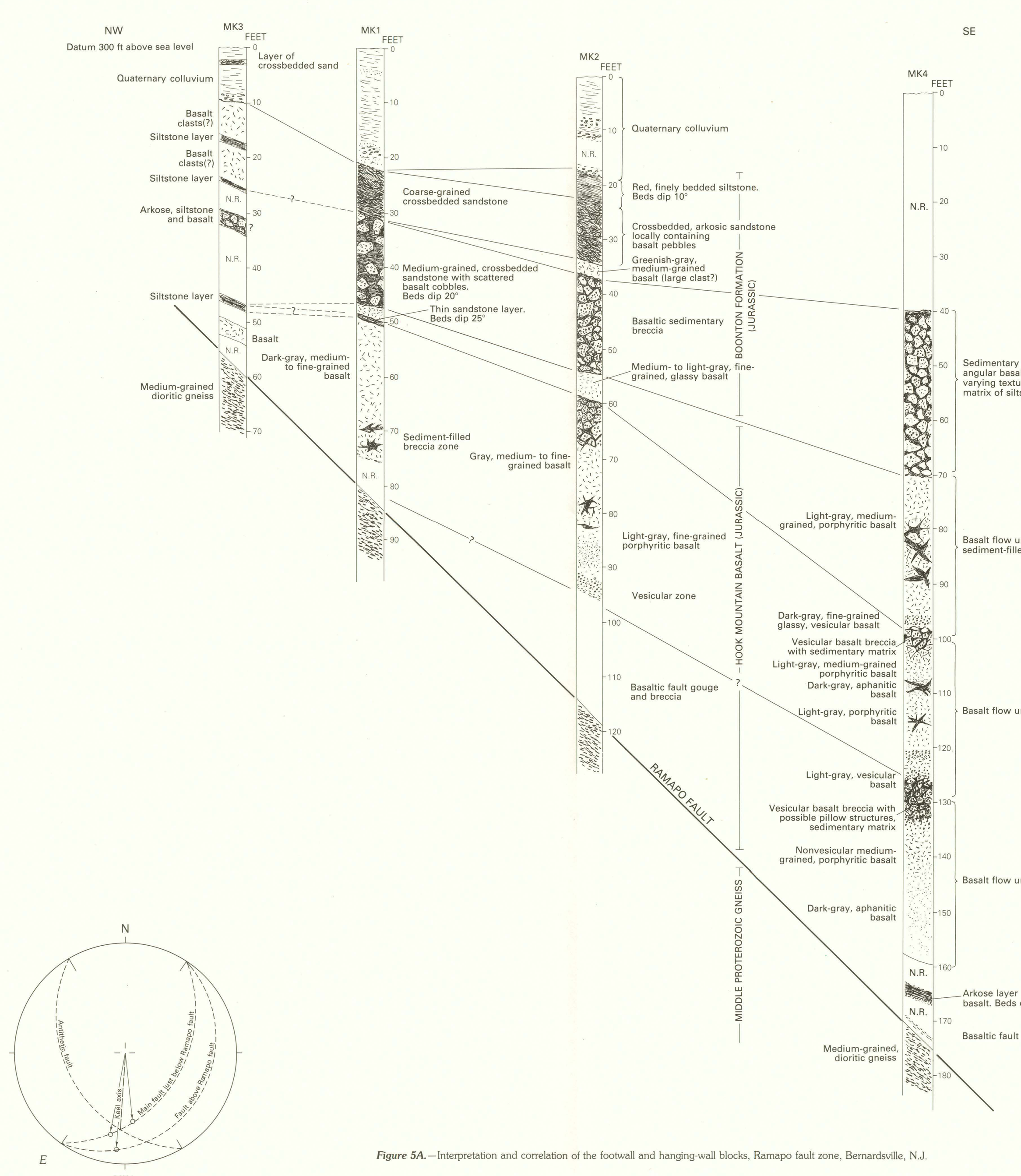


Figure 5A.—Interpretation and correlation of the footwall and hanging-wall blocks, Ramapo fault zone, Bernardsville, N.J.

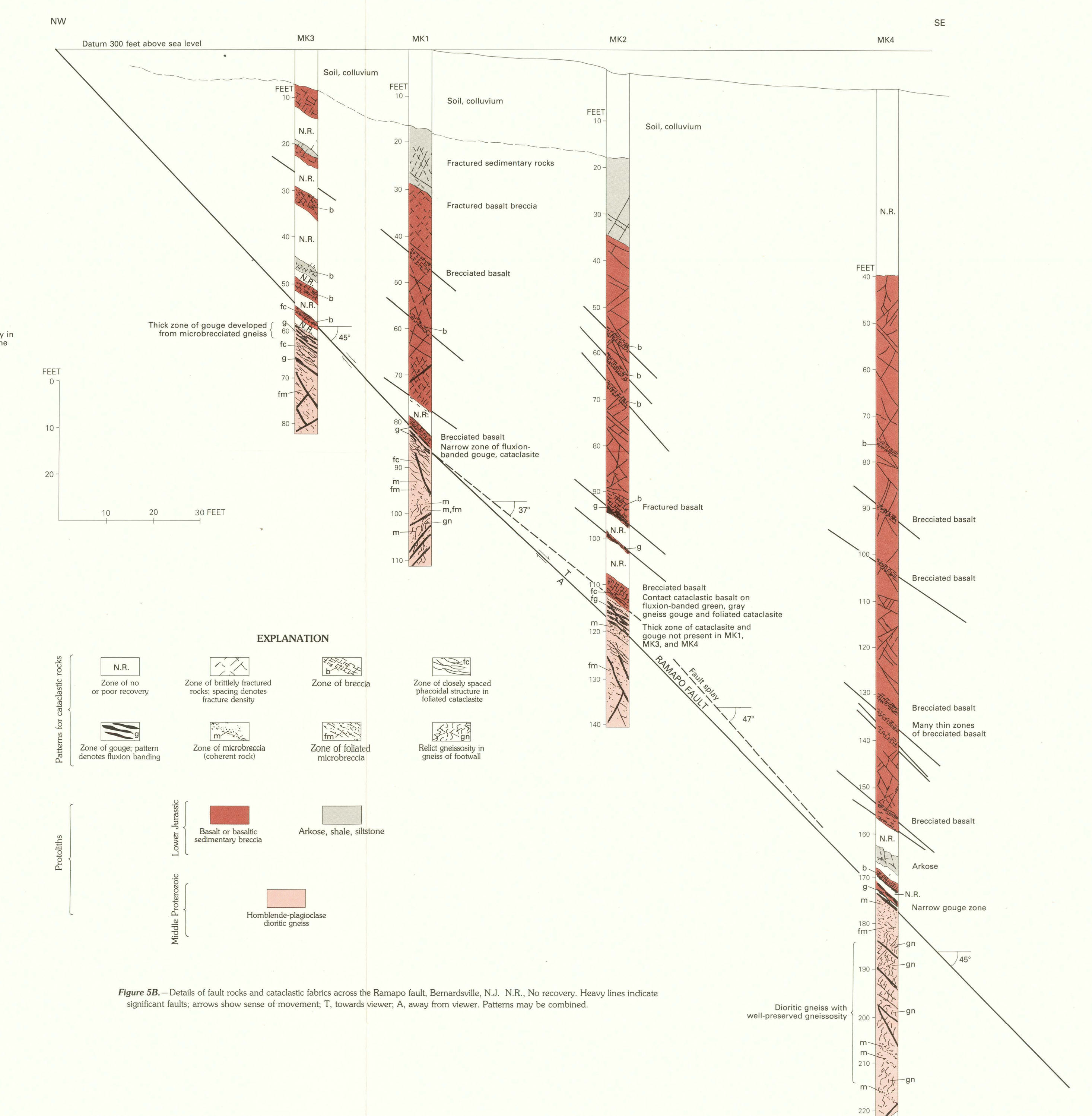


Figure 5B.—Details of fault rocks and cataclastic fabrics across the Ramapo fault, Bernardsville, N.J. N.R., No recovery. Heavy lines indicate significant faults; arrows show sense of movement; T, towards viewer; A, away from viewer. Patterns may be combined.

Figure 6.—Photomicrographs of thin sections of cataclastic gneiss from the footwall block of drill hole MK4 showing increase in cataclasis as fault contact at a depth of 174 ft is approached. All taken in ordinary transmitted light with upward direction towards top of photograph. *A*, Cataclastic dioritic gneiss at 180.4 ft showing a steeply dipping band of cataclasite and brittlely fractured quartz, plagioclase, and hornblende. *B*, Ultrafine-grained, recemented microbreccia at depth of 178.2 ft showing steeply dipping cataclastic fabric and darker layers of recrystallized and altered microbreccia, derived from Middle Proterozoic gneiss. *C*, Ultrafine-grained, well-foliated cataclasite at a depth of 173.3 ft showing well-defined, steeply dipping vein of calcite-chlorite and laumontite cutting cataclastic fabric that dips southeast at about 45° (upper right to lower left of photograph).

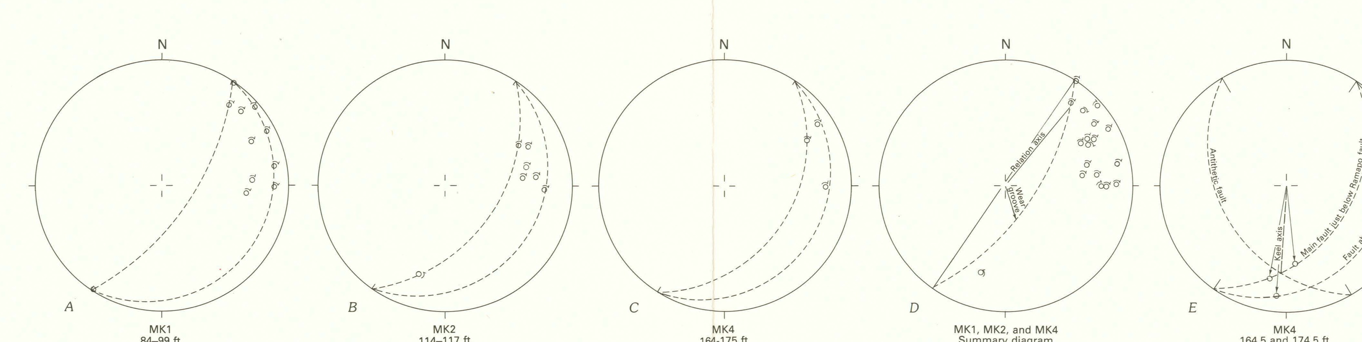


Figure 7.—Stereograms of fault fabrics and wear-groove rotation axes from fault surfaces in MK1, MK2, and MK4 at or near the Ramapo fault. Dashed lines in *A*, *B*, and *C* depict the range of dips of faults in intervals shown. The rotation axis is defined as the position of a line normal to the slickenline or wear groove within the fault plane. The small arc and arrow show the sense of motion on faults. Clockwise indicate a component of normal motion. *A*, Wear-groove rotation axes from MK1 at 84 to 99 ft. *B*, Wear-groove rotation axes from MK2, 114 to 117 ft. *C*, Wear-groove rotation axes from MK4, 164 to 174 ft. *D*, Synoptic diagram of wear-groove rotation axes from MK1, MK2, and MK4 showing one illustration of the relationship of rotation axis to wear-groove lineation in one fault plane. *E*, Geometry of minor normal faults and antithetic faults in relation to wear-groove lineations from MK4 at 164.5 and 174.5 ft. Note how wear-groove lineations cluster about the keel axis defined by the intersection of main and antithetic faults indicating movement is parallel to wedge keel axis. Lower hemisphere, equal-area projection.

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1990

DISCUSSION

INTRODUCTION

The U.S. Geological Survey (USGS) has been conducting a program of rock coring and trenching along the Ramapo fault and other border faults of the Newark basin in New Jersey and New York since 1978. This work was largely funded by the USGS's Reactor Hazards and Earthquake Hazards programs. In these programs, we have been attempting to determine the position and attitude of these poorly exposed faults in order to establish a possible correlation with recent instrumental data which indicates low-level seismicity in the Ramapo seismic zone in and adjacent to the Newark basin. In addition, through study of the physical nature of the gouge and deformation characteristics of the fault zone materials recovered in drill core, we are attempting to evaluate the hypothesis that Mesozoic faults of the Newark basin have been reactivated recently in the present compressive stress field (Aggarwal and Sykes, 1978) to produce the current seismicity. At those localities in which the surface traces of faults can be accurately predicted from the drill data, possible fault disruption of Pleistocene and Holocene sediments was evaluated by trenching of surficial deposits. Previously published reports may be found in Ratcliffe (1980, 1982a), and Burton and Ratcliffe (1985).

This report presents data collected in 1979 and 1983 at a locality near Bernardsville, N. J. along the Ramapo fault. Four continuously cored holes were drilled across the Ramapo fault by the USGS to a maximum depth of 220 ft. Two deeper water wells (maximum depth 480 ft) were drilled by the New Jersey Department of Environmental Protection. The data on fault depth from each of these holes were used to calculate the strike and dip of the fault and its probable surface projection. A trench was dug across the calculated fault trace to examine possible evidence of recent faulting in surficial deposits.

ACKOWLEDGMENTS

Coring of holes MK1, MK2, and MK3 was performed by Warren George, Inc. Hole MK4 was cored by Donald Queen and Robert Steinruck of the U.S. Geological Survey. Scott Robinson assisted in logging of holes MK1, MK2, and MK3, and the two water wells. The cooperation of the New Jersey Department of Environmental Protection in allowing us to log the water wells is greatly appreciated.

REGIONAL GEOLOGIC SETTING

Figure 1 shows a generalized geologic map of the Newark basin adjacent to the Ramapo fault near Bernardsville, N. J. The drill site discussed in this paper is located north of Bernardsville at the old Mount Kemble swimming pool shown on the Bernardsville 7.5-minute quadrangle. The geologic map is modified from that of Olsen (1980), chiefly as a result of our mapping of a 4-km-wide strip along the trace of the Ramapo fault in the Mendham, Bernardsville, and Gladstone quadrangles. Strike and dip data is ours except for some symbols in the core of the Watchung syncline which were taken from the unpublished field sheets of H.B. Kummel in possession of the New Jersey Geologic Survey in Trenton. The stratigraphic nomenclature used is that of Olsen (1980) and the reader is referred to that publication for descriptions of the units. The geologic map differs markedly from older maps of Bayley and others (1914) because of new outcrop data, detailed tracing of units, and Olsen's (1980) identification of fish beds diagnostic of the Feltville and Towaco Formations in the Basking Ridge area. The map resolves some of the obvious inconsistencies in the area between Basking Ridge and Bernardsville shown by Bayley and others (1914).

Major folds and faults

The major structure in the region is the northeast-plunging Watchung syncline that affects all units from the Passaic Formation of Olsen (1980) through the Boonton Formation. Several other small northeast-trending folds are shown, as well as two cross folds that trend northwest at an oblique angle to the border fault. The largest cross fold, the New Vernon anticline, appears to be a dome formed by intersection of northeast and northwest-trending anticlines. These folds are truncated by the Ramapo fault and are older than or synchronous with the faulting.

The Ramapo fault forms the western border of the basin and strikes N. 45° E. and N. 37° E. from Bernardsville north past the northern limb of the New Vernon dome, where it changes abruptly to a north-south orientation. South of Bernardsville, a well-defined border fault extends S. 70° W. into the Gladstone quadrangle where the fault splays out southwestward into a complex of faults shown as the Ramapo-Hopewell fault system on the map. An ancillary splay, the Mine Brook fault, extends from Bernardsville southwest and south along the Watchung syncline and is interpreted to truncate the Orange Mountain Basalt on the nose of the syncline. The angular trace of the Ramapo and associated faults is entirely characteristic of the Jurassic or younger border faults in the northern part of the Newark basin (Ratcliffe, 1980). Additionally, a change in strike along the border fault is accompanied by sympathetic changes in orientations of associated fracture patterns such that one fracture set always is parallel or subparallel to the trace of the fault. At or near changes in strike, ancillary fault splays emanate from the main fault and extend into the basin. The position of faults on figure 1A have been determined on the basis of detailed tracing of fracture zones, identification of faults in outcrop, attitude of bedding, and stratigraphic juxtaposition.

Locally, at the extreme western margin of the map, the contact between the arkosic facies of the Passaic Formation (₸ps) and Middle Proterozoic basement gneiss and Kittatinny Limestone is interpreted as an unconformity rather than a fault. Outcrops of Hardyston Quartzite intruded by diabase are present below the unconformity. The lowland to the south may be underlain by Kittatinny Limestone although no outcrops are present. Immediately west of the map border, in the Gladstone quadrangle, arkosic sandstone, conglomerate, and quartzite of the Passaic(?) Formation rest unconformably on Proterozoic gneiss and Kittatinny Limestone (Ratcliffe, unpub. data).

Jurassic strata on the west limb of the Watchung syncline

The Hook Mountain Basalt forms a prominent continuous ridge from Long Hill, in the core of the Watchung syncline, to Basking Ridge, where the ridge and outcrop of basalt terminate. The correlation of the Hook Mountain Basalt with outcrops at Bernardsville is somewhat problematical because the basalt is not continuous between the two areas. Abundant outcrops of red, gray, and greenish siltstone west of Basking Ridge have been identified as Boonton Formation by Olsen (1980) and the basalt at Bernardsville overlies beds typical of the Towaco Formation. We therefore adopt the correlation of the basalt at Bernardsville (Jh) with the Hook Mountain Basalt. The Hook Mountain Basalt is terminated by faults in the lowland to the west of Basking Ridge which is underlain by a down-faulted block of the Boonton Formation.

The basalt northeast of Bernardsville and the basalt on Long Hill are correlated in the subsurface (fig. 2, section *B-B'*) with the Hook Mountain Basalt which forms the rim of the New Vernon dome. The Mount Kemble drill site is located on the southwest flank of this dome near the contact with the overlying Boonton Formation. The drill cores at Mount Kemble penetrate the upper contact of the Hook Mountain basalt with the overlying Boonton Formation. In this general area, dips are southward off the west or southwest flank of the dome.

A well drilled by the New Jersey Department of Environmental Protection (fig. 1) and logged by us, located 0.5 km south of the Mount Kemble drill site, is sited on sedimentary rocks of the Boonton Formation. Generalized cross sections *A-A'* and *B-B'* (fig. 2) illustrate that the structural repetition of the Hook Mountain Basalt shown on figure 1A results from the fold interference pattern of the Watchung syncline and New Vernon anticline. The changing apparent dip of the Ramapo seen in section *B-B'* (fig. 2) is the result of the change in strike of the fault with respect to the line of section. The minor faults and repetition of units in the area near and south of Bernardsville are based on new mapping of that area. Orange Mountain Basalt, Feltville Formation, Preakness Basalt, Towaco Formation, and Hook Mountain Basalt are present just east of the Ramapo fault in a north-plunging syncline that is complicated by normal faults. This sequence of rock appears to be thinner than the same sequence shown on the east limb of the Watchung syncline (fig. 2).

Age of the folding and faulting

Most of the folding and faulting of the Triassic and Lower Jurassic rocks probably postdated extrusion of the Hook Mountain Basalt and deposition of the Boonton Formation. No evidence from this area requires older deformation, but the unconformable contact of Passaic Formation on the Kittatinny Limestone and older rocks southwest of Bernardsville suggest pre-Passaic-age faulting. The folding has been attributed to fault-related deformation derived from right-oblique normal faulting on the Ramapo fault (Ratcliffe, 1980). Drag-related synclines result from dip-slip motion (Watchung and Osborn Mills synclines) that formed marginally to the fault in the hanging-wall block. Additional northwest and northeast-trending cross folds (New Vernon and Basking Ridge anticlines) formed from the buttressing effects of the footwall against oblique and dip-slip motion of the hanging wall in areas of left-step-over[1] such as the transition from the Hopewell fault into the Ramapo fault.

Block rotations along hidden, northwest-trending, sinistral strike-slip faults splaying off the Ramapo fault were invoked by Van Fossen and others (1986) to explain differences in paleomagnetic data from the Preakness Basalt along the axis of the Watchung syncline and the Orange Mountain Basalt on the east limb of the syncline, where a discrepancy of 32° in magnetic declination remained after unfolding. We could not find any evidence for these faults. Recent information (McIntosh and others, 1985; Prevot and McWilliams, 1986), furthermore, indicates that samples from the Preakness Basalt in the Newark basin and from the equivalent Holyoke Basalt from the Hartford basin yield inherently aberrant Lower Jurassic paleoinclination and azimuthal values when compared to known values for the Lower Jurassic units from the Orange Mountain Basalt to the Hook Mountain Basalt. The complex block rotations proposed by Van Fossen and others (1985) may not be required to explain the paleomagnetic data.

[1]The stepping sense of a fault is defined by the lateral (for example, left or right) step over in a main fault trace as the viewer observes the fault looking along the strike.

Surficial deposits

The upper Quaternary deposits in the Bernardsville area are not extensive, but multiple deposits are preserved. Evidence of two episodes of continental glaciation is preserved in the Bernardsville area. Glacial sediments of probable pre-Wisconsinan age are preserved in four areas (fig. 1*A*,*B*). The late Wisconsinan terminal moraine and associated lacustrine sand and clay units overlie rocks of the Newark basin north and northeast of Bernardsville (figs. 1 and 2) (Bayley and others, 1914). Mineralogy and weathering characteristics led Owens and others (1983) to conclude that the older glacial sediments, exposed near Bernardsville, are pre-Wisconsinan and probably Illinoian in age. Analysis of the clay fraction showed well-developed 14Å dioctahedral vermiculite, developed as a product of deep weathering down to 90 cm below the surface, and an increasing abundance of unaltered 10Å illite from that point downward to 610 cm. 7.5Å halloysite was found in three samples from depths of 90, 300, and 610 cm (Owens and others, 1983).

South of the late Wisconsinan terminal moraine (Q_2), glaciolacustrine silt and clay of glacial Lake Passaic (Q_3) underlies the lowland north of and between the basalts of the Watchung syncline (fig. 1*B*). Reimer (1984) documented as much as 120 ft of late Wisconsinan lacustrine sediment in the basin. No pre-late-Wisconsinan sediment was found. The margin of glacial Lake Passaic as mapped by Bayley and others (1914) overlaps the trace of the Ramapo fault in two areas north of Bernardsville. The Mount Kemble drill site (fig. 1*B*) is both underlain and overlain by glaciolacustrine deposits.

Recent earthquake activity

The epicenter for the March 10, 1979 earthquake of magnitude 2.4 near Bernardsville is shown on figure 1 and figure 2, section *A-A'*. The hypocenter located at 6 km depth is based on data from the Lamont-Doherty Geological Observatory (1980). The lengths of the error bars indicate the standard errors for vertical and horizontal position. No fault plane solution is available for this event. In section *A-A'* (fig. 2), the base of the Triassic section is projected to the Ramapo fault. Assuming the dip of the Ramapo fault does not increase with depth and assuming the depth location of the Bernardsville event is approximately correct at 6 km, this event appears to have occurred within the basement rocks of the footwall block; however, given the high degrees of uncertainty of the depth of the basin and hypocenter, this event could be construed to have occurred on the Ramapo fault. This event is one of the largest instrumentally located earthquakes in the Ramapo seismic zone, an area of anomalously high frequency of activity that is subparallel to the Ramapo fault in New York and New Jersey. Aggarwal and Sykes (1978) attribute some of this activity to reactivation of the Ramapo fault as a present compressional fault. Sixty-one earthquakes in the New York City area, recorded since 1974, show a wide range of both depth and areal distribution. In general, an area of seismicity frames the Newark basin, with events occurring west of the Ramapo fault, north of the basin, in a belt east of the Hudson River, and in a southeast-trending belt east of the Newark basin in New Jersey (Aggarwal and Sykes, 1978).

Shallow, low-magnitude events occur in a belt up to 15 km west of the Newark basin. Higher magnitude and deeper events tend to occur east of the Ramapo fault in New Jersey and in Westchester County, N.Y. The entire Ramapo seismic zone (Ratcliffe, 1980) is about 40 km wide and roughly centered on the Ramapo fault. When the 61 earthquakes are screened for bias resulting from station distribution, only 27 earthquakes remain with Richter magnitudes greater than M_{bLg}=1.5 (Kafka and others, 1985). These events tend to be distributed in two northeast-trending belts: one within 10 km of and subparallel to the Ramapo fault and the other in the New York City area south to the Coastal Plain in New Jersey. These belts are not associated clearly with any single structural feature.

The Bernardsville event on March 10, 1979 of M_{bLg}=2.4 (Kafka and others, 1985) is the fifth largest instrumentally recorded earthquake in the New York City area. Analyses of fault-plane solutions for New York and New Jersey earthquakes indicate that the present-day stress field is compressional although there is disagreement regarding the azimuth of the principal horizontal compressive stress. According to Aggarwal and Sykes (1978), the direction of maximum horizontal compression is northwest to southeast and normal to the strike of the Ramapo fault. Reanalysis of some of their data, analysis of new information (Quittmeyer and others, 1985), and recent hydrofracture experiments (Zoback and others, 1985) suggest an orientation of approximately N. 70° E. to N. 55° E. Reactivation of the Ramapo fault in the present-day stress field is expected to produce either high- to moderately high-angle thrust faulting or oblique-right lateral thrust faulting. The segment of the Ramapo fault near Bernardsville strikes N. 31° E. and dips 44° SE and is suitably oriented for reactivation in a northeasterly directed compressive stress field as a right-oblique thrust fault. No paleostress indicators are known from the New York area and no post-Pleistocene faulting of tectonic origin has been clearly demonstrated at any locality in the Ramapo fault zone or in southeastern New York. Examination of all the exposures of faulted glacial pavement observed by Oliver and others (1970) in southeastern New York and of numerous new localities failed to yield definitive evidence for tectonic displacement. Indeed, each of the localities studied in Dutchess, Columbia, and Putnam Counties, N.Y. have structures that can be attributed to ice wedging of fractured rocks in or near brittle faults rather than to tectonic faulting (Ratcliffe, 1982b). A careful search for similar structures in the Ramapo seismic zone has yielded no clear-cut examples of faulted glacial pavement.

MOUNT KEMBLE SITE INVESTIGATIONS

A program of drilling and trenching was conducted during 1978, 1979, and 1983 to better understand the history of faulting along a section of the Ramapo fault near Mount Kemble (fig. 1).

Four continuously cored NQ- and NX-diameter drill holes were completed on the Mount Kemble pool property (fig. 3). Drill holes MK1, MK2, and MK3 were completed in 1979, and MK4 was drilled in 1983. Recovery was not exceptional because of the highly weathered basalt and breccia encountered at the shallow depths, especially in hole MK3. All four holes encountered rocks of the footwall (Middle Proterozoic gneiss) and hanging wall (Jurassic basalt and sedimentary rock) and good definition of the Ramapo fault position and attitude was obtained (fig. 3). However, the critical fault contact was not recovered in any of these holes.

In 1979, a trench in surficial deposits (fig. 4) was dug across the projected fault trace according to the results of drill holes MK1, MK2, and MK3. The trench exposed a vertical plane containing the footwall gneiss and the hanging wall basalt and sedimentary rock. Quaternary sediments of the Newark basin unconformably overlie the pre-Cenozoic rocks exposed in the trench.

Results of drilling

Core sections of the hanging-wall block consist of variable thicknesses of siltstone, arkose, and basaltic sedimentary breccia above the vesicular to aphanitic Hook Mountain Basalt (fig. 5*A*). The basalt in the cores has a slight variation in texture. In the deepest hole (MK4), the 90 ft of recovered basalt consists of three flow units, each approximately 30 ft thick (fig. 5*A*). The borders of these units, interpreted as flow-top breccias, are marked by brecciation and an increase in vesicularity of the basalt, with fine-grained reddish sediment (mudstone) filling the voids and fissures. The breccia clasts show signs of having been rotated and slightly transported. In each flow unit, zones of fracturing are present in which the blocks have been merely separated and the fractures filled with fine-grained sediment. In all the holes, the basalt is truncated by the fault and the original total thickness could not be determined.

Overlying the basalt in the cores is approximately 15–30 ft of sedimentary breccia or conglomerate composed of angular to subrounded basalt fragments in a reddish matrix of siltstone and sandstone. Transportation and mixing of the clasts in this unit are implied by the juxtaposition of basalt fragments with contrasting textures and degrees of vesicularity. Lenses of sand-sized basalt grains are found in thicker sections of sandstone. In hole MK1, large basalt clasts are less common and the sedimentary unit is dominated by cross-bedded, locally basaltic arkosic sandstone. A thin (2 ft) basalt layer on top of this unit in hole MK2 (fig. 5*A*) is interpreted to be a large boulder in the sediment based on the lack of hornfels in the underlying rock. Poorly recovered zones of basaltic material in MK3 are also tentatively considered to be part of the unit. This unit is assigned to the Boonton Formation because of its stratigraphic position over the Hook Mountain Basalt. The unit may represent a reworked flow-top breccia, or possibly fan material from an adjacent uplifted fault block of basalt.

In holes MK1 and MK2, the conglomeratic unit is overlain by approximately 10 ft of crossbedded arkosic sandstone, presumably also of the Boonton Formation (fig. 5*A*). Basalt clasts are locally abundant, implying a proximal sediment source, although grains of quartzite and gneiss(?), probably from more distal sources, are generally far more common. In hole MK2, this unit is overlain by 5 ft of finely bedded, reddish siltstone, which more closely resembles typical Boonton lithologies known elsewhere.

The character of the lithologies seen in the Mount Kemble drill cores does not agree with earlier field descriptions of the Hook Mountain (Third Watchung) Basalt flow and its contact with the overlying sediments (Faust, 1975; Olsen, 1980), although such descriptions are few due to poor exposure. Thin, repetitive flow units have not been observed in the field, although Kummel (unpub. data) noted pahoehoe structures at the top of the basalt (as noted in Faust, 1975). These structures have not been recognized in the core, but it is nonetheless possible that the basalt in the core consists of toes of small pahoehoe flows. The intraflow sediment-filled fracture zones have likewise not been observed in the field, and their significance is unknown. The base of the Boonton Formation as described by Olsen (1980) is a blocky to well-bedded siltstone with no mention of a basaltic conglomeratic facies or crossbedded sandstone as seen in the core.

Correlation of the hanging-wall units is shown in figure 5*A*. The major units project downdip to the southeast toward hole MK4. This dip is a reversal of the regional southwest dip of the flank of the New Vernon dome and is interpreted as the result of local normal drag folding of the hanging-wall rocks. Because of the inferred continuity of the units in the cross section, no major faults were postulated to cross the line of section in the hanging wall.

Data from nearby water wells

Two water wells were drilled by the New Jersey Department of Environmental Protection in 1979 to the south of the Mount Kemble drill site to assess the possibility of migration of gasoline leaked from service station storage tanks along the Ramapo fault. The wells (fig. 1) were drilled approximately 350 ft and 300 ft east of the Ramapo fault trace. Our exmaination of the cuttings revealed that the wells encountered the fault at 380 ft and 335 ft, respectively. The footwall rock in each is plagioclase-biotite-quartz dioritic gneiss identical to the rock seen in the bottom of the Mount Kemble holes. Basalt directly overlies the fault in both wells. In one well, the upper contact of basalt with overlying red, gray, and brown siltstone of the Boonton Formation was encountered at 200 ft depth. Dips for the fault of 40° to 50° are likely, but the actual distance from the fault trace is uncertain and the uncertainty in dip is about 10°.

Attitude of the Ramapo fault

Due to the unconsolidated nature of the fault gouge and breccia near the fault, recovery of the fault zone was poor in all holes. In each drill core, the top of cataclastic gneiss was chosen to mark the fault plane. In cores MK1, MK2, and MK3, the uncertainty in fault location may be as much as 3 ft. In core MK4, recovery near the fault was somewhat better, and the fault is located accurately to within 1 ft (figs. 5*A*,*B*). From the data in core MK4, MK1, and the trench exposure, we calculate a strike of N. 31° E. and a dip of 44° SE for the Ramapo fault by the three-point solution (fig. 3). In the sections in figure 5, the data from all holes are projected onto a section normal to the calculated strike of the fault. The fault depths from holes MK3 and MK2 agree moderately well on this section, suggesting that the calculated orientation obtained from the larger triangle (fig. 3) generally agrees with that of the smaller triangle (holes MK1, MK2, and MK3). In figure 3, the surface trace of the fault is obtained by projection of the three-point solution to the surface.

Description of the fault zone rocks

Fault rock terminology

The terminology used in this report generally follows that of Higgins (1971). Two elements are critical to classification of the Ramapo fault-zone rocks seen in these cores: the presence or absence of primary cohesion and the presence or absence of fluxion structure. All of the deformation seen in the Mount Kemble cores reflects predominantly cataclastic processes (rock and mineral fracturing, grinding, and grain rotation) with brittle deformation of plagioclase, quartz, hornblende, and potash feldspar. Nonetheless, some of the fault-zone rocks, especially in the footwall block, exhibit a weak to well-defined fluxion banding which is further accentuated by growth of lepidoblastic chlorite and fine-grained sericite to produce a mylonite-like foliation. The terminology of Higgins (1971) cannot be strictly applied to these rocks. Coherent rocks possessing a weak to strong foliation and fluxion structure are here termed foliated microbreccia or foliated cataclasite. Locally, zones of cataclasis in basalt or in the gneiss of the cores are composed of ultrafine-grained material with a primary cohesion. This material is termed ultracataclasite. Rocks without primary cohesion are termed breccia or gouge, after Higgins (1971), except that some gouge may be well banded and possess a crude fluxion structure (fluxion-banded gouge).

Because grain refinement is solely by cataclastic processes, the terms "mylonite" or "ultramylonite" are not used. However, the sericite- and chlorite-rich zones in the footwall block resemble ultramylonite in gross appearance.

Description and distribution of the fault zone rocks

In each of the cores (fig. 5*B*), the general character and distribution of cataclastic rocks is similar, although not identical. Rocks of the hanging-wall block are characteristically more highly fractured and less well indurated than rocks of the footwall block and comprise a thicker zone of gouge and breccia. *Fault breccia* is confined to the hanging-wall block and is common in zones 10–15 ft above the fault. The breccia consists of rotated fragments of scaly, chlorite-coated basalt having nonoriented fabric. The breccia has been produced by late fault disruption of previously formed chloritic cataclasite or microbreccia. These zones were poorly preserved in the Mount Kemble cores, probably because of the shallow depth of drill penetration and weathered state of the zones. In cores from other sites drilled along Mesozoic faults (Ratcliffe, 1982a; Burton and Ratcliffe, 1985), the zone of cataclasis above the fault is better preserved and represented by well-foliated, banded gouge and phacoidally sheared cataclastic basalt or fanglomerate.

Narrow zones of *microbreccia* and *cataclasite* are found throughout both the footwall and hanging-wall rocks. In thin section, the microbreccia or cataclasite is cemented by chlorite, sericite, and veins of calcite. Throughout the footwall block, significant zones of aphanitic, apparently structureless microbreccia occur, but the thickness of these zones varies from core to core.

True *fault gouge* is restricted to a narrow zone approximately 5 ft above and below the main fault in each core. The gouge consists of dark-gray-green, basalt-derived gouge with a weakly banded structure in the hanging-wall block and a gray to light-greenish-gray, well-banded gouge derived from rocks of the footwall block. Porphyroclasts in both types of gouge are coherent, silicified cataclasite and (or) microbreccia of an earlier stage of fault zone development.

Cataclastic rocks of the footwall include unconsolidated gouge or fluxion-banded gouge for several inches or feet below the fault. At distances of more than 1 ft below the fault, the cataclastic gneiss is semicoherent cataclastic rock. Within 1–2 ft of the fault, coherent chlorite-calcite-cemented microbreccia and foliated cataclasite are conspicuous. Therefore, there is a marked discrepancy in degree of induration of fault zone materials between the hanging-wall and footwall blocks. Also in the footwall block, a contrast in dip angle can be seen between earlier, more coherent fault materials and later, more steeply dipping crosscutting brittle features. For example, in hole MK4, fluxion-banding in the semiconsolidated cataclasite below the fault is much more gently dipping (10° to 15° SE) than the cataclastic fabric in adjacent microbreccia and the late steep fractures in the cataclasite, which dip 45° to 68° SE.

Mineralization of pyrite, calcite, and laumontite(?) has occurred both prior to and after the latest episode of movement along the fault, with some mineralization postdating formation of all catalastic materials. In hole MK4, for instance, euhedral crystals of pyrite are present in gray, banded gouge immediately beneath the main fault.

Petrographic descriptions

Samples of coherent cataclastic gneiss from the bottom of the core from Mount Kemble (MK4 at 180.4, 178.2, and 173.3 ft) (see fig. 6) show excellent and complete progression of alteration as the fault is approached. The sample from 180.4 ft depth contains relict plagioclase, brown hornblende, and diopside in an equigranular texture characteristic of undeformed Middle Proterozoic dioritic gneiss. Shear zones and extensional fractures crosscut the gneiss, but the original fabric and mineralogy are only partially altered. Hornblende is replaced along cracks by colorless amphibole and diopside is altered to green, iron-rich chlorite. Plagioclase shows no obvious alteration but is fractured, as are all the mineral constituents. Abundant disseminated pyrite is found throughout. Sample 178.2 is a banded cataclasite or microbreccia that consists of bands of ultrafine-grained silicified microbreccia alternating with dark, fine-grained layers of material that resemble devitrified pseudotachylyte. Felted crystals of feldspar and chlorite form distinct radial patterns in an irresolvable matrix. No relict Proterozoic minerals remain in this rock. Sample 173.3 is also ultrafine-grained, well-banded microbreccia and weakly foliated cataclasite crosscut by veins of pure chlorite and calcite-laumontite-chlorite. A crude lamination subparallel to the overlying fault surface is preserved.

From 174 ft depth up to the probable fault contact in hole MK4, the cataclasite and microbreccia is pulverized to a green-gray gouge and foliated cataclasite. No thin sections were attempted of this material.

Thin section examination of the footwall rocks reveals that grain refinement was entirely by cataclastic processes. Extensive mineralization by quartz, calcite-chlorite-laumontite(?) and pyrite has resulted in a coherent silicified or calcite-cemented microbreccia. Locally, zones resembling pseudotachylyte are present, but low-temperature replacement of microbreccia cannot be ruled out for these zones because no glassy or vesicular material is preserved. There is no evidence in any of the cores of either ductile deformation or of mylonitic rocks in the strictest sense. This site differs markedly from some cores of the Riverdale, N.J. site (Ratcliffe, 1980) where footwall rocks contain excellent phyllonite with greenschist mineralogy and ductile deformation fabrics. At the Riverdale site (Ratcliffe, 1980), the phyllonite is interpreted as an Ordovician mylonitic rock formed in a regionally important set of metamorphic shear zones.

Sense of (fault) movement from small-scale structures

Microfault displacements visible in the core are overwhelmingly of a normal sense, with abundant accompanying evidence of dilation and vein injection. Numerous zones of gouge with rotated and subrounded porphyroclasts are present and these gouge zones contain subtle wear grooves on fault surfaces. Fault surfaces associated with gouge zones within 5 ft of the main fault and in foliated cataclasite have rather consistent wear groove orientations for MK1, MK2, and MK4. Preservation of material near the fault was poor in MK3, and measurement of wear grooves was not possible. The wear-groove data are shown in stereograms (fig. 7*A-D*). In these diagrams, the dip range of fault planes on which the wear grooves were measured is indicated. The strike is assumed to be parallel to the main fault, although this probably is not strictly true. The circles plotted are normal to the wear grooves within the fault plane (see fig. 7*D*). The circles, therefore, are rotation axes, and the arrows indicate the rotation sense around each axis. As shown in the synoptic diagram (fig. 7*D*), the rotation associated with the gouge or foliated cataclasite is largely right-oblique normal sense of motion on faults dipping 15° to 60° SE.

Locally in the core, small west-dipping, antithetic faults are seen to curve downward to join east-dipping master faults to define wedgelike pieces of fault-bounded rock with south-plunging keels (fig. 7*E*). Wear grooves on the master faults associated with these wedges plunge in a generally southerly direction parallel to the intersection of the master and antithetic faults. One or both faults may be coated with calcite, laumontite, and (or) pyrite, suggesting dilation. These small-scale features suggest that bulk strain within the deforming cataclasite was subjected to a general south or southeastward extension, consistent with right-oblique normal fault movement on the Ramapo fault.

Commonly within the fluxion-banded gouge near the fault, older banded gouge dips at very shallow angles (10° to 15°) to the southeast, but is invariably faulted by steeper, more sharply defined faults dipping 60° to 35° SE, as mentioned above. This observation suggests that the cataclasite-gouge complex evolved through time by rotation of early-forming moderately steep faults into shallow 30° to 10° surfaces that were abandoned in favor of, and truncated by, more steeply dipping fault surfaces which merge downward with the main fault. The wear-groove data from both shallow and steep surfaces agrees in general sense of rotation, although the range of variation appears greater for the shallow, more evolved fault surfaces.

Summary of movement history

The fault-zone rocks from the Mount Kemble cores clearly represent a suite of materials formed during repeated movements and episodes of mineralization. Silicified microbreccia of the footwall block, foliated cataclasite, and weakly cemented fluxion-banded gouge are all crosscut by zones of later brittle fracture and gouge. Porphyroclasts of coherent, silicified, early-forming microbreccia occur in the gouge near the fault. The gouge zone is composite, having crosscutting zones of cataclasite. Pyrite and calcite-mineralized microbreccia is crushed and ground down to fine gouge, which also contains veins of calcite with no evidence of cataclasis. Calcite-laumontite veins intruded between dilated shear surfaces have been subsequently faulted and reduced to gouge by reactivation of older fault surfaces. Despite these diverse fault features and the evidence of repeated movement, the overall mineralogy of the veins and the cataclastic rocks and the consistency of fault movement (to the extent studied) all suggest protracted movement in one stress and geothermal regime.

Faulting postdates the Early Jurassic and is associated with minimum displacements of at least 0.5 km, which is the maximum thickness of the Boonton Formation preserved above the Hook Mountain Basalt in the Watchung syncline. Assuming that post-Mesozoic erosion has removed approximately 2 km of material (Pratt and others, 1985), a maximum depth of burial at the time of fault formation is approximately 2.5 km.

There is no evidence in the core that would require reactivation of the fault by reverse movement, although the incomplete recovery within the zones of extensive gouge precludes resolution of this problem. The fault fabrics are consistent with right-oblique and normal faulting under conditions of no higher metamorphic grade than zeolite facies. The low grade of the vein mineralization and the completely brittle deformation exhibited by all minerals suggest shallow-level faulting between depths of 0.5 to about 4 km.

Although the actual fault contact is marked by development of unconsolidated gouge or breccia, the mineralization of chlorite, calcite, pyrite, and laumontite(?) appear to have at least locally postdated formation of the gouge. These same minerals fill extension cracks within the more coherent microbreccia of the hanging-wall block and, therefore, we conclude that the gouge and breccia zones developed along the fault surface do not represent a period of faulting distinctly younger than the extension, mineralization, and dilation veining seen in the cores. No veins of any kind were discovered within the overlying colluvium or saprolite of the trench. From these data, we conclude that the fault materials were formed during normal or oblique-normal faulting at shallow depths in an extensional tectonic regime in the Jurassic (Sinemurian or slightly younger).

Results of trenching across fault zone

A 74-ft-long trench about 10 ft deep was dug across the projected trace of the Ramapo fault determined by the three-point solution following completion of holes MK1, MK2, and MK3 (fig. 3). The trench exposed a 6-ft vertical section of Quaternary sediments that comprise three stratigraphic units (fig. 4).

Description of deposits in trench

The excavation revealed the following stratigraphy (fig. 4):

Unit 1.—This unit is a fine sandy to cobble colluvium derived from weathered basalt. The weathered basalt clasts and sand matrix are brown to slightly reddish brown. The colluvium is a matrix-supported, poorly sorted sediment; clasts are included in a predominantly fine sandy to clayey matrix. Grain size varies from very coarse cobbles to clay, but is predominantly fine sand. The unit thickens to the west into a depression along the trace of the fault (fig. 4) (possibly a stream valley). The source rock, highly fractured and weathered basaltic bedrock, was encountered in the base of the eastern part of the trench. Silt-clay matrix of the weathered basalt colluvium (fig. 4, sample 9) shows abundant plagioclase feldspar, minor pyroxene, and abundant smectite clay by X-ray diffraction analysis. The clay is probably a product of alteration of the pyroxene. No quartz or other allochthonous phases were identified. The colluvium is more weathered than the in situ basalt as indicated by a higher ratio of smectite to plagioclase. The absence of quartz in the colluvium indicates that unit 1 is distinct from overlying units 2 and 3 and that unit 1 is not glacially or fluvially derived.

Unit 2.—This unit includes coarse colluvium and slumped, banded, clayey gouge derived from weathered Middle Proterozoic gneiss and gneissic fault gouge, respectively. Colors are gray to purple for the gouge and yellowish brown for the colluvium. The colluvium thins to the east and overlies unit 1. Grain size varies from clay to coarse cobbles. Analysis by X-ray diffraction of the weathered colluvium (fig. 4, sample 8) shows plagioclase, quartz, hornblende, and a smectite clay. Clay-rich samples exhibit a strong smectite peak. The clay is probably a product of hornblende alteration. The upper 20 cm of unit 2 contains a stone line consisting of abundant subangular to subrounded clasts of dioritic gneiss in a clay-rich matrix (fig. 4). The stone line most likely records a period of land-surface stability, but only limited pedogenesis, and serves as a stratigraphic marker between unit 2 and unit 3.

Unit 3.—This unit is a massive, brown sand with clay lenses. Most of the clay lenses, as much as 2 ft thick and 30 ft long, are reddish in color, but the uppermost lenses on the western side of the trench are blue-gray. X-ray diffraction analysis (fig. 4, samples 6, 7, 10, 11) shows that the sediment is of mixed origin. The unit contains abundant quartz, minor plagioclase feldspar, mica, and smectite clay. X-ray diffraction of the silt and clay in the clay lenses reveals chiefly quartz, as well as plagioclase feldspar and smectite clay. Absence of hornblende or pyroxene suggests that this material is not derived from the underlying deposits. The red color suggests that this clay was derived from Triassic-Jurassic red beds, transported glacially or fluvially to the trench site. Blue-gray clay near the top of the west end of the trench may have a different provenance or may have lost its red color due to iron reduction.

A weakly developed brown soil covers all the units. Soil development and rooting are deeper on the west side of the trench. The blue-gray clay may be related to soil development by gleying and iron reduction.

Age of trench deposits

The three units exposed in the trench contain abundant plagioclase feldspar, indicating that they have not been intensely weathered. They probably were deposited in the middle or late Pleistocene. The quartz-free mineralogy of the colluvium of unit 1 contrasts with the glacial sediments of probable Illinoian age that contain abundant quartz (Owens and others, 1983). Units 1 and 2 contain different silt- to clay-sized minerals than glacial sediments of probable Illinoian age deposited near Bernardsville (Owens and others, 1983), about 3 mi to the southwest.

Units 1 and 2 contain apparently autochthonous smectite-clay weathering products, and both contain plagioclase and nonweathered ferrosilicates. In contrast, silt- to clay-sized minerals in the Illinoian(?) glacial beds at Bernardsville include detrital kaolinite and illite, and dioctahedral vermiculite as an apparent weathering product (Owens and others, 1983).

The sand-sized fraction in the beds at Bernardsville contains plagioclase and labile heavy minerals. The original differences of composition between units 1 and 2 at Mount Kemble and the glacial beds at Bernardsville thus preclude a definitive relative age assignment of the Mount Kemble units. The thickness of the basalt colluvium, unit 1, and the thoroughly saprolitized nature of the slumped gneiss colluvium and gouge however, indicate an extensive period of subaerial weathering and slope transport. The overlying stone line and related yellow-brown pedogenic clay are evidence of additional slope erosional and pedogenic processes. The basalt colluvium possibly is at least as old as middle Pleistocene as defined by Fullerton (1986) (perhaps older than 200 ka). The timing of slope movement and slumping of the saprolitized gouge is likewise speculative; these events and the development of the pedogenic horizon and stone line may be as young as middle Wisconsinan (30 ka) (Fullerton, 1986).

Alternatively, if Illinoian glaciation stripped all the regolith from the Mount Kemble area and deposited allochthonous material near Bernardsville (Owens and others, 1983), then any locally derived colluvial regolith here could, as the weathering characteristics suggest, be mostly post-Illinoian in age.

The provenance and specific depositional environment of unit 3 is uncertain, but the lack of extensive soil development at the exposed surface of this unit indicates that it is no older than late Wisconsinan in age. Late Wisconsinan sandy sediments within the Lake Passaic basin exhibit cambic to slightly argillic B-horizons. The pedogenic alteration observed in unit 3 is less intense than that observed in late Wisconsinan sandy sediments of the Newark basin.

Because there is no evidence for late Wisconsinan till this far south of the late Wisconsinan terminal moraine, unit 3 is not an ice-marginal deposit (Bayley and others, 1914). The presence of red clay derived from Triassic-Jurassic strata indicates, however, that this deposit was not a local colluvium and was most likely transported some distance by water. The trench site is on a sloping colluvial surface that has been incised several meters by nearby Primrose Brook (fig. 3). Modern floodplain alluvium is more than 2 m below the trenched surface. The sediment in unit 3 is mineralogically complex relative to the older colluvial units and its stratification and sorting suggest lacustrine deposition. The discontinuous clay beds in the sandier matrix indicate periods of slack or quiet water in weak currents transporting suspended sediment. These silt and clay beds, therefore, probably are disrupted lacustrine deposits that correlate with glacial Lake Passaic sediments; this supports the evidence presented by Salisbury (Bayley and others, 1914) that the Lake Passaic shoreline was higher than the elevation at the trench site. The sediments in unit 3 do not exhibit characteristics of the varved lacustrine deposits documented by Reimer (1984) and notably lack rhythmites. They do not contain organic-rich beds and are therefore unlikely to be Holocene fluvial deposits. Despite the uncertainty in the origin of unit 3, the deposit is correlated with glacial Lake Passaic of late Wisconsinan age.

The succession of deposits in the trench is reasonable considering the long period between pre-Illinoian or Illinoian glaciation and Wisconsinan flooding of the basin by Lake Passaic. Sufficient time elapsed during one or two interglacials for rock weathering and colluvial transport to occur. Basalt is more easily weathered than crystalline rock due to its open jointing and its content of labile minerals. Thus, weathered basalt and colluvium derived from weathered basalt are expectable as the initially deposited local regolith. Following a longer period of weathering, apparently enough regolith accumulated on the crystalline rocks to produce a mobile colluvium which covered the basalt colluvium. When colluvial transport ceased, soil formation became an active process. The period of deposition of units 1 and 2 and the pedogenesis seen in the Mount Kemble trench could have occupied much of pre-late Wisconsinan time from roughly 130 to 20 ka; therefore, the deposits are not tightly constrained in time.

A cooler periglacial climate may have facilitated the formation of these deposits, but no periglacial congeliturbation or wedge structures such as those documented by Washburn (1980) were observed.

Structure of trench deposits

The stratigraphy and structure in the trench site show no evidence of late Quaternary movement on the Ramapo fault. The contacts between units 1, 2, and 3 appear to be sedimentary in origin and there is no evidence of tectonic deformation of these contacts, as discussed below. No evidence was observed for a tectonic involvement in the deposition of these sedimentary units. The simplest interpretation of the multiple colluvial units is that they were slope deposits graded to different topographic lows (for example, stream valleys).

At the extreme west end of the cut, a distinctively banded saprolite derived from gneissic gouge was encountered as part of unit 2 (fig. 4). Bands of cataclastic rock and clay-rich gouge dip steeply west or are overturned to the east at the base of the cut. This same gouge is slumped downslope (southeastward) over a dark-brownish basaltic colluvium of unit 1. The stone line at the top of unit 2 shows little evidence of downslope slumping and appears undeformed by soil creep. The contact of the gneiss gouge colluvium of unit 2 and the basalt-derived colluvium of unit 1 in the floor of the trench is shown on figure 4 to mark the probable surface trace of the Ramapo fault. In figure 3, this position is used to locate the surface trace of the Ramapo fault.

The massive sand of unit 3 contains beds and lenses of dark-red, compact clay which are strongly deformed into overturned folds which have a general west over east (high over low) sense of displacement rotation and west-dipping disarticulated limbs (fig. 4). An upper blue-gray, possibly reduced clay zone at the west end of the trench shows similar movement sense. These structures are probably related to slope movement and soil creep.

The wall of the trench was examined carefully for signs of faults, zones of rotated clasts, or other indications of fault-related disruption. None was found. None of the slickensided surfaces in the cataclastic basalt were found to penetrate the overlying basalt-derived colluvium. The only faults discovered were those required by the apparent downslope, soil-creep movement displayed in unit 3.

From these observations, we conclude that reactivation movement along the Ramapo fault after slumping of the saprolite is, if present, not of sufficient displacement to be recognized in this exposure.

Fractures in bedrock in the trench

Strike and dip measurements of the fractures in the Hook Mountain Basalt exposed in the trench (between the 26-ft and 58-ft marks) reveal patterns in azimuth or dip not readily correlated with the Ramapo fault. Well-developed fractures dip 70° to 80° either east or west and strike approximately north. Another set trends N. 70° W. and N. 70° E. with steep to moderate dips either northeast or southeast. Both sets are approximately equally abundant. Only a minor number of fracture surfaces, near the 48-ft and 50-ft marks, are northeast-striking and dip 40° to 60° southeast, subparallel to the main fault.

Assessment of recent movement and minimum age of faulting

Our analysis of the trenched deposits directly overlying the fault trace suggests that no fault activity has disrupted the surficial deposits. Deformation structures seen in the trench are consistent with downhill creep of sediments of unit 3. Although we have no way of accurately determining the age of the colluvium (units 1 and 2) seen in the trench, we believe that these are most likely middle Pleistocene or younger. All faulting seen in the bedrock, therefore, must be pre-Wisconsinan and may be older.

Implications for modern seismicity

None of our results provide indications of reactivation of the Ramapo fault as a thrust fault in the present-day compressive stress field. The available evidence suggests that the cataclastic features seen in the cores are largely dilational in origin, as indicated by abundant fracture filling of faults. The wear grooves on southeast-dipping faults which plunge to the southwest are not consistent with right-oblique thrust motion nor with pure thrust faulting predicted from the two possible orientations of the modern principal compressive stress, NE-SW or SE-NW.

From these data, and from the trench information, we conclude that present-day seismicity, if controlled by reactivation of the Ramapo fault, has not propagated to the surface or has a sufficiently low rate of recurrence that even cummulative offsets are not detectable at the surface.

REFERENCES CITED

Aggarwal, Y.P., and Sykes, L.R., 1978, Earthquakes, faults, and nuclear power plants in southern New York and northern New Jersey: Science, v. 200, no. 4340, p. 425–429.
Bayley, W.S., Salisbury, R.D., and Kümmel, H.B., 1914, Raritan folio, New Jersey: U.S. Geological Survey, Geologic Atlas of the United States, folio 191, 233 p., 5 maps, scale 1:125,000.
Burton, W.C., and Ratcliffe, N.M., 1985, Attitude, movement history, and structure of cataclastic rocks of the Flemington fault—Results of core drilling near Oldwick, New Jersey: U.S. Geological Survey Miscellaneous Field Studies Map MF-1781.
Faust, G.T., 1975, A review and interpretation of the geologic setting of the Watchung basalt flows, New Jersey: U.S. Geological Survey Professional Paper 864-A, p. A1-A42.
Fullerton, D.S., 1986, Stratigraphy and correlation of glacial deposits from Indiana to New York and New Jersey, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., Quaternary glaciations in the northern hemisphere; a report of the International Geological Correlation Program, Project 24: Oxford, Pergamon Press, p. 23–37.
Higgins, M.W., 1971, Cataclastic rocks: U.S. Geological Survey Professional Paper 687, 97 p.
Kafka, A.L., Schlesinger-Miller, E.A., Barstow, N.L., 1985, Earthquake activity in the greater New York City area; magnitudes, seismicity, and geologic structures: Bulletin of the Seismological Society of America, v. 75, no. 5, p. 1285-1300.
Lamont-Doherty Geological Observatory, 1980, Regional seismicity bulletin: Palisades, N.Y., Columbia University, [pagination unknown].
McIntosh, W.C., Hargraves, R.B., West, C.L., 1985, Paleomagnetism and oxide mineralogy of Upper Triassic to Lower Jurassic red beds and basalts in the Newark basin: Geological Society of America Bulletin, v. 96, no. 4, p. 463-480.
Oliver, Jack, Johnson, Tracy, and Dorman, James, 1970, Postglacial faulting and seismicity in New York and Quebec, *in* Symposium on recent crustal movements, Ottawa, Canada, 1969, Papers: Canadian Journal of Earth Sciences, v. 7, no. 2, pt. 2, p. 579-590.
Olsen, P.E., 1980, Triassic and Jurassic formations of the Newark basin, *in* Manspeizer, Warren, ed., Field studies of New Jersey geology and guide to field trips, 52nd annual meeting of the New York State Geological Association: Newark, N.J., Rutgers University, p. 2-39.
Owens, J.P., Hess, M.M., Denny, C.S., and Dwornik, E.J., 1983, Postdepositional alteration of surface and near-surface minerals in selected coastal plain formations of the Middle Atlantic States: U.S. Geological Survey Professional Paper 1067-F, p. F1-F45
Pratt, L.M., Vuletich, A.K., and Dews, T.A., 1985, Geochemical and isotopic characterization of organic matter in rocks of the Newark Supergroup, *in* Robinson, G.P. and Froelich, A.J., eds., Proceedings of the second U.S. Geological Survey workshop on early Mesozoic basins of the Eastern United States: U.S. Geological Survey Circular 946, p. 74–78
Prevot, M., and McWilliams, M., 1986, Paleomagnetic correlation of Early Jurassic volcanic units of the Newark Supergroup [abs.]: EOS, (Transactions, American Geophysical Union), v. 67, no. 44, p. 929.
Quittmeyer, R.C., Statton, C.T., Mrotek, K.A., and Houlday, M., 1985, Possible implications of recent microearthquakes in southern New York State: Earthquake Notes, v. 56, no. 2, p. 35-42.
Ratcliffe, N.M., 1980, Brittle faults (Ramapo fault) and phyllonitic ductile shear zones in basement rocks of the Ramapo seismic zone, New York and New Jersey, and their relationship to current seismicity, *in* Manspeizer, Warren, ed., Field studies of New Jersey geology and guide to field trips, 52nd annual meeting of the New York State Geological Association: Newark, N.J., Rutgers University, p. 278–311.
———1982a, Results of core drilling of the Ramapo fault at Sky Meadow Road, Rockland County, New York, and assessment of evidence for reactivation to produce current seismicity: U.S. Geological Survey Miscellaneous Investigations Series Map I-1401.
———1982b, Tectonic versus frost wedging origin of faulted glacial surfaces in the lower Hudson River valley area [abs.]: Geological Society of America, Abstracts with Programs, v. 14, nos. 1 and 2, p. 76.
Reimer, G.E., 1984, The sedimentology and stratigraphy of the southern basin of glacial Lake Passaic, New Jersey: New Brunswick, N.J., Rutgers University, unpublished M.S. thesis, 204 p.
Van Fossen, M.C., Flynn, J.J., Forsythe, R.D., 1986, Paleomagnetism of Early Jurassic rocks, Watchung Mountains, Newark Basin; evidence for complex rotations along the border fault: Geophysical Research Letters, v. 13, no. 3, p. 185–188.
Washburn, A.L., 1980, Permafrost features as evidence of climatic change: Earth-Science Reviews, v. 15, no. 4, p. 327–402.
Zoback, M.D., Anderson, R.N., and Moos, Daniel, 1985, In-situ stress measurements in a 1 km-deep well near the Ramapo fault zone: Transactions, American Geophysical Union (EOS), v. 66, no. 18, p. 363.

ORIENTATION, MOVEMENT HISTORY, AND CATACLASTIC ROCKS OF RAMAPO FAULT BASED ON CORE DRILLING AND TRENCHING ALONG THE WESTERN MARGIN OF THE NEWARK BASIN NEAR BERNARDSVILLE, NEW JERSEY

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