ATTITUDE, MOVEMENT HISTORY, AND STRUCTURE OF CATACLASTIC ROCKS OF THE FLEMINGTON FAULT—RESULTS OF CORE DRILLING NEAR OLDWICK, NEW JERSEY

By
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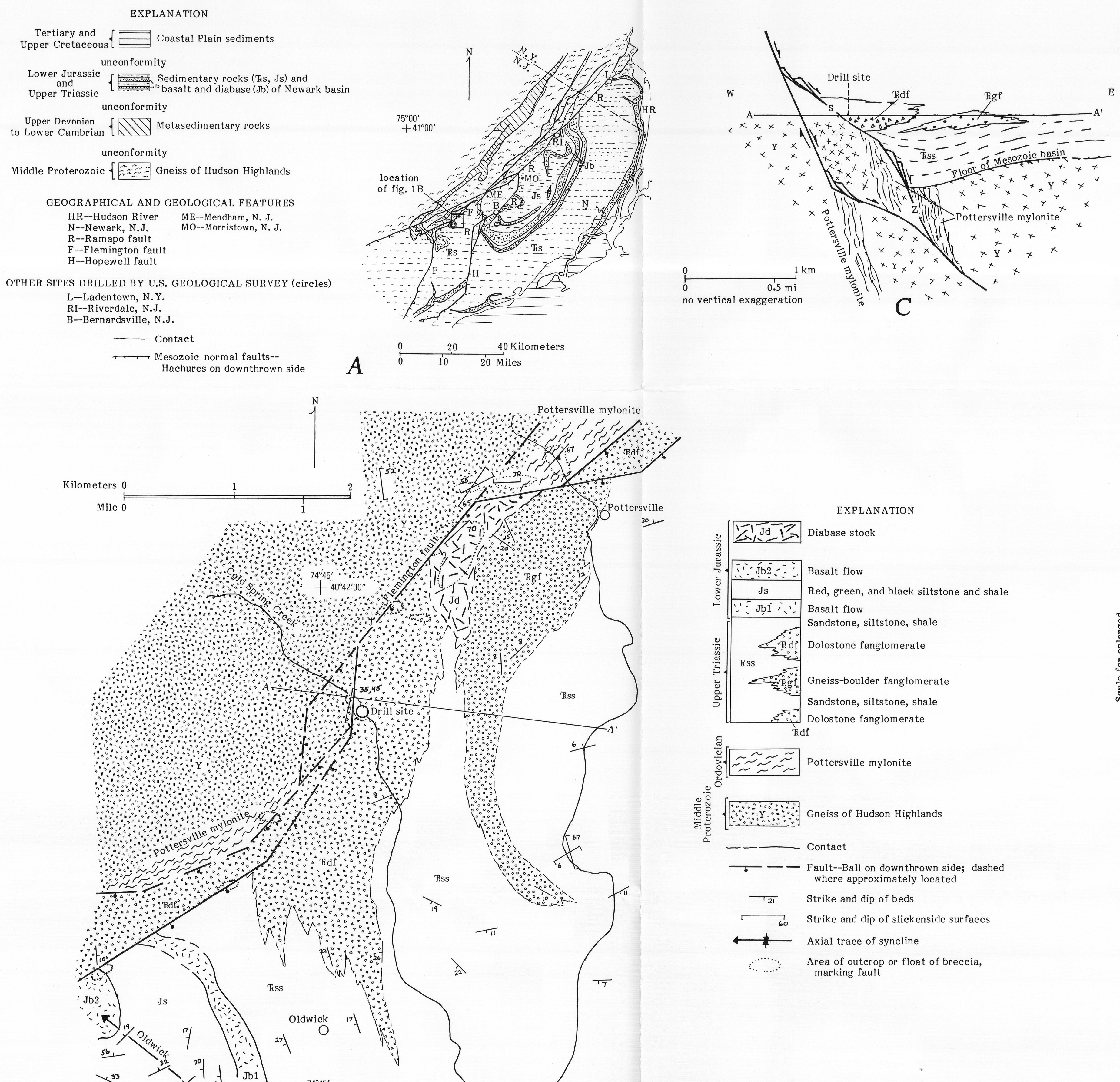


Figure 1.--*A*, Regional geologic map showing location of Flemington drill site in relation to major Mesozoic faults and other drill sites; *B*, Generalized geologic map of the Gladstone-Oldwick area showing location of drill site. Adapted from unpublished mapping in the Califon and Gladstone 7.5-minute quadrangles by Ratcliffe and Burton (1979, 1983); *C*, Diagrammatic cross section across the Flemington fault showing rhomboidal fault block in fault zone and offset Pottersville mylonite. S and Z denote north-south-striking, gently dipping fault surface and northeast-striking, steeply dipping fault surface, respectively.

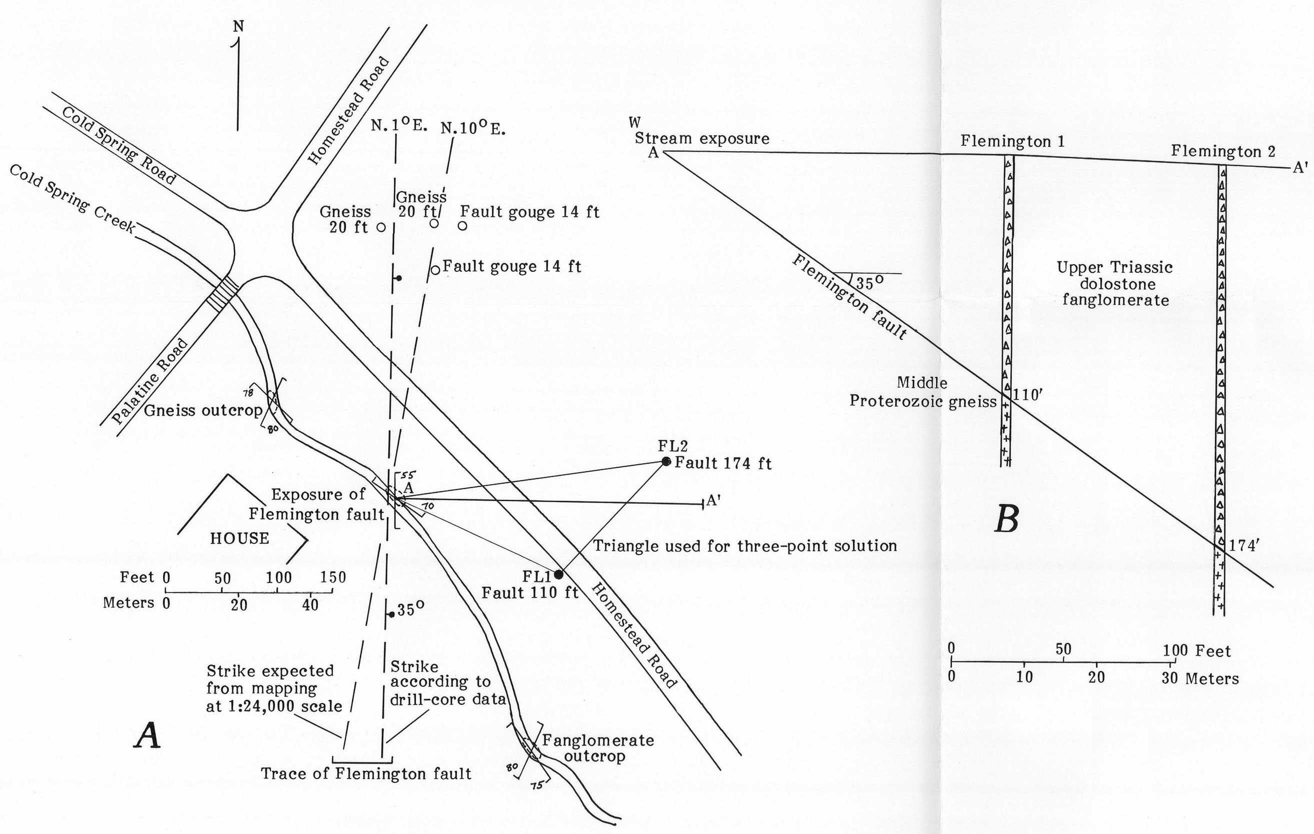


Figure 2.--*A*, Plane-table map of drill site showing location of drill holes Flemington 1 (FL1) and Flemington 2 (FL2) (filled circles), auger drill holes to bedrock (open circles), and trace of fault determined from mapping and drill-core data; *B*, Generalized section drawn normal to strike of fault showing results of drilling projected into plane of section and solution of three-point problem.

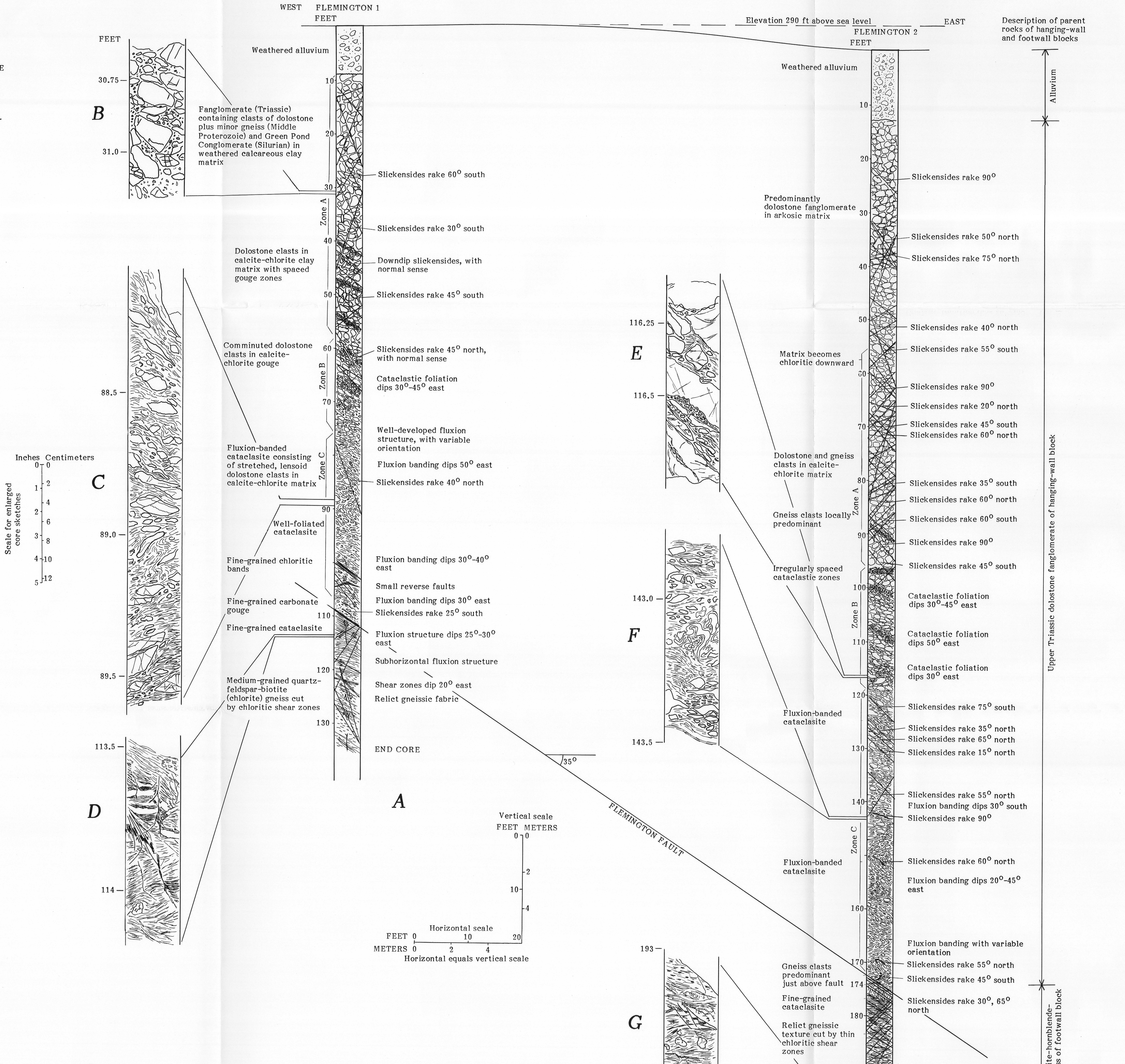


Figure 3.--*A*, Interpretative cross section of Flemington fault at the Oldwick, N. J. drill site. Section is normal to the north-south strike of the fault. Width is exaggerated to show major structural features in core. More significant fault surfaces shown by heavy line. Orientation of features is speculative due to imperfect recovery and orientation of core. Zones A, B, and C show regions in core with respectively greater degrees of cataclasis. *B-G*, Detailed sketches of selected portions of cores. No exaggeration of scale.

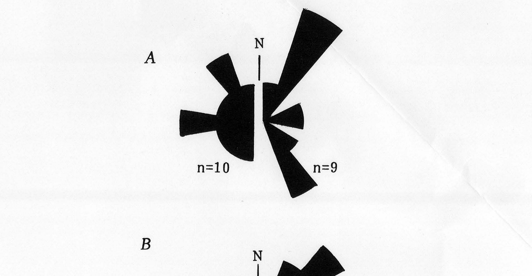


Figure 4.--Rose diagram of slickenside azimuths on fracture surfaces in hanging wall. All fracture orientations assigned to single west- or east-dipping surface. *A*, Flemington 1; *B*, Flemington 2.

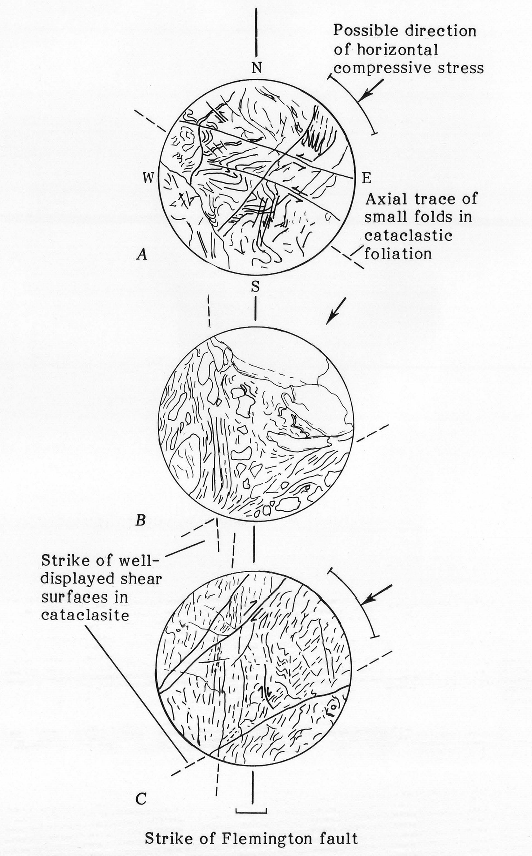
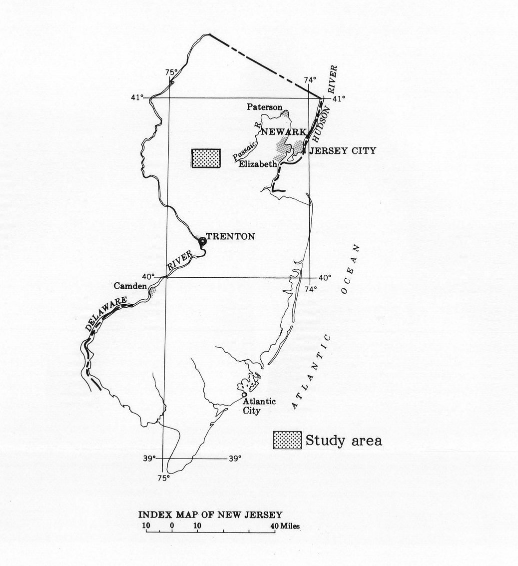


Figure 5.--Sketches of horizontal cross sections of core in map view, showing structures parallel and oblique to fault direction. *A*,--Flemington 1, 119.2 ft, mylonite gneiss below fault. *B*,--Flemington 2, 164 ft, fluxion-banded mylonite above fault. *C*,--Flemington 2, 180.7 ft, mylonite gneiss below fault. Scale 1:1.



INTRODUCTION

Since 1978, the U.S. Geological Survey (USGS) has cored cataclastic rocks at six localities along border faults of the Early Mesozoic Newark basin in New York and New Jersey. This drilling was done as part of fault definition studies for the USGS Earthquake and Reactor Hazard Programs. The purposes of these studies are to: (1) determine the attitude and location of major faults, (2) assess evidence for recent reactivation, and (3) identify the movement history and depth of formation of the faults. The results of these studies up to 1980 are summarized in Ratcliffe (1980) and a detailed study of a site in Rockland County, N.Y. appears in Ratcliffe (1982).

The attitude and movement history of these faults is particularly important because of the possible association of recent low-level seismicity in the New York-New Jersey area with the Ramapo-Flemington fault system (Aggarwal and Sykes, 1978). Previous studies have shown that the Ramapo fault dips to the southeast at angles varying from 70° to 45° and strikes N. 40° E. to N. 10° E. In all of the cored fault zones, the actual contact of hanging-wall and footwall blocks is expressed as a relatively narrow zone, 3 to 8 inches thick, of dark, finely comminuted, fluxion-banded gouge. The intensity of cataclasis decreases rapidly upwards so that rocks 60 ft or so above the fault are not strongly cataclastic. Gneiss, dolostone, and phyllonite in the footwall block are generally weakly deformed more than 30 ft below the fault. Movement sense on the Ramapo fault is largely dip-slip and right-oblique normal faulting.

In the summer of 1983, two holes were drilled through the border fault of the Newark basin near Oldwick, New Jersey, in the Gladstone 7.5-minute quadrangle. Figure 1A shows the location of the drill site in relation to regional geology and the major faults. The fault drilled in this study connects to the south with the Flemington fault, which trends southwestward across the Newark basin, as shown. To the north, the fault can be traced along the valley that extends towards Mendham, N. J., beyond the limits of exposed Mesozoic rocks, to connect with the Ramapo fault near Morristown N. J. (fig. 1A; Ratcliffe, 1980). For this reason, we use the name "Flemington" for the border fault in the region of the drill site. A detailed map (fig. 1B) shows the local geology along the border fault from Pottersville, N. J. southward to the axis of the Oldwick syncline.

Between Pottersville and the Oldwick syncline, the border fault exhibits a jagged trace with an overall N. 40° E. trend. Rocks of the footwall block consist of Middle Proterozoic high-grade gneiss of the Hudson Highlands in which Proterozoic gneissic structure is dominant.

Two localities west of the Flemington fault (fig. 1B) display an intensely developed zone of mylonite and mylonite gneiss (the Pottersville mylonite; figs. 1B and 1C), which exhibits excellent ductile deformation fabric. Quartz, epidote, actinolite, and muscovite grew in the mylonite, indicating retrograde, greenschist-facies conditions during ductile deformation of the gneiss. This mylonite zone appears to belong to a group of regionally recognized, steeply dipping shear zones that cut the rocks of the Hudson Highlands west and north of the Newark basin, and that are not restricted to areas of Mesozoic faulting. North of the Newark basin, these retrogressive shear zones are dated as Ordovician in age from geochronological studies (Ratcliffe, 1980).

Ratcliffe (1971) recognized Proterozoic high-grade mylonite zones and Ordovician greenschist-facies shear zones as having been locally reactivated in Mesozoic time to produce the Ramapo fault. The Pottersville mylonite petrographically resembles the greenschist-facies shear zones found along the northeastward projection of the Ramapo fault into the Hudson Highlands. It may thus be Ordovician in age and may have been reactivated to form the Flemington border fault in this region.

Rocks of the hanging-wall block of the Flemington fault consist of Upper Triassic and Lower Jurassic clastic sediments and basalt flows of the Newark basin (fig. 1B). The Upper Triassic rocks (Ꞧss, Ꞧdf, Ꞧgf) include fanglomerate, arkose, siltstone, and red shale, with the coarser-grained sediments becoming more thinly bedded and finer grained southeastward into the basin. In figure 1B, two discrete fanglomerate deposits are differentiated on the basis of clast lithologies: gneiss fanglomerate (gf), with abundant gneiss and minor quartzite clasts, and dolostone fanglomerate (Ꞧdf), a carbonate-boulder deposit containing clasts of Cambrian and Ordovician dolostone and limestone. Rocks of Early Jurassic age, found in the Oldwick syncline, consist of two basaltic flows (Jb1 and Jb2) separated by siltstone and red, green, and black shale. The basalt flows and a coarse-grained diabase stock southwest of Pottersville (Jd) are truncated by the Flemington fault. The mapped relationship between the Oldwick syncline and the Flemington fault (fig. 1B) indicates that the last movement along the Flemington fault either postdated folding of the strata along northwest trends or was synchronous with that folding.

On a regional scale, transverse folds with axial traces that trend N. 40° W. (such as the Oldwick syncline) are common throughout the Newark basin and have been interpreted as folds produced during right-oblique slip along the Ramapo and other faults (Ratcliffe, 1980). In oblique-normal faulting the axial planes of such transverse folds form approximately normal to a horizontal intermediate principal stress(σ_2).

A site near Cold Spring Creek was chosen for drilling because exposures of bedrock in the stream tightly constrained the position of the fault contact. Structural control obtained from outcrops to the north suggested that the fault should strike approximately N. 10° E. at the Cold Spring Creek drill site (fig. 2A).

Terminology

The textural classification of cataclastic rocks of Higgins (1971) is used where possible in the description of the cores. Many of the cataclastic rocks in the cores are poorly cemented to incoherent and should be termed "gouge" or "cataclasite," although they exhibit well-developed fluxion banding and weak to strong foliation. Lepidoblastic chlorite occurs locally along fault surfaces and in the matrix of the more coherent rocks. Grain-size reduction occurred through brittle processes (comminution) even in carbonate rocks. Therefore, even though the rocks megascopically resemble mylonites, terms such as "foliated cataclasite" and "fluxion-banded gouge" are more appropriate than either mylonite, mylonite gneiss or ultramylonite, which connote a significant proportion of ductile strain.

DESCRIPTION OF THE FAULT EXPOSURE

The Flemington fault is exposed in a five-foot-long outcrop of cataclasite in the northeast bank of Cold Spring Creek, 250 ft downstream from the bridge on Palatine Road (fig. 2A). Approximately two feet of dark-brown cataclastic gneiss (microbreccia) at the west end of the exposure is overlain by a gently east-dipping, three-foot-thick zone containing an upward sequence of dark-green-, gray-, and light-gray-weathered, clay-rich gouge and cataclasite. The dark-green gouge at the base is banded and contains abundant porphyroclasts of gneiss. The sequence of cataclastic material becomes lighter in color upwards as the percentage of dolostone porphyroclasts increases; dolostone and thin zones of grayish-white gouge are dominant near the top. The transition from cataclasite with predominantly gneiss porphyroclasts to cataclasite with predominantly dolostone porphyroclasts takes place over a distance of about half a foot. This narrow zone is considered to mark the trace of the Flemington fault contact between the protoliths of gneiss and dolostone fanglomerate.

The orientation of cataclastic structure in the gneiss is variable but generally strikes N. to N. 10° W. and dips 35° to 50° E. to NE. Ellipsoidal porphyroclasts within the cataclasite are bounded by anastomosing shear surfaces and exhibit a crude elongation in a N. 80° E. direction. Slickenside surfaces have wear grooves plunging N. 50° to N. 60° E. The exposed contact and cataclastic rocks are identical to the cataclastic zones seen at the fault in both of the cores. This exposure was used in a three-point calculation of the orientation of the fault.

Results of Drilling

Two holes were drilled for continuous recovery of two-inch core. They penetrated through 110 ft (Flemington 1) and 174 ft (Flemington 2) of Triassic carbonate fanglomerate of the hanging wall into approximately 30 ft of Middle Proterozoic gneiss of the footwall. Recovery was approximately 85% for Flemington 1 and 95% for Flemington 2. The lithology and structure of the cores were recorded and measurements made of fault-related features.

Although a wide zone of shearing and cataclasis is associated with the Flemington fault, the location of the fault in the core is taken to be the point of transition, which is quite distinctive, between cataclastic rock with carbonate clasts and fluxion-banded cataclasite derived from leucocratic gneiss. In Flemington 1, which had better recovery of the actual fault, the precise nature of the transition could be seen in the core samples.

Orientation of the fault

The depth of the fault in drill holes Flemington 1 and 2 is 110 ft and 174 ft, respectively. By using the exposure of the fault in Cold Spring Creek (fig. 2A) as a third data point, the strike and dip of the fault was calculated as a three-point solution. The calculation gives a strike for the Flemington fault of N. 1° E. and a dip of 35° E. Four supplemental holes to bedrock were drilled north of Flemington 1 and 2 in order to determine the trace of the fault in the field (fig. 2A). These data suggest that the fault trace extends N. to N. 10° E. from the stream exposure, in approximate agreement with the three-point solution.

Structure of the fault zone

In both cores, the Flemington fault is associated with a thick zone of distinctive cataclasite. This zone is approximately 50 ft thick; 40 ft is contained in the carbonate fanglomerate above the fault and 10 ft in the gneiss below the fault. The type of cataclasite in the zone ranges from poorly consolidated, unfoliated fault gouge to strongly fluxion banded, chloritic cataclasite and fine-grained siliceous cataclasite.

In the hanging wall, the progressive downward increase in deformation of the fanglomerate associated with faulting is marked by several zones (fig. 3). They are:

Zone A (50 to 120 ft above fault).--Minor rotation of fanglomerate clasts towards an orientation parallel with the fault is coupled with an alteration of the original reddish arkose matrix to a green, fine-grained matrix containing calcite, chlorite, and clay. Brittle chlorite- and calcite-coated fractures, some with slickensides, as well as thin zones of poorly consolidated fault gouge, are interspersed throughout the zone.

Zone B (35 to 80 ft above fault).--Further rotation, flattening of clasts, and reduction in clast size is accompanied by an increase in percentage of cataclastic matrix.

Zone C (0 to 55 ft above fault).--Extreme smearing out of clasts, further reduction in grain size, and development of a penetrative fluxion structure produces a green-, white-, and red-banded cataclasite containing phacoidal shear structures. Brittle fractures, common in zones A and B, are largely absent.

The brittle fractures in the hanging wall have a wide range of orientations although dips average about 45°. Trends of slickensides on these fracture surfaces also vary considerably (fig. 4). The fluxion structure of the hanging-wall cataclasite, although generally parallel to the dip of the fault, locally displays flexures and reversals of dip (fig. 3C) as well as sigmoidal and plume-shaped flow structures (fig. 3F).

Although recovery was not complete, results from the Flemington 1 drill hole show that the fault is marked by the downward transition, over one to two inches, of fluxion-banded, carbonate-bearing cataclasite into a 0.4- to 0.8-inch-thick zone of poorly consolidated, green, sand-sized gouge, followed by a thin (<0.4 in.) band of dense, black, fine-grained material (probably chlorite) which grades sharply into a dark-green, fine-grained, fluxion-banded cataclastic gneiss.

The zone of shearing and deformation is much thinner in the gneiss of the footwall and consists primarily of a fine-grained, fluxion-banded, chloritic cataclasite whose structures generally parallel that of the overlying fault. Complex features such as small folds and faults (figs. 3D and G) are present. About 10 ft below the fault, relict textures of the gneissic country rock appear in the form of sheared lenses of quartz and alkali feldspar. Shearing decreases downward until a gneissic fabric predominates at 10 ft below the fault. There, medium-grained gneiss containing quartz, alkali feldspar, possible plagioclase, and chlorite (altered from biotite), is cut by thin chloritic shear zones. Brittle fractures, without slickensides, are fairly common in the footwall and decrease downward in abundance.

Petrographic descriptions of cataclastic rocks from beneath the fault

Standard petrographic thin sections were prepared from the coherent cataclastic rocks from beneath the fault in both cores. Samples from depths of 110.5, 110.75, 111.3, 112.3, 112.9, 113.5, 113.7, 114.3, and 122.7 ft from Flemington 1 and of 114 and 193.5 ft from Flemington 2 were examined. In all cases, the dominant penetrative cataclastic fabric in the gneiss consists of a cataclastic layering which dips 30° to 40° E. This layering is locally more strongly foliated in zones 0.2 to 0.4 in. thick. Varying degrees of comminution and recrystallization of chlorite account for the principle variations among the cataclastic layers. Finer grained layers of foliated to poorly foliated microbreccia consist of brittlely fractured subgrains of quartz, plagioclase, microcline, and hornblende. Biotite is kinked, shredded and altered to chlorite as *in situ* replacement and as extensional fiber growth. Pyrite, calcite, and fine-grained sericite and chlorite are abundant throughout the matrix of the cataclastic rocks.

In all of the examined cataclastic rocks, the dominant gently east-dipping cataclastic layering is cut by more steeply dipping, discrete, brittle faults that dip 60° to 70° E. or 45° to 70° W. Most of these faults have produced apparent normal fault displacement of both the cataclastic fabric and extensional veins, filled by calcite or quartz, which cut this fabric.

All of the examined rocks are properly termed cataclastic rocks and exhibit no evidence of ductile deformation, even in the more quartzofeldspathic layers. Nonetheless, they exhibit excellent fluxion structure and crystallization of calcite and chlorite. None of the cataclastic rocks of the Flemington fault examined in the footwall block resemble the mylonitic rocks seen in outcrop in the Pottersville mylonite zone. The petrographic data suggest that these two deformation zones formed under distinctly different temperature and pressure conditions: the Pottersville mylonite formed under greenschist-facies conditions of presumed Paleozoic age, and the Flemington fault cataclasite formed under very low grade conditions during Mesozoic faulting. During cataclasis along the Flemington fault, abundant injection of calcium-carbonate-bearing fluids appears to have been important, as was chemical alteration of the cataclasite.

Thin sections of the poorly consolidated cataclastic fanglomerate above the fault were not made due to the incoherent nature of the gouge.

CONCLUSIONS

Comparison of the Flemington fault drill core data with data obtained from the major Mesozoic boundary fault in this region, the Ramapo fault, reveals several significant differences:

1. The north-south-striking, 35° E.-dipping Flemington fault contrasts in orientation with the Ramapo, which has more northeasterly strikes and steeper dips. At the Sky Meadow drill site in Ladentown, N.Y. (fig. 1A) the Ramapo fault strikes N. 40° E. and dips 55° E. (Ratcliffe, 1982), and at Riverdale, N.J., it strikes N. 31° E. and dips 48° SE., while at Bernardsville, N.J., the strike and dip of the Ramapo fault is N. 31° E. and 44° SE., respectively (Ratcliffe, unpub. data).
2. The Flemington fault has a thicker zone of deformation associated with it than the Ramapo, particularly in the hanging-wall block, where rock as much as 40 ft above the fault has been extensively sheared. The sequence of deformation fabrics in the hanging-wall rocks, described above and first observed in the Flemington 1 cores, permitted a fairly accurate prediction of fault depth during drilling of Flemington 2. In contrast, drill core of the hanging wall of the Ramapo fault contains markedly thinner zones of foliated cataclasite immediately above the fault and could not be used to predict fault depth.
3. The rocks in the footwall of the Ramapo fault (for example, at Riverdale, N.J.) locally display a set of steeply dipping mylonite structures which are apparently pre-Mesozoic in age (Ratcliffe, 1980), implying that the Ramapo was formed from an older high-angle shear zone, possibly created during Taconic thrusting, which was reactivated and converted into a normal fault zone during the Mesozoic. A significant portion of the movement along the Ramapo fault may have occurred in these pre-existing basement shear zones, leaving the hanging-wall block mostly undeformed. In contrast, the major shear structures in the cores of the Flemington fault zone parallel the shallow dip of the main fault, and are all probably Mesozoic or later in age. The lack of pre-existing shear surfaces in the footwall gneiss at the drill site could have resulted in a concentration of fault slippage in the weaker sedimentary rocks of the hanging wall.

The north-south strike and shallow dip of the Flemington fault near Cold Spring Creek and its exclusively post-Paleozoic (and possibly post-Mesozoic?) history suggest that this segment of the fault is a relatively young branch of a boundary fault complex (fig. 1B), whose more northeasterly segments possibly have a longer tectonic history. The sense of movement along the Flemington fault is thought to be predominately dip-slip, as shown by the offset of the Newark basin strata. However, diverse trends of slickensides (fig. 4), the presence of minor reverse faults (figs. 3D, 3G), folding of the fluxion-banded cataclasite in zone C, and structures in the core which are not parallel to the principle fault orientation (fig. 5) suggest more complex movements.

The folds and reversals of dip observed in the fluxion structure indicate that it has been deformed or rotated subsequent to formation, in directions oblique to the principle dip-slip direction. In the hanging-wall cataclasite, some of these irregularities are due to flowage of matrix around clasts and resulting volume adjustments. Other features, such as the microfolds in figure 3F and folds observed with axes parallel to the dip-slip direction, indicate a more complex movement history. Folds and fractures in the footwall cataclasite (figs. 5A, 5C) suggest a general northeasterly orientation for the intermediate stress axis (σ_2), and hence a right-oblique slip component. These data contradict the N. 80° E. elongation direction and N. 50°- to N. 60° E.-plunging wear grooves seen in the surface exposure of the fault, which suggest left-oblique slip.

SUMMARY

Preliminary examination of the cores of the Flemington fault reveals:

1. an unusually thick zone of cataclasite up to 60 ft thick dominated by extensive elongation of dolostone clasts and flattening in the dominant cataclastic foliation;
2. a gentle, 35° E. dip for the fault plane;
3. abundant evidence of multiple-movement history most clearly revealed by the complex deformational patterns in the folded cataclastic fabric; and
4. multiple-slickenside surfaces indicating left-oblique normal faulting, dip-slip, and right-oblique normal faulting.

These data, while complex, are consistent with the structural setting of the drill site. According to the drill-core data the site is located on a small north-south-trending fault segment, which connects two longer northeast-trending segments of the Flemington fault, forming a left-stepping pair (fig. 1B). For east-dipping faults, the left-stepping pair suggests general left-oblique movement as the main deformation mode. To the north, a right-stepping branch suggests right-oblique normal faulting. It seems likely that the border fault system here is composite and underwent both right- and left-oblique slip movement.

A diagrammatic cross section (fig. 1C) across the drill site suggests that the segment drilled might be the north-striking, shallow- dipping upper surface of a large rhomboidal block bounded by steeply-dipping, northeast-striking master faults. The high degree of cataclasis and extreme width of the sheared zone may be a consequence of the shallow dip of the fault and greater normal component of stress on this surface (S) as compared to the deeply dipping surface (Z). Alternatively, the shallow-dipping surface (S) may have formed earlier in the fault movement, was then rotated into a shallow attitude by basin rotation, and later faulted on younger, steeply-dipping faults with less displacement.

ACKNOWLEDGMENTS

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