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A Characterization of Faults in the Appalachian Foldbelt

Prepared by A. L. Odom, R. D. Hatcher, Jr.

Florida State University

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Prepared by
A. L. Odom, R. D. Hatcher, Jr.

Contributing Authors:
D. E. Dunn - University of New Orleans
T. J. Engelder - Lamont-Doherty Geologic Observatory
P. A. Geiser - University of Connecticut
S. A. Kish - University of North Carolina
S. Schamel - Lafayette College
D. U. Wise - University of Massachusetts

Florida State University
Tallahassee, FL 32306

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ABSTRACT

The characterization is a synthesis of available data on geologic faults in the Appalachian foldbelt regarding their description, generic implications, rate of movement, and potential as geologic-seismic hazards. It is intended to assist applicants and reviewers in evaluating faults at sites for nuclear facilities. Appalachian faults were found to fall into 13 groups which can be defined on either their temporal, generic, or descriptive properties. They are as follows: Group 1, faults with demonstrable Cenozoic movement; Group 2, Wildflysch type thrust sheets; Group 3, bedding plane thrusts - décollements; Group 4, pre- to synmetamorphic thrusts in medium to high grade terranes; Group 5, post-metamorphic thrusts in medium to high grade terranes; Group 6, thrusts rooted in low crystalline basement; Group 7, high angle reverse faults; Group 8, strike slip faults; Group 9, normal (block) faults; Group 10, compound faults; Group 11, structural lineaments; Group 12, faults associated with local centers; and Group 13, faults related to geomorphic phenomena. Unhealed faults (Groups 1, 6, 8, 9, and 12) must be considered candidates for reactivation. Heated brittle or ductile faults (Groups 4, 5, and 10) are not places of mechanical discontinuity and are unlikely candidates for reactivation. The remaining groups (2, 3, 7, 11, and 13) should be individually assessed as to their potential for reactivation.

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I. INTRODUCTION

A. Purpose.

The purpose of this study has been to collect and synthesize available data on faults and fractures pertaining to their description, genetic implications, tectonic setting, and potential as geologic-seismic hazards. This is done in a regional context for the Appalachian orogen. While it is recognized that it would be desirable to do such an investigation for the whole U.S., the study is limited to one of the major problem areas in the eastern U.S. The Appalachian foldbelt is an area of complex geology which is close to large population centers. About one third of the commercial nuclear reactors are situated in this zone. It is anticipated that licensing activity will continue in this area. A major goal of this investigation is to aid the licensing process.

Nuclear power plant license application reviews show three major fault-associated problem areas: (1) their significance in a regional context, (2) their genetic significance, and (3) their nomenclature. An understanding of the regional and temporal differences in the characteristics and nature of Appalachian faults could reduce the effort presently spent in the investigation of many faults which are not capable and thus provide more effort for those faults which are not readily related to Appalachian tectonics. It is probably correct to state that, in most areas of the Appalachians, more effort should be spent in investigation of those faults, which in characteristics or orientation, are anomalous (albeit often smaller) than to those clearly associated with Appalachian tectonism.

In the past difficulties have arisen as the result of the use and misuse of terminology relating to faults and fractures. Such problems have arisen in part because a real confusion and sometimes contradiction of nomenclature that exist in the geologic and engineering literature and, in part, because of reluctance to call a fault a "fault".

This study was conducted under contract NRC-78-01-004 of the Office of Standards Development of the U.S. Nuclear Regulatory Commission to The Florida State University, by the following panel of geologists:

D. E. Dunn	University of New Orleans
James T. Engelder	Lamont-Doherty Geological Observatory
Peter Geiser	University of Conneticut
Robert D. Hatcher, Jr.	Florida State University
S. A. Kish	University of North Carolina
A. Leroy Odom	Florida State University
Steven Schamel	Lafayette College
Donald Wise	University of Massachusetts

B. Rationale.

This report attempts to reflect the organization of some of the principal tectonic features whose assemblage constitutes the Appalachian orogen. These tectonic features, faults, and fractures, form a critical part of the framework of the mountain belt, knowlege of which is imperative both for our understanding of its past and present deformational history as well as towards predicting its future behavior. The Appalachian system of faults and fractures represent the principal mechanical discontinuities of the mountain belt. These discontinuities can be grouped in both space and time, although this grouping is complex, it is possible to distinguish a recognizable framework for these elements. The development and interlinkings of the group reflect the complex interplay of the changing mechanical properties of the orogen as it responded to varying boundary conditions throughout its long deformational history. Thus we can recognize a progression from a period dominated by early block faulting and extension becoming one of syndepositional thrusting and Taconic type structures. As deformation proceeded, thrusts involving pre-Appalachian cycle (Grenville) basement apparently sheared from the leading edge of the North American craton,began their development, in some cases becoming incorporated in the growing metamorphic aureoles produced by convergent plates, but in others escaping entirely. During these periods of thermal events and pre- and synmetamorphic fault development incorporating large sections of the old continental slope and rise and in their turn were incorporated into the growing orogenic belt. Finally,postmetamorphic faults appeared possibly driving bedding plane thrusts in more external forelands.

Throughout this history, a variety of concommitant tectonic elements such as normal, reverse, and strike slip faults developed, reflecting the varied stress conditions of the irregular geometries of the interacting plates and probable microplates. As deformation continued, appropriately located older elements would be reactivated, forming compound faults which often reflected displacements and thermal regimes alien to that of their initiation. Many of these compound faults were of such a nature as to be reactivated again and again to form some of the longest-lived elements of the tectonic framework. As the Appalachian Wilson cycle of orogenic activity closed and another begun in the Mesozoic, major block fault terranes reappear to be superseded by the present phase of still poorly understood Cenozoic faulting.

Finally, superposed on this complex assemblage of faults and fractures are the superficial deformations associated with local centers and the geomorphic products of the weather and sea.

In attempting to set up the various groups of Appalachian faults, it became clear that no single clear-cut criterion could be applied to give a unique category to every fault. Instead, various groupings were based on a variety of criteria, each recognizable to some degree by faults representing a relatively pure end member based on that criterion. Among these end members we recognize that most real faults will fall into the gray zone defined by partial dominance of a number of criteria.

The criteria used to distinguish the fault groupings include:

(a) The standard Andersonian distinctions producing compressional, extensile, and strike-slip motions.

(b) The timing of the fault motion in relation to other events in the orogen, such as folding and metamorphism. A separate group of Cenozoic faults was distinguished less on the basis of intrinsic differences than on the practical significance of these structures. In addition, a class of structures which may be more geomorphic than tectonic were distinguished because of their potential confusion on outcrop scale with true tectonic faults of young displacement.

(c) The tectonic position of the fault with respect to the core versus foreland of the orogen.

(d) The relationship of the fault to anistrophy of the rock mass, particularly bedding planes.

(e) The involvement of various rock types and ages of units. In particular, the distinction between 1100 m.y. Grenvillian basement and younger crystalline masses were preserved when possible. The Taconic-type of moving submarine slabs were also distinguished because of their distinctive mechanical and tectonic significance.

II

SUMMARY OF CHARACTERISTICS AND DISTRIBUTION OF FAULTS IN THE APPALACHIAN FOLDBELT

Table II-I lists the 13 groups that we have selected to characterize faulting associated with the Appalachian orogen along with a brief description of the primary characteristics making each particular group unique. This grouping of faults is intended to be neither a pure and rigorous classification, nor a hierarchy of Appalachian faults. However, we feel that the 13 groups accomodate all Appalachian faults and are well suited to considerations of the significant Appalachian faults both in a regional and genetic context.

Figure II-I is a map of the Appalachian foldbelt, and it shows some of the geologic subdivisions discussed in this report. Figures II-2 through II-12 delineate regions of the Appalachians characterized by the various groups of faults. It should not be inferred from the maps that faults of a particular group are completely restricted to the region indicated (through in some cases this is true) and cannot occur outside the region. In a few cases, the maps give the location of specific members of the group (for example Figure II-II shows the location of specific vidual members of group 12 faults, because most faults associated with local centers have no obvious relationship to Appalachian tectonics).

Accompanying the maps, Tables II-2 through II-14 give, in abbreviated form, some of the characteristics of each fault group. More detailed descriptions and examples are presented in later sections of this report.

With few exceptions faulting processes and, hence, fault zones are complex. The number of parameters necessary to completely characterize most fault zones is large (our outline includes more than 40, Table II-15).

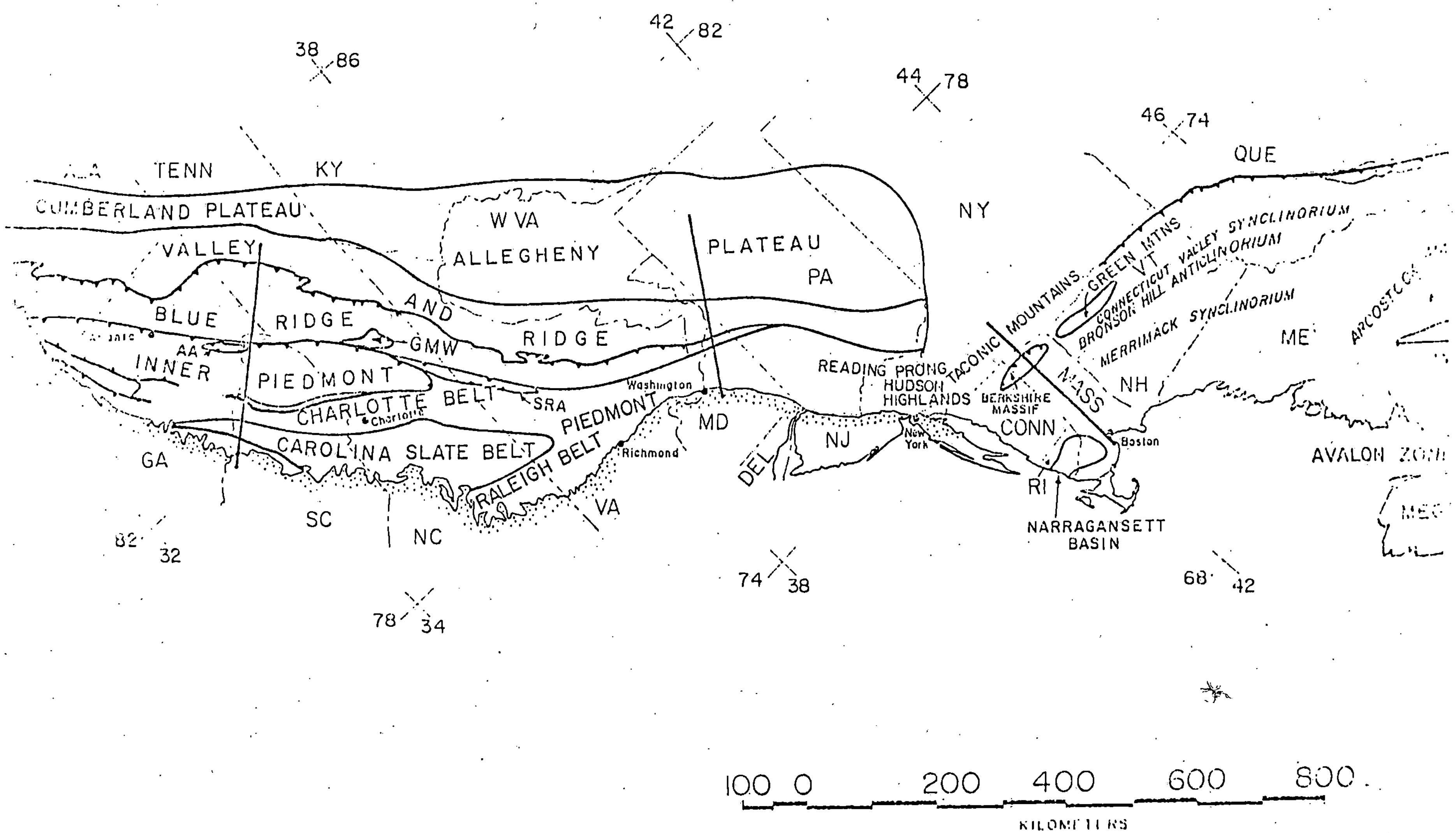


Figure II-1 Geotectonic map of the Appalachian Foldbelt. (Hatcher, 1980).

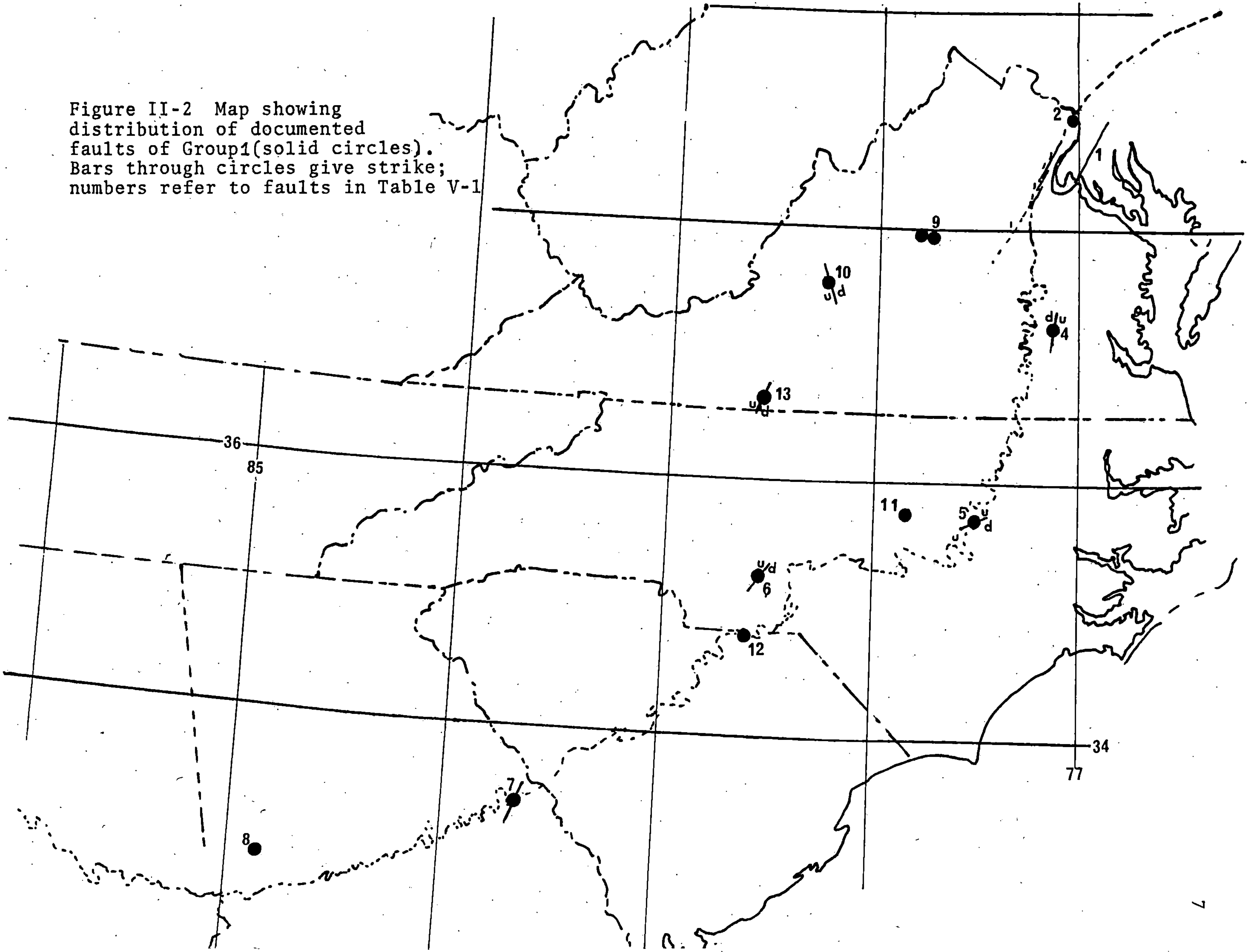
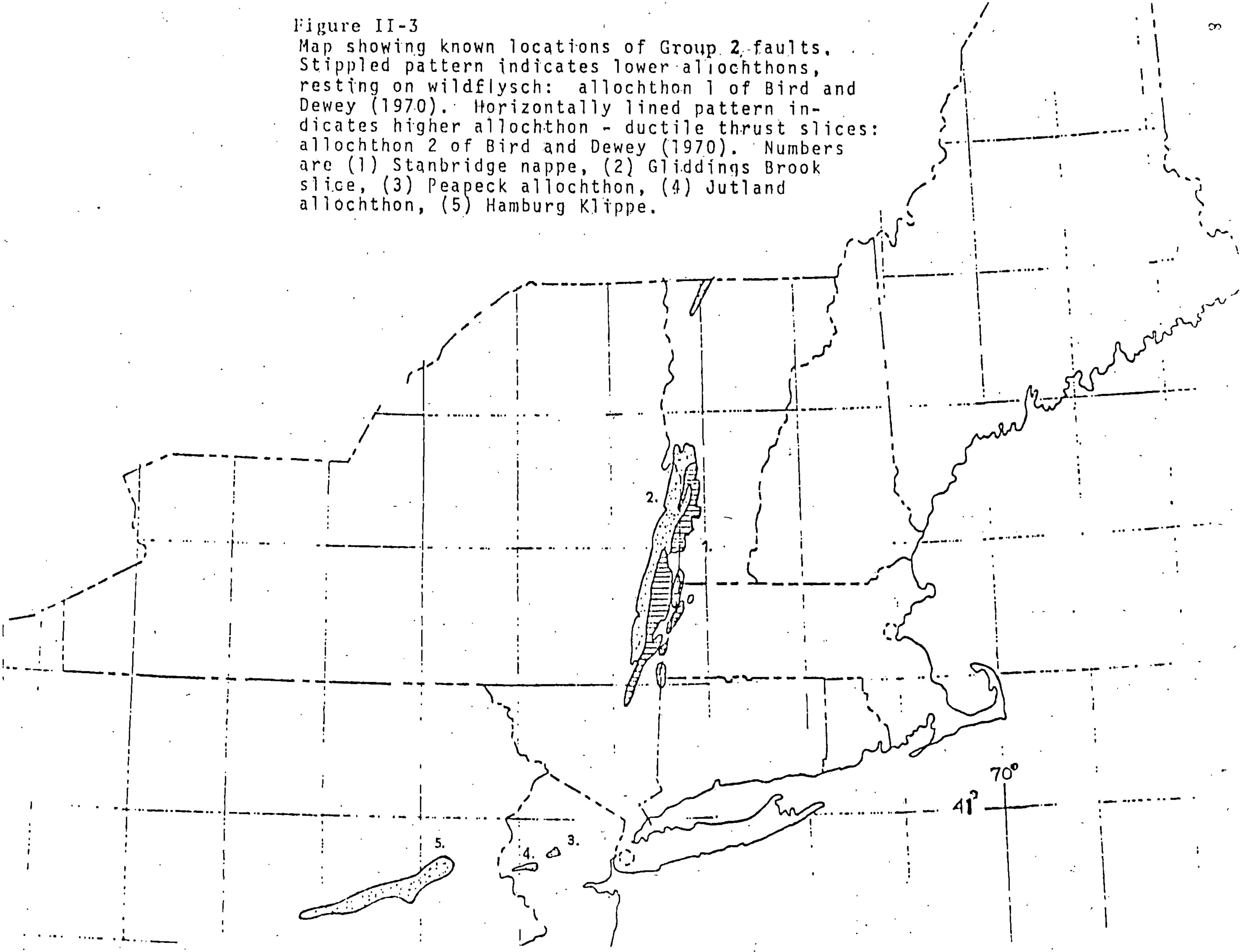


Figure II-2 Map showing distribution of documented faults of Group1(solid circles). Bars through circles give strike; numbers refer to faults in Table V-1

Figure II-3

Map showing known locations of Group 2 faults. Stippled pattern indicates lower allochthons, resting on wildflysch: allochthon 1 of Bird and Dewey (1970). Horizontally lined pattern indicates higher allochthon - ductile thrust slices: allochthon 2 of Bird and Dewey (1970). Numbers are (1) Stanbridge nappe, (2) Gliddings Brook slice, (3) Peapeck allochthon, (4) Jutland allochthon, (5) Hamburg Klippe.



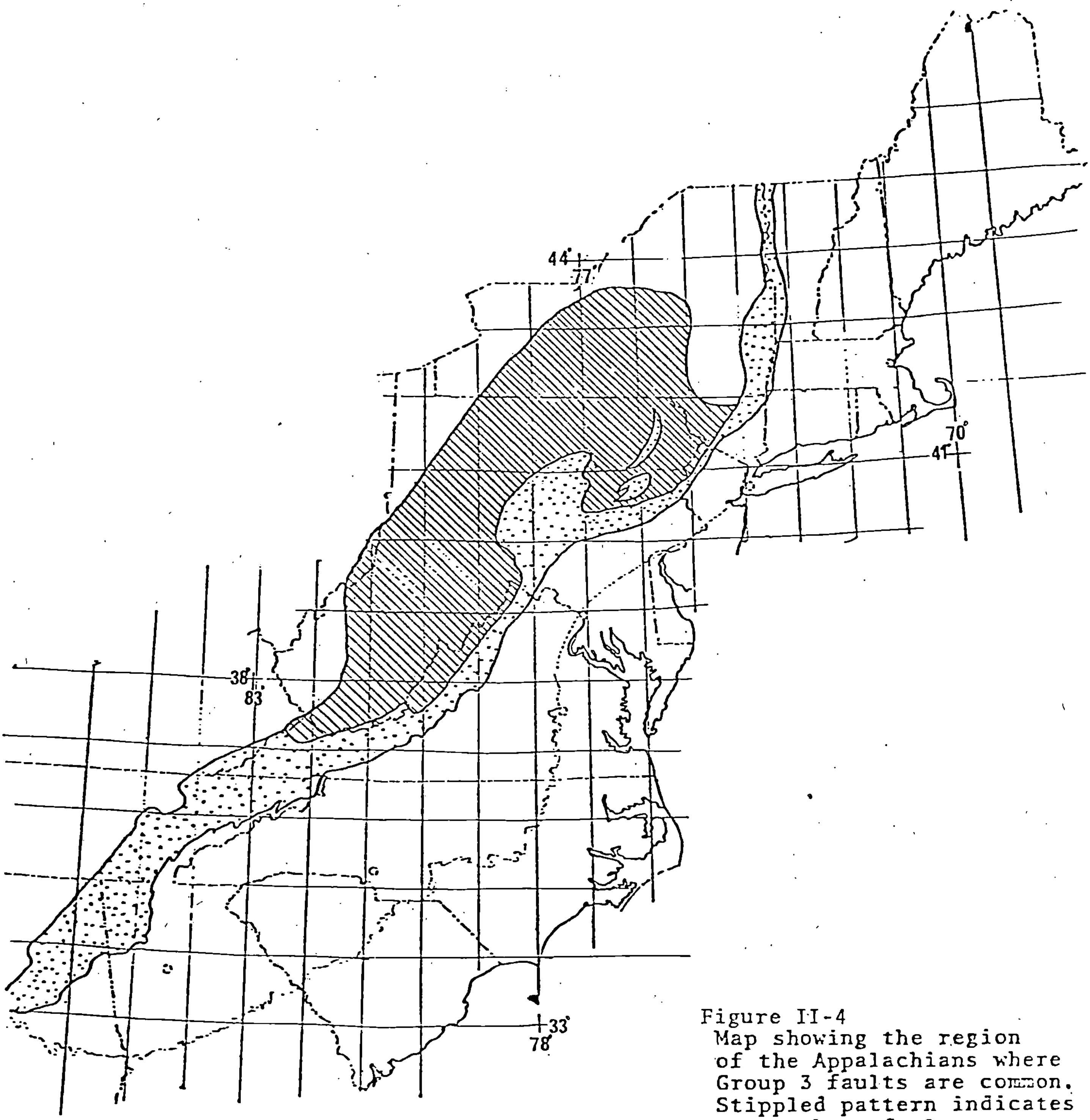


Figure II-4
Map showing the region of the Appalachians where Group 3 faults are common. Stippled pattern indicates areas where faults are exposed at surface; diagonal lines indicate areas where such faults are probably present in the subsurface.

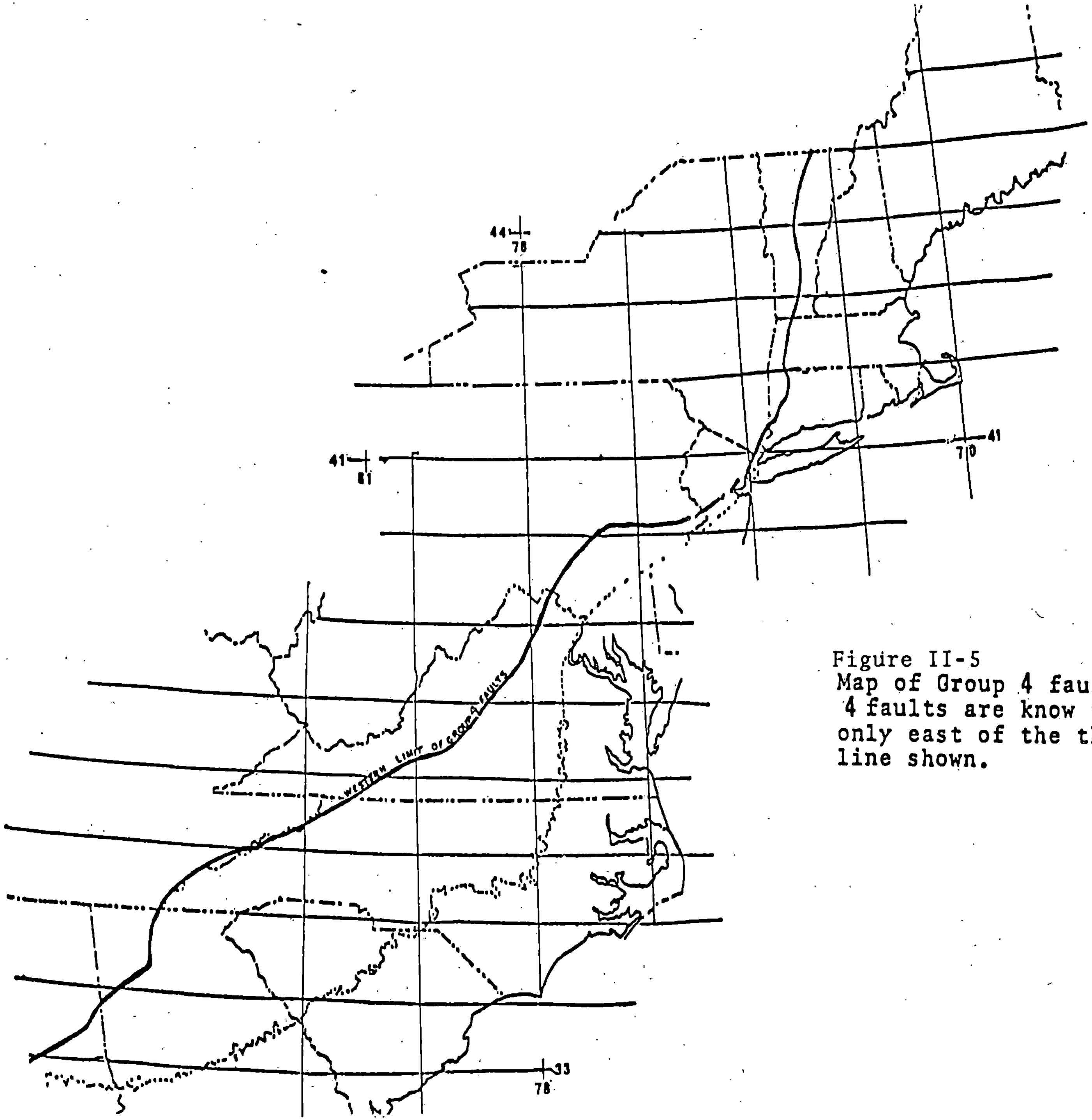


Figure II-5
Map of Group 4 faults. Group 4 faults are know to occur only east of the thick bounda line shown.

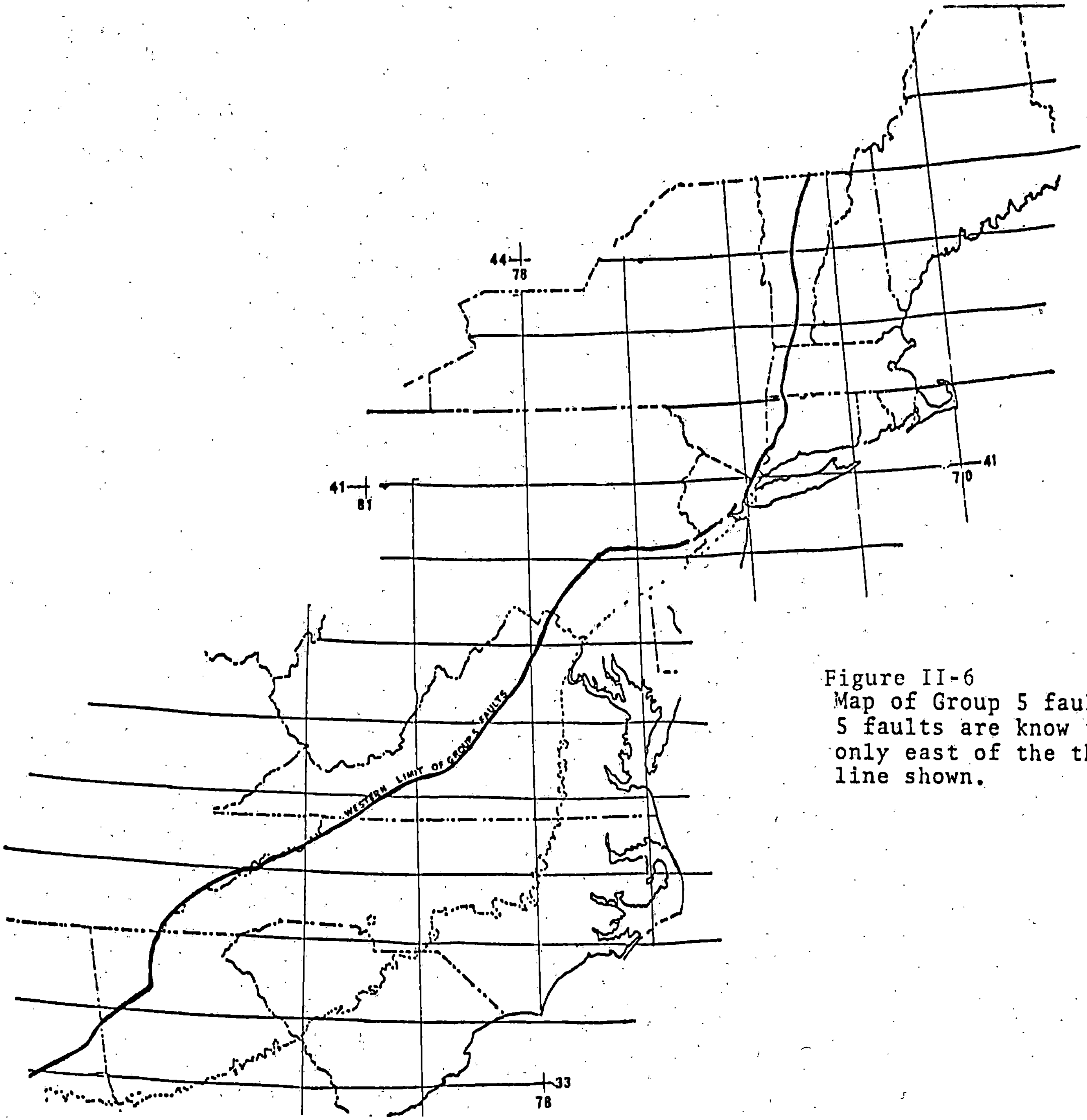


Figure II-6
Map of Group 5 faults. Group 5 faults are know to occur only east of the thick boundar line shown.

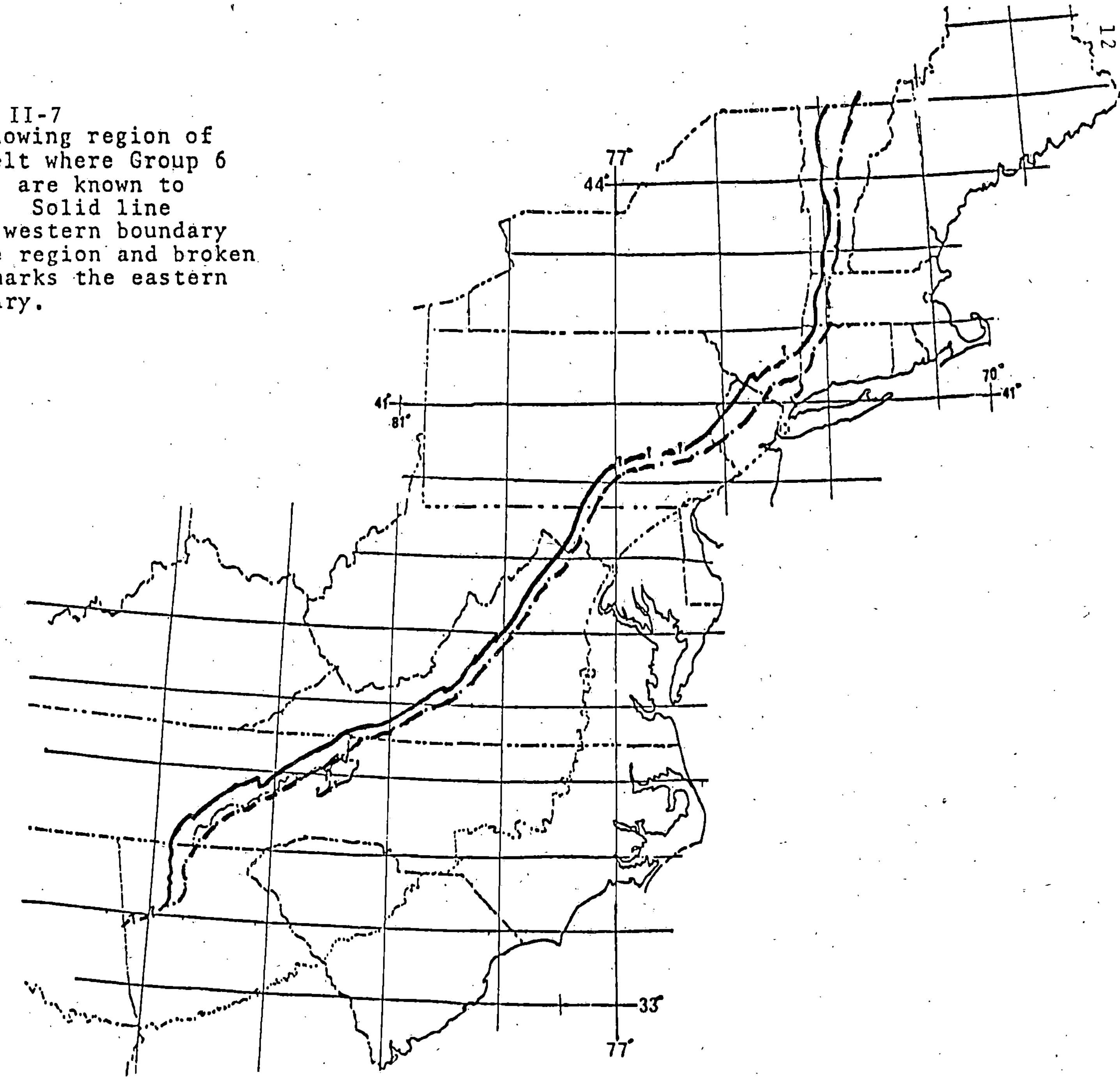


Figure II-7
Map showing region of foldbelt where Group 6 faults are known to occur. Solid line marks western boundary of the region and broken line marks the eastern boundary.

Figure II-8
Map showing areas where Group 8 faults are common. Stippled pattern indicates region where major tear faults associated with thrusts are common. Diagonal lines mark area where small displacement faults in nearly flat-lying sedimentary rocks occur. Checkered pattern marks area of small displacement faults on the limbs of folds. Thick solid lines indicate major tear faults, and thin solid lines indicate faults in crystalline or metamorphosed rocks displaying slip movement. Solid pattern indicates area of horizontal slickensides in eastern Connecticut.

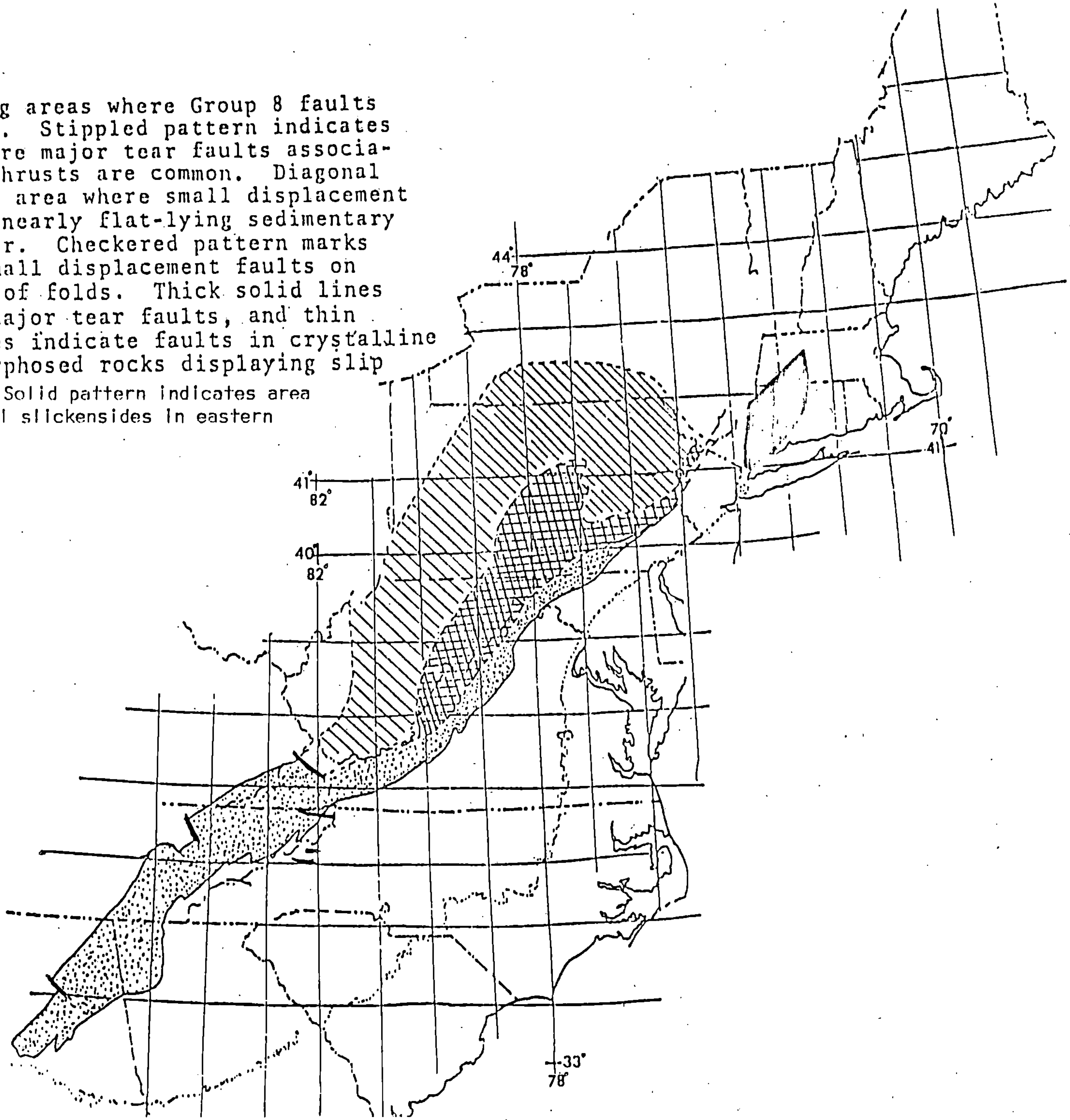


Figure II-10
Map showing location of some known, large faults of Group 10. Such faults are most common in Piedmont Province.

Letters are:

a. Clinton-Newbury fault zone
b. Bloody Bluff fault zone
c. Ramapo fault zone
d. Hylas fault zone
e. Nutbush Creek fault zone
f. Silver Hill fault zone
g. Gold Hill fault zone
h. Brevard fault zone
i. Modoc fault zone
j. Fowaliga fault zone

Small +++'s indicate extension of faults beneath Coastal Plain based on geophysical evidence.

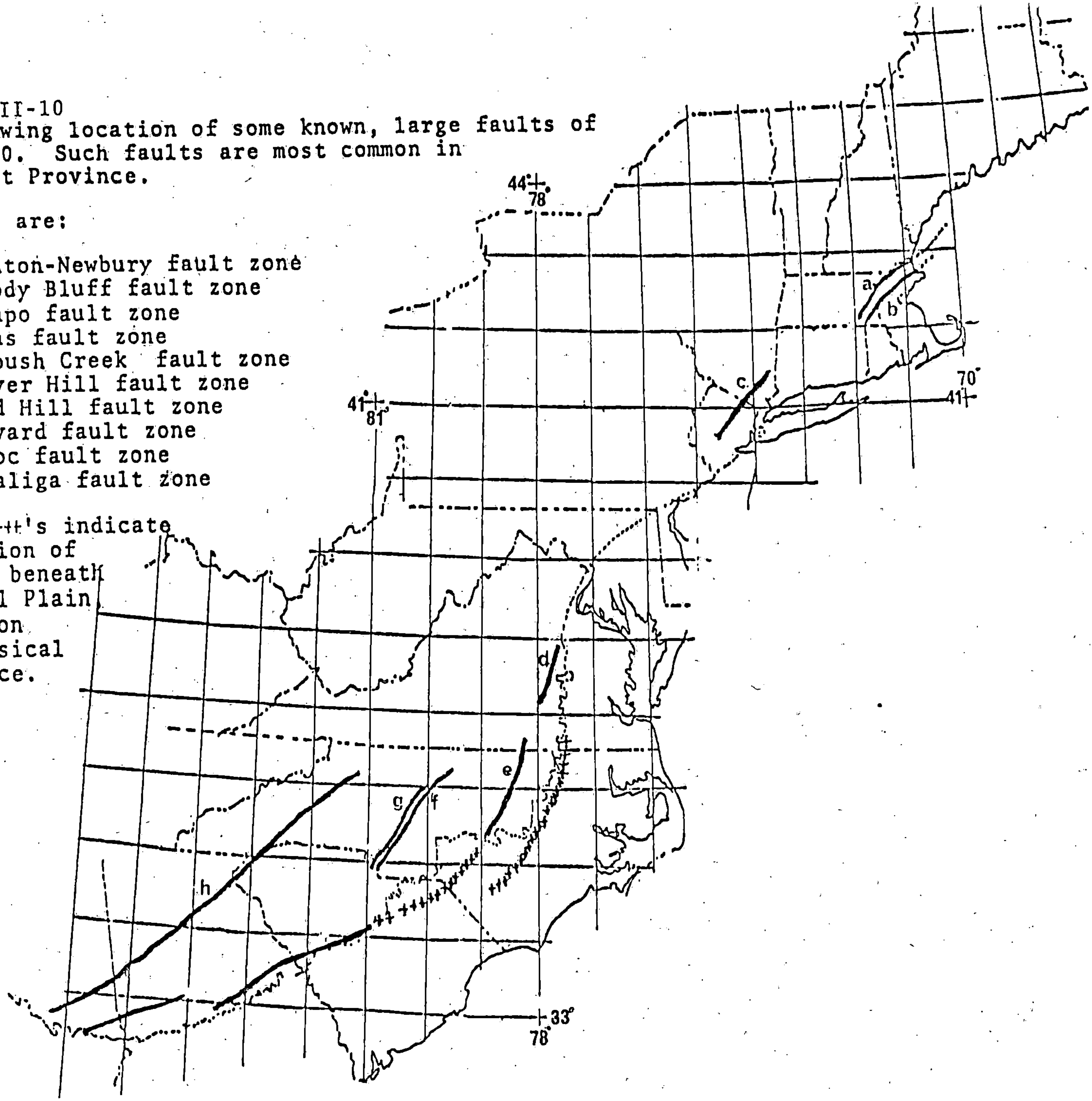


Figure II-9
Map showing the location of basins associated with Group 9 faults. Stippled pattern indicates Mesozoic basins, diagonal lines indicate Paleozoic basins in the subsurface The large south Georgia-north Florida Mesozoic graben is not shown. As mentioned in the text, faults of this class might be expected nearly anywhere in the Piedmont Province and they need not be presently associated with basins.

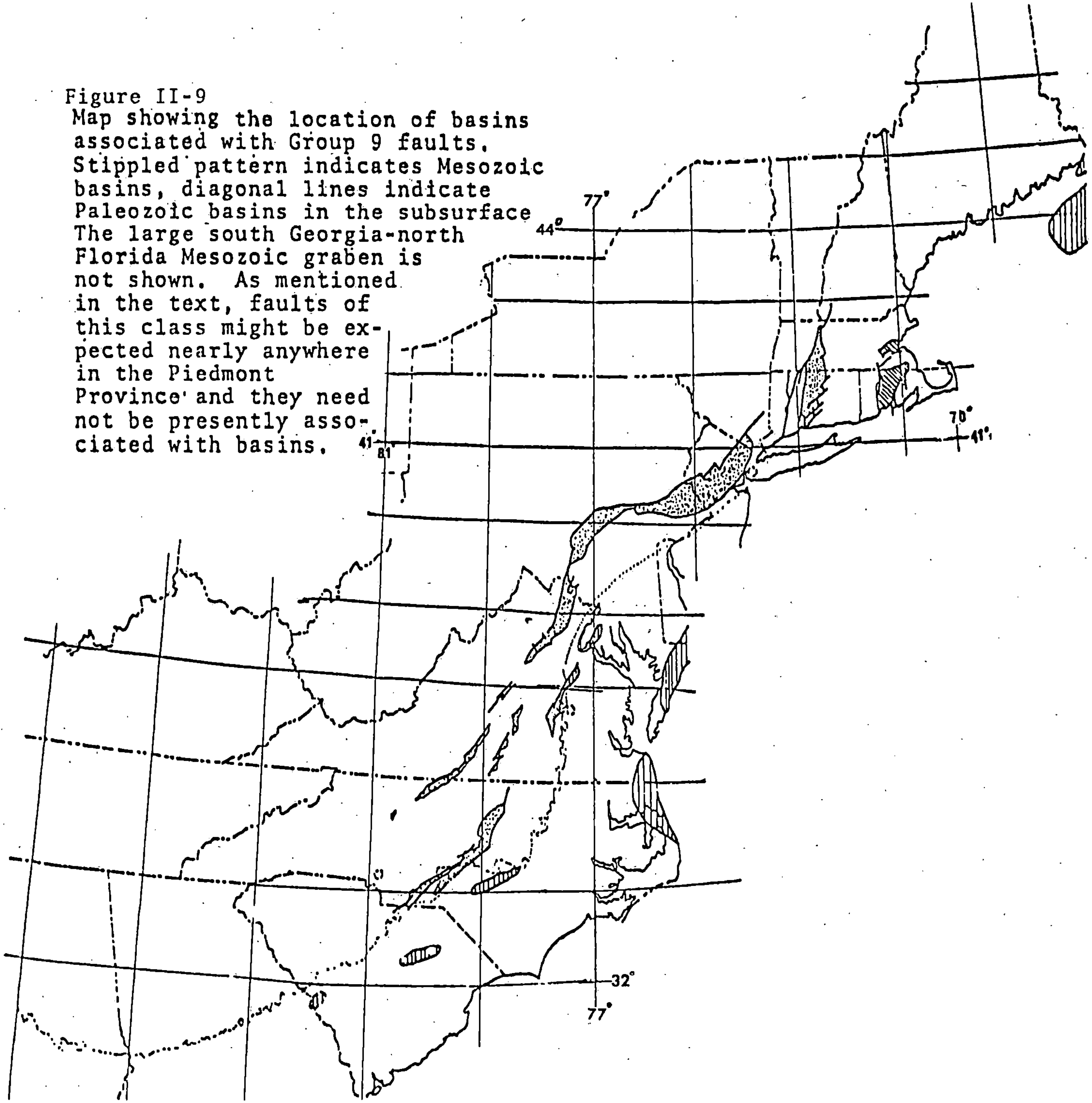


Figure II-11 Map showing local centers with which faults are associated (Group 12). Crypto explosion features are indicated by letters:

a) Panther Mountain
b) Serpent Mountain
c) Jeptha Knob
d) Versailles
e) Dycus
f) Flynn Creek
g) Well's Creek
h) Howell disturbance
i) Wetumpka

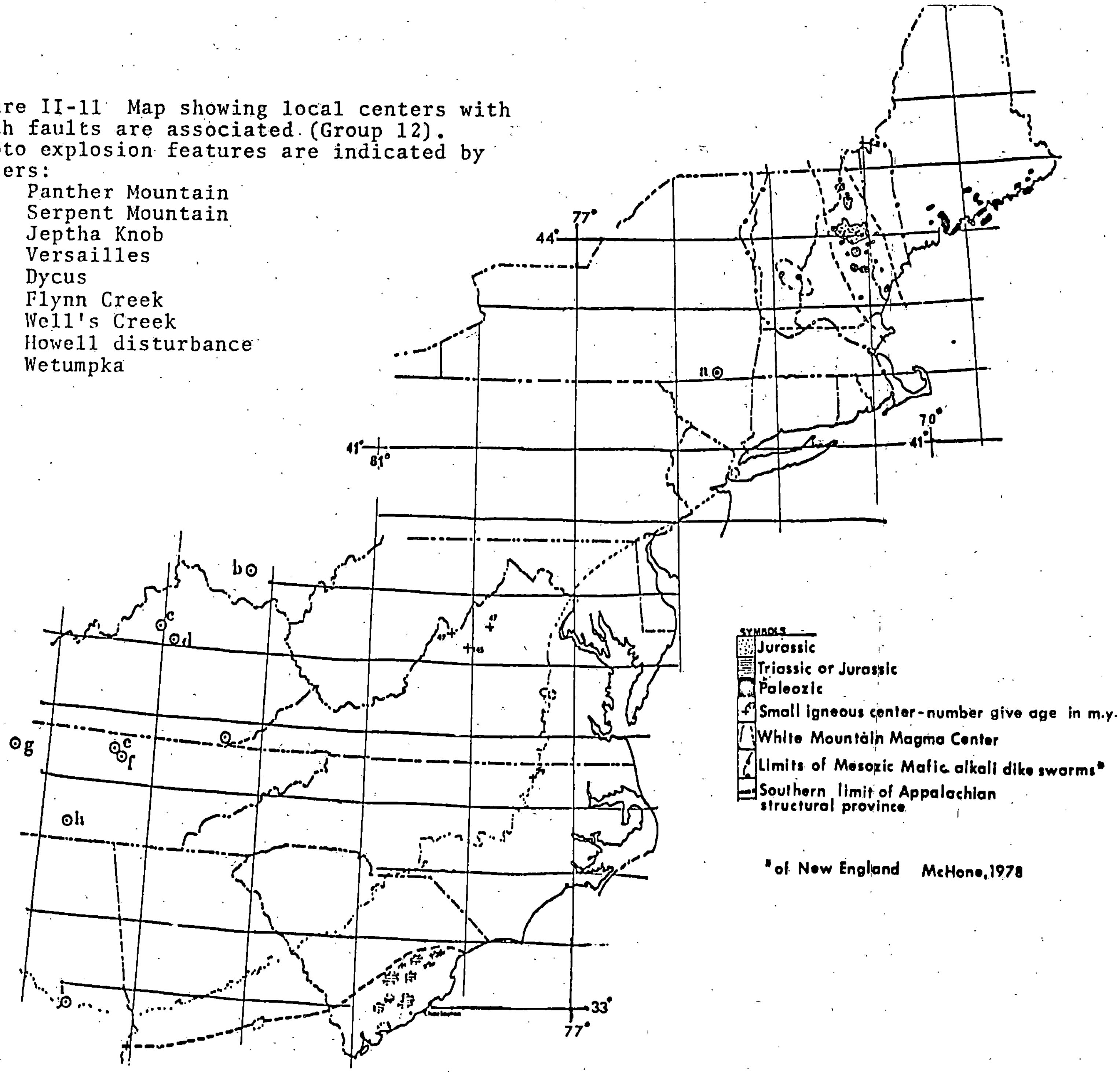


Figure II-12
Map showing distribution of Group 13 faults and features.

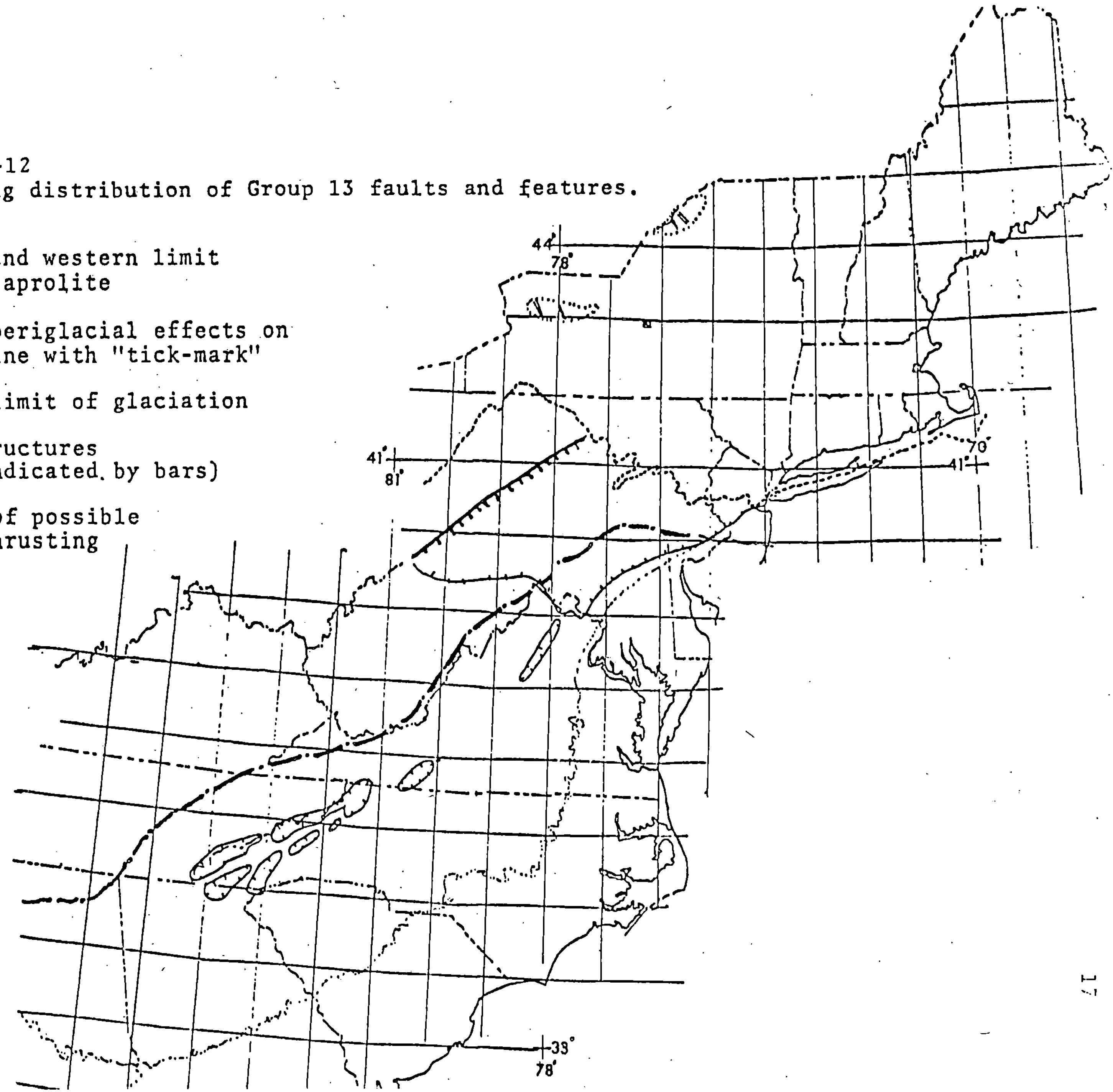
northern and western limit of thick saprolite

areas of periglacial effects on side of line with "tick-mark"

southern limit of glaciation

pop-up structures (strike indicated by bars)

location of possible glacial thrusting



To compare any two faults zones is idealistic, particularly because more than 40 variables are involved. Yet to provide a reasonable summary of faulting in the Appalachian orogen, faults were placed into one or more of thirteen groups. We placed each fault in a particular group because it is primarily characterized by attributes of that group. This by no means implies that attributes of that group are unique to that group nor does it imply that all geologists will agree with our selection of groups or the placement of faults within certain groups.

We have relied on field characteristics of fault zones as a parameter for distinguishing among the various fault groups. These parameters are, therefore, characteristics of fault zones as seen near the surface of the crust rather than hypothetical characteristics of fault zones at depth with the crust. A second parameter in guiding the selection of fault groups is the genetic relationship of faults with in the group. This led to some faults being grouped even though they have different characteristics. The third parameter in guiding the selection of groups is the sequence of events surrounding the tectonic organization of the Appalachians.

In way of explanation,one other point should be made for the most part, the detailed discussions of the various groups of faults rely heavily on the format given in Table II-15. This format was not used for groups 8, 11, 12, and 13 (strike-slip faults, enigmatic faults, faults associated with local centers, and geomorphic faults), both because these faults do readily fit such a format and the forceful use of the format to these groups would imply an internal homogeneity of character which does not exist. For the remaining nine groups the outline of Table II-15 is used, but because of insufficient information, not all items in the outline are discussed - but all were considered before being omitted.

TABLE II-I: FAULT GROUPS CHARACTERIZING THE APPALACHIAN FOLDBELT

Group I: FAULTS WITH DEMONSTRABLE CENOZOIC MOVEMENT

Excluded from this group are those which are known to be associated with recent near surface stress release. Most are high angle reverse faults. Because recognition is rare except where Cenozoic cover is present, these faults are known primarily where Coastal Plain strata onlaps the Piedmont (southern Appalachians). Exceptions to this are known and it seems probable that these faults occur in much of the piedmont.

Group 2: WILDFLYSCH TYPE THRUST SHEETS

This group of faults is composed of thrust sheets which are pene-contemporaneous with and spacially associated with wildflysch sedimentation. All known faults of this group appear to be Middle Ordovician age and located along the inner margin of the foreland between central Pennsylvania and Newfoundland.

Group 3: BEDDING PLANE THRUSTS - DECOLLEMENTS

Faults of this group are those formed from the thin-skinned deformation of the Appalachian foreland. Characteristic of the Valley and Ridge Province, these faults have most of their displacement along surfaces which parallel bedding and cut up section in the direction of tectonic transport.

Group 4: PRE- to SYNMETAMORPHIC THRUSTS IN MED to HIGH GRADE TERRANES

Faults of this group known throughout much of the Blue Ridge and Piedmont provinces and probably originated by a variety of fault mechanisms. These faults have been overprinted Paleozoic deformation and metamorphism. Premetamorphic faults of this group are knife sharp contacts separating rocks of the same metamorphic grade. Synmetamorphic faults appear to be largely represented by mylonite zones.

Group 5: POST METAMORPHIC THRUSTS IN MEDIUM TO HIGH GRADE TERRANES

Faults of this group are thrusts which occur in the medium to high grade metamorphic terrane of the Blue Ridge and Piedmont Province. These thrust usuallly displace or juxtapose contrasting isograds. Shearing or mylonitic fabric affects metamorphic minerals.

Group 6: THRUSTS ROOTED IN LOW GRADE CRYSTALLINE BASEMENT

Because thrusts which occur in the unmetamorphosed regions of crystalline basement cannot be assigned to either pre- or post- metamorphic groups, group 6 is recognized. Characteristically occur along the foreland/metamorphic core boundary as transported external massifs.

Group 7: HIGH ANGLE REVERSE FAULTS

Small scale faults of this type are so ubiquitous in much of the Appalachians that a regional characterization is not attempted. The focus of this group are the large, high angle, reverse faults bounding major structural features, such as the Boston, Norfolk, and Narragansett basins of southeast New England.

Group 8: STRIKE SLIP FAULTS

This group includes faults on all scale whose major component of slip is parallel to the fault strike. Seven subgroups are recognized.

Group 9: NORMAL (BLOCK) FAULTS

The overwhelming majority of faults are within the Piedmont Province along a zone of Mesozoic rifting. They are brittle, high angles, post-metamorphic, and commonly associated with sedimentary basins and dolerite dikes.

Group 10: COMPOUND FAULTS

Faults of this group have experienced multiple periods of reactivation (often of completely different styles) during a long history of movements and changing stress fields. They are restricted to the metamorphic terranes of the Appalachians.

Group 11: STRUCTURAL LINEAMENTS

This group includes complex and, enigmatic, linear structural elements which are not true faults and along which faults cannot always be detected. Faulst of various types do occur along these lineaments and help in defining them.

Group 12: FAULTS ASSOCIATED WITH LOCAL CENTERS

These are faults which are associated and genetically related to small local centers of disturbances such as igneous intrusions, cauldron subsidence, diapirs, and crypto-explosive structures.

Group 13: FAULTS RELATED TO GEOMORPHIC PHENOMENA

This group is composed of small to medium scale faults which are geomorphic and not tectonic in nature. They have a Late Tertiary history overprinting older Appalachian structure. This group includes saprolitic faults, karst and collapse structure, glacio-tectonic structures, mass wasting, "pop-ups" and other near-surface stress release.

TABLE II-2: FAULTS WITH DEMONSTRABLE CENOZOIC MOVEMENT (GROUP I)

	CHARACTERSITICS
BASIC GEOMETRY	Mostly high angle thrusts/reverse include Coastal Plain growth faults and salt diapir-related faults (local centers). En echelon, single faults variable length, most are nearly parallel to structural grain (Belair N-NE). Very linear commonly splay terminates into monoclines.
TECTONIC SETTING	Occur in all provinces.
CHARACTERISTICS OF SURFACE OR ZONE	Brittle. Sharp planes. Fault planes hard to discern in massive unconsolidated sands. May have 1-10cm gouge zones. Slickensided. C^{14}, fossils, geomorphic features used for dating.
RELATION TO COUNTRY ROCK	Most subparallel to regional grain. Most thick-skinned. Related to changes in stratigraphic thicknesses. Independent of rock type.
HISTORY	Most late Cretaceous and pre-Eocene. Do not cut late Tertiary.
STRESS FIELD	σ_1 Horizontal-NW.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Some associated with seismicity.
GEOMORPHIC RELATIONSHIPS	Changes in streams, Scarps, fault line scarps. Aligned ravines, rapids, falls.
METHODS OF IDENTIFICATION	Faulted Cretaceous or Cenozoic rocks. Absence of zeolite facies minerals. Detailed mapping.
PITFALLS IN IDENTIFICATION	May be old faults of small displacement.
POSSIBILITIES OF REACTIVATION	Good.
KEY REFERENCES	Mixon and Newell (1977), Howell and Zupan (1974).

TABLE II-3: FAULTS PENECONTEMPORANEOUS WITH WILDFLYSCH (GROUP 2)

	CHARACTERISTICS
BASIC GEOMETRY	Penecontemporaneous bedding thrusts. Allochthonous masses parallel regional grain. Strongly curved.
TECTONIC SETTING	Associated with destruction of early Paleozoic margin in Appalachians. Moved by gravity into active basin. Shed blocks off front during movement (wildflysch).
CHARACTERISTICS OF SURFACE OR ZONE	Ductile, low angle, old strata on young rarely ideal bedding thrusts. Lack slickensides, mineralization. Fault surfaces may be cryptic. May contain competent slices along faults. May be accompanied by zeolite facies metamorphism.
RELATION TO COUNTRY ROCK	Parallel local grain. Thin-skinned, occur in regions of maximum U. Ordovician clastic thickness. All in Appalachians are pre-Upper Ordovician low T-P.
HISTORY	Arrival indicated initial destruction of eastern shelf edge of N. America during the Paleozoic. Overlain by U. Ordovician molasse in New York and Pennsylvania.
STRESS FIELD	Unknown
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Coextensive with major gravity low along western edge of Appalachians.
GEOMORPHIC RELATIONSHIPS	None
METHODS OF IDENTIFICATION	Stratigraphic, paleontological methods, unique exotic lithologies carried in sheets. Rocks of autochthon may be truncated beneath lowest slices.
PITFALLS IN IDENTIFICATION	May be mistaken for blocks in wildflysch. May not recognize faults. Overprinted by younger structures.
POSSIBILITIES OF REACTIVATION	None, except by landsliding.
KEY REFERENCES	Bird and Dewey (1970); Potter (1979); Root and MacLachlin (1978); Voight and Cady (1978); Zen (1967; 1972).

TABLE II-4: BEDDING PLANE THRUSTS (GROUP 3)

	CHARACTERISTICS
BASIC GEOMETRY	Concave up. Parallel to bedding except at ramps and parallel to regional grain. Cut up section in direction of transport (toward the craton). Propagate along zones of weakness. Basement not involved. Imbricated, curved. Terminated into folds and tears.
TECTONIC SETTING	Miogeoclinal foreland areas. Valley and Ridge, and Plateau.
CHARACTERISTICS OF SURFACE OR ZONE	Discrete surface or surfaces. Slickensides, grooves. Calcite and quartz mineralization.
RELATION TO COUNTRY ROCK	Parallel or obliquely cut regional trends. Changes in style; occur at promontories. Thin-skinned controlled by stratigraphic interval of decollement. Steeply ramp across competent units. Low pressure-temperature. Locally injected shale gouge.
HISTORY	Generally among last structures to form in any orogen. Time of inception of foreland thrusting uncertain.
STRESS FIELD	σ_1 generally perpendicular regional grain. Considerable variation in strain along fault plane and within thrust sheets.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Basement not involved (except locally). Stacking of sheets may have produced gravity low.
GEOMORPHIC RELATIONSHIPS	Sheets seldom outlined (except Pine Mountain). May bring up units of differing erosional properties.
METHODS OF IDENTIFICATION	Restriction of fault to one or two stratigraphic units. Properties described under Basic Geometry.
PITFALLS IN IDENTIFICATIONS	May overprint or be overprinted by other structures making identification difficult. Flexural-slip along beds. Local wedging overlooked because of thin deformed zones.
POSSIBILITIES OF REACTIVATION	Slight. Artificial loading or in situ stress may cause some readjustments.
KEY REFERENCES	Chapple (1978); Dahlstrom (1970); Gwinn (1964); Harris and Milici (1977); Rich (1934); Wiltschko (1979).

TABLE II-5: PRE-TO SYNMETAMORPHIC FAULTS IN MEDIUM TO HIGH GRADE TERRANES (GROUP 4)

	CHARACTERISTICS
BASIC GEOMTERY	Thin-skinned (brittle) pre-metamorphic thrusts, fold nappes, tectonic slides (ductile); transported ophiolite sheets. Subparallel to regional grain. May merge with folded zones.
TECTONIC SETTING	Pre - Detachments within shelf or slope sediments along a collapsing margin. Become part of metamorphic core. Syn - Metamorphic core under greenschist or higher grade conditions.
CHARACTERISTICS OF SURFACE OR ZONE	Boundaries range form knife-sharp to thick mylonites. All may be annealed during metamorphism. Generally complexly folded.
RELATION TO COUNTRY ROCK	Pre - May have any orientation relative to regional grain. May parallel or cross layering. Isograds overprint. Syn - Generally related to one or more dominant s-surface. Behave as thick slabs. Moderate to high T-P. May parallel or truncate isograds.
HISTORY	Tied to thermal peak(s), type of behavior, relation to isograds, whether there is reactivation are keys to history.
STRESS FIELD	Best reconstructions yield σ_1 oriented toward the craton.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Not expressed on seismic reflection profiles or gravity maps. Faults do not produce a magnetic signature but thrust sheets of contrasting properties would likely have different magnetic properties.
GEOMORPHIC RELATIONSHIPS	Few, depending upon the erosional properties of juxtaposed rocks.
METHODS OF IDENTIFICATION	Differences in rock type, stratigraphy, mylonites, cataclastics where they occur.
PITFALLS IN IDENTIFICATION	Not recognizing stratigraphic differences, mylonites. Confusing brittle/ductile events. Age dates may indicate metamorphism or cooling rather than movement.
POSSIBILITIES OF REACTIVATION	Slight along brittle, high angle segments.
KEY REFERENCES	Armstrong (1951); Dixon and Lundgren (1968); Hadley and Goldsmith (1963); Hatcher (1978); King (1964); Lundgren (1973); Roper and Dunn (1973); Wise (1970).

TABLE II-6: POSTMETAMORPHIC THRUSTS IN MEDIUM TO HIGH GRADE TERRANES (GROUP 5)

	CHARACTERISTICS
BASIC GEOMETRY	Juxtapose isograds. Commonly folded. Parallel or subparallel to regional grain. Occur as sheets, and isolated allochthons.
TECTONIC SETTING	Metamorphic core- formed during waning stages of metamorphism.
CHARACTERISTICS OF SURFACE OR ZONE	Contacts may be knife-sharp; some may contain mylonites. Ductile faults.
RELATION TO COUNTRY ROCK	Regionally parallel to trends but may cross. Subparallel dominant s-surface. May follow weaker lithologies. Low to medium P-T. Truncate isograds.
HISTORY	Always on cooling side of thermal peak. May considerably postdate thermal peak.
STRESS FIELD	σ_1 directed toward the craton.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Poorly to moderately expressed on seismic reflection data. Expressed on gravity or aeromagnetic data if sheets produce contrast with adjacent rocks.
GEOMORPHIC RELATIONSHIPS	Few, depending upon erosional properties of juxtaposed rocks.
METHODS OF IDENTIFICATION	Offsets, juxtaposition of metamorphic zones. Truncation of rock units. Deletion of rock units.
PITFALLS IN IDENTIFICATION	Confusion with pre- to synmetamorphic faults. Must identify juxtaposed metamorphic zones.
POSSIBILITIES OF REACTIVATION	Unlikely except locally along high angle segments.
KEY REFERENCES	Bryant and Reed (1970); Conley and Henika (1973); Griffin (1974); Hatcher (1978b, 1978c); Ratcliffe and Harwood (1975)

TABLE II-7: THRUSTS ROOTED IN LOW GRADE TO UNMETAMORPHOSED CRYSTALLINE BASEMENT (GROUP 6)

	CHARACTERISTICS
BASIC GEOMETRY	Low angle thrusts that carry basement and may behave as thin-skinned thrusts where they involve cover. Thrusted fold nappes, basement thrust sheets, ductile to brittle faults, commonly imbricated. May terminate into folds.
TECTONIC SETTING	Boundary between metamorphosed core and foreland. External massifs. Maybe the thinned eastern edge of the continental crust of eastern N. America.
CHARACTERISTICS OF SURFACE OR ZONE	Occur in transition zone between brittle and ductile behavior. Fault zones may range from knife-sharp to mylonites several m. thick. Determined partly by lithologies present. Minimal metamorphism-prograde greenschist to retrograde.
RELATION TO COUNTRY ROCK	Parallel structural grain regionally but locally cross-cutting. Thick-skinned but show thin-skinned properties. May relate to original basement highs where sedimentation absent. Low to moderate T-P. Generally parallel isograds, locally truncate.
HISTORY	Timing varies within orogen. Overprinted by later structures, cut by veins, Mesozoic dikes. May have been reactivated later.
STRESS FIELD	Uncertain, σ_1 probably oriented N.W. or W.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Faults do not have magnetic or gravity expression. Massifs do have. Blue Ridge thrust easily recognized on seismic reflection profiles.
GEOMORPHIC RELATIONSHIPS	Transported rocks of varying resistance to erosion produce Blue Ridge, other highlands (Reading Prong, Hudson, Berkshire, etc.).
METHODS OF IDENTIFICATION	Stratigraphic analysis, recognition of transported basement resting upon cover rocks, deformed zones.
PITFALLS IN IDENTIFICATION	Confusion with faults in higher grade rocks; with thin-skinned decollement thrusts.
POSSIBILITIES OF REACTIVATION	Slight along brittle and/or high angle segments.
KEY REFERENCES	Cloos (1971); Drake (1970, 1976); King and Ferguson (1950); USGS Prof. Paper 888; Ratcliffe (1975); Wickham (1972).

TABLE II-8: HIGH ANGLE REVERSE FAULTS (GROUP 7)

BASIC GEOMETRY	strike length up to 20-50 km; width of zone from knife sharp to a few hundred feet; displacement perhaps in excess of 10,000 ft. Major faults show broad arcuation; local offsets by cross faults.
TECTONIC SETTING	Late stage in the Paleozoic history of the Appalachian orogeny.. Some in SE New England might be a continuation of Carboniferous basin development and associated strike slip motions in Nova Scotia.
CHARACTERISTICS OF SURFACE OR ZONE	Largely brittle. Some are knife sharp, others are zones of high sheared and crushed rock. Drag folds and slickensides common.
RELATION TO COUNTRY ROCK	Thick-skinned (crystalline basement involved). Regionally most are sub-parallel to grain of Boston platform and deformed basement fills, some are basin boarder faults.
HISTORY	Some could be as old as Precambrian. Carboniferous activity can be documented. There are no certain indications of post Paleozoic movements.
STRESS FIELD	Magntiude and orientation uncertain - see text. (Chapter XI)
GEOPHYSICAL AND SUBSURFACE CHARACTERISTICS	No seismicity known to be associated with land portions of basin related fautls (however faults of the area north of Boston strike NE toward Cape Ann epicentral region. Geophysical anomalies due to contrasting lithologies juxtaposed.
GEOMORPHIC RELATIONSHIPS	Fault line scarps fromed by removal of less resistant basin fills.
METHODS OF IDENTIFICATION	Through association with contacts at edge of sedimentary basins and observed displacement in outcrops (such as tunnel exposures)
PITFALLS IN IDENTIFICATION	To SE New England, it is erroneous to assume that all basin boundaries are fault related. Because of knife sharp contacts, these faults may be difficult to recognize outside of basins.
KEY REFERENCES	Skehan (1968), Quinn and Moore (1968) and Billings (1976).

TABLE II-9: STRIKE-SLIP FAULTS (GROUP 8)

	CHARACTERISTICS
BASIC GEOMETRY	Steep dips, horizontal transport parallel fault plane. Splays and anastomosing segments. Curved and straight segments.
TECTONIC SETTING	Occur in any part of an orogen.
CHARACTERISTICS OF SURFACE OR ZONE	Generally knife-sharp with thin cataclastic zones in shallow faults; at depth become broad ductile shears.
RELATION TO COUNTRY ROCK	Parallel to or across regional trends. Generally not stratigraphically controlled, except tears associated with thrust sheets.
HISTORY	Generally post-metamorphic. Older dip-slip faults may be reactivated with strike-dip motion.
STRESS FIELD	Tears - σ_I horizontal toward craton. Cross faults - σ_I N.S.? Strike-slip faults - left lateral σ_I N.S. right lateral - σ_I E.W.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	May broaden at depth to ductile shears. May be expressed as magnetic lineaments. Not detected on seismic reflection profiles.
GEOMORPHIC RELATIONSHIPS	Topographic lineaments related.
METHODS OF IDENTIFICATION	Truncation and/or offset of stratigraphic units. Recognition of near-vertical fault zones.
PITFALLS IN IDENTIFICATION	All steep fault zones not strike-slip. Apparent strike-slip produced by oblique or dip-slip.
POSSIBILITIES OF REACTIVATION	Good if proper stress regime is restored and fault not annealed.
KEY REFERENCES	King and Ferguson (1960); Moody and Hill (1959).

TABLE II-10: BLOCK (NORMAL) FAULTS (GROUP 9)

	CHARACTERISTICS
BASIC GEOMETRY	Steep dips disrupt basement. Straight to arcuate. May reactivate old faults.
TECTONIC SETTING	Rifts which formed along continental margin upon opening of Iapetus and Atlantic. None found west of the Piedmont in the Appalachians (except Rome trough).
CHARACTERISTICS OF SURFACE OR ZONE	Brittle faults, splays form blocks and complex zones. Zeolite and calcite mineralization.
RELATION TO COUNTRY ROCK	Parallel to sub-parallel to regional trends. Orientation of foliation in country rocks may control orientation of faults.
HISTORY	Rifting stage of Wilson cycle. Successor to orogenic phase. Syndepositional movement. (Triassic-Jurassic).
STRESS FIELD	σ_1 vertical. Parallel to strike.
GEOPHYSICS AND SUB-SURFACE CHARACTERISTICS	Seismic profiles show configurations of basin sediments. Basins and boundaries expressed as magnetic lows.
GEOMORPHIC RELATIONSHIPS	Fault scarps well expressed (fault line scarps in some cases).
METHODS OF IDENTIFICATION	Evidence of basin fill. Mineralization increases fracture density.
PITFALLS IN IDENTIFICATION	Brittle behavior with the strike parallel to the regional may not be Triassic. Timing may not be restricted to Mesozoic, could also be Tertiary. Splays.
POSSIBILITIES OF REACTIVATION	Should be considered a possibility, but all studies to date have not shown any reactivations.
KEY REFERENCES	

TABLE II-11: COMPOUND FAULTS (GROUP 10)

	CHARACTERISTICS
BASIC GEOMETRY	High to low angle. Variable length/width. Ductile to brittle behavior. Maybe stratigraphically controlled. Generally parallel regional strike. Multiple stage of movement is characteristic.
TECTONIC SETTING	Metamorphic core.
CHARACTERISTICS OF SURFACE OR ZONE	Wide ductile mylonitic zones and narrow, more sharply-defined cataclastic zones. Some phases retrogressive. Rb-Sr whole rock-technique used to date ductile events.
RELATION TO COUNTRY ROCK	Dominant foliation generally parallel to regional foliation, but may transpose it. May control depo-centers. Character of fault varies with nature of adjacent country rocks. Isograds may overprint portions of faults not reactivated.
HISTORY	Range from p-Є into PZ for times of inception. Movement episodic throughout PZ, some in Mesozoic to possibly still active.
STRESS FIELD	Varies considerably with time. σ_1 ranges from normal to fault plane and parallel to the surface to oblique to plane; from compressional to tensional.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Range from aseismic to active. May be expressed on magnetic maps, visible on seismic reflection surveys.
GEOMORPHIC RELATIONSHIPS	May be strongly expressed in topography. Fault scarps, line scarps, mylonitic cataclastic ridges and valleys. Nearby lineaments may be mistaken for fault.
METHODS OF IDENTIFICATION	Prove polyphase motion, and both ductile and brittle. (Multiple or both).
PITFALLS IN IDENTIFICATION	Changing character along strike. Misinterpretation of lineaments which are not related to faults. Misidentification of mylonitic and cataclastic features as part of complex fault when part of another fault.
POSSIBILITIES OF REACTIVATION	Good to excellent along high angle segments.
KEY REFERENCES	Vary with individual faults.

TABLE II-12: ENIGMATIC FAULTS (GROUP II)

	CHARACTERISTICS
BASIC GEOMETRY	Includes faults, fractures, folds, intrusions. Basement involved and thin-skinned. Variable lengths, widths and orientations, generally at large acute angle to regional strike. Generally not very continuous.
TECTONIC SETTING	May be found anywhere in orogen (basement controlled). Supracrustals confined to plates. Increase in intensity of some structures or set of structures at high angle to strike.
CHARACTERISTICS OF SURFACE OR ZONE	Increase in intensity of some structures or set of structures at high angle to strike. Termination or change in strike of structures. Belts of igneous activity.
RELATION TO COUNTRY ROCK	High angle to regional grain. No relation to embayments and promontories. Generally basement-related changes in isopachs. Basement-controlled types may be stratigraphically passive or active.
HISTORY	Varies from structure to structure. Basement controlled types are oldest.
STRESS FIELD	Unknown
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Site of seismic activity. Gravity and magnetic lineaments commonly associated. Subsurface displacement not well documented.
GEOMORPHIC RELATIONSHIPS	Ridge offsets, water and wind gaps.
METHODS OF IDENTIFICATION	Detailed geological mapping though visible on many LANDSAT plates.
PITFALLS IN IDENTIFICATION	Overuse of LANDSAT.
POSSIBILITIES OF REACTIVATION	Many are active, all should be treated with caution.
KEY REFERENCES	Wheeler, _et al._, (1978).

TABLE II-13: FAULTS ASSOCIATED WITH LOCAL CENTERS (GROUP 12)

	CHARACTERISTICS
BASIC GEOMETRY	Local disturbances with associated faulting. Includes intrusives, diapirs, cryptoexplosives. Generally high angle faults.
TECTONIC SETTING	May be found in parts of orogen where intrusives occur. Or in the case of cryptoexplosives, any part of the orogen.
CHARACTERISTICS OF SURFACE OR ZONE	Generally brittle faults with cataclasite (breccias, gouge).
RELATION TO COUNTRY ROCK	May offset and involve country rocks.
HISTORY	Wide range.
STRESS FIELD	Related to centers that control faults.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Related to centers.
GEOMORPHIC RELATIONSHIPS	Some cryptoexplosives expressed as ring-shaped structures and basins.
METHODS OF IDENTIFICATION	By association with local centers.
PITFALLS IN IDENTIFICATION	May not be related to center.
POSSIBILITIES OF REACTIVATION	Some active.
KEY REFERENCES	

TABLE II-14: GEOMORPHIC FAULTS (GROUP 13)

	CHARACTERISTICS
BASIC GEOMETRY	Saprolite slickensides. Karst collapses, glacio-tectonic structures. Permafrost structures, landslides and mass movements, stress-release features. Mostly high angle faults, though some can be low angle.
TECTONIC SETTING	Occur in any tectonic subdivision where proper conditions occur.
CHARACTERISTICS OF SURFACE OR ZONE	Generally brittle.
RELATION TO COUNTRY ROCK	Spacial relation to country rocks.
HISTORY	Generally post-Appalachian tectonics.
STRESS FIELD	Unique to each process.
GEOPHYSICS AND SUBSURFACE CHARACTERISTICS	Not applicable.
GEOMORPHIC RELATIONSHIPS	All surficial.
METHODS OF IDENTIFICATION	Confined to surface processes.
PITFALLS OF IDENTIFICATION	May be mistaken for older bedrock features.
POSSIBILITIES OF REACTIVATION	Good. But may not be seismic. If so, are in another realm.
KEY REFERENCES	

TABLE II-15: FEATURES CONSIDERED IN FAULT DESCRIPTIONS

1. Basic geometry
   a. strike length
   b. width perpendicular to strike
   c. spatial orientation
   d. displacement
   e. continuity
   f. curvature
   g. termination along strike
2. Tectonic setting
3. Characteristics of surface or zone
   a. type of faults, i.e., brittle vs. ductile
   b. surface texture
   c. material present, i.e., gouge, mylonite, etc.
   d. metamorphism and/or mineralization
   e. datable materials
4. Relation to country rock
   a. parallel or across regional grain (scale)
   b. salient or re-entrant
   c. thick-skinned or thin-skinned
   d. relation to stratigraphic thickness changes (isopachs)
   e. stratigraphic interval affected
   f. relation to folds
   g. relation to S-surfaces
   h. change in fault character with changing lithology
   i. P-T conditions
   j. relation to isograds
   k. relation to intrusions
   l. tectonic injections

5. History

    a. age of inception

    b. recognition of syndepositional effects

    d. relation to erosional unloading

    e. indications of last motion

6. Stress field

    a. orientation of principal stresses at inception

    b. magnitude of principal stresses and strains

    c. variation through time of stress and strain

    d. present _in situ_ stress

    e. seismic first motion studies

    f. rates of motion

    g. fluid pressure changes and effects

7. Geophysical and subsurface characteristics

    a. seismic activity level

    b. subsurface displacements

    c. relation to gravity, magnetic, etc. anomalies

    d. relation to geophysically expressed lineaments

8. Geomorphic relations

9. Methods of identification

10. Pitfalls in identification

11. Possibility of re-activation

12. Selected reference list for this fault group

III. FAULT REACTIVATION

A. Fault Groups Most Subject to Reactivation

Fault groups 1, 6, 8, 9 and 12 are brittle faults, either unhealed or filled; consequently, these faults are planes or zones of mechanical discontinuity with respect to the country rocks enclosing them. All must be considered as possible candidates for reactivation, depending on the magnitude of the resolved shear stress they support, because they have lower shearing strength than the country rocks.

Particular attention must be given to group 12 faults. The largest historic earthquakes located in the Appalachian Orogen were at Cape Ann, Massachusetts (1755) and Charleston, South Carolina (1886). Both were on the flanks of local intrusive centers where stress intensification exists because of a mismatch of mechanical properties between the intrusion and the country rock (Kane, 1977; Simmons, 1978).

Finally, group 10 faults have long histories of reactivation and at least some portions of their total movement histories were brittle. Moreover, some modern seismicity has been associated with the Ramapo fault (Aggarwal and Sykes, 1978). However, the location of foci on the Ramapo has been disputed by a 1977 investigation by Dames and Moore (see chapter XIV).

B. Fault Groups Least Subject to Reactivation

Fault groups 4, 5 and 10 are either healed brittle faults or ductile faults (terminology defined in Section II. below); consequently, they are not planes or zones of mechanical discontinuity with respect to the country rocks enclosing them. A word of caution is in order with respect to the foregoing generalization. Mylonitic rocks frequently have a higher degree of preferred orientation and more penetrative foliation than the rocks from which they were derived. In this case the penetrative mylonitic foliation does have a lower shear strength than the country rocks. Jackson (1973) has demonstrated as much as 62% reduction in shear strength for mylonites compared to their source rocks where the mylonitic foliation was oriented near the plane of maximum resolved shear stress. The extent of this effect is demonstrated by the common occurrence of brittle faults superimposed on faults of groups 4, 5 and 10. Typically the brittle features constitute the more easily eroded and less well exposed portions of these fault zones.

C. Successful Techniques For Dating Last Motion

1. Dikes, veins, or other rocks which cross-cut a fault may be dated isotopically or placed in the relative geologic time scale.
2. Rocks which cover a fault may be dated isotopically or placed in the relative geologic time scale.
3. Faults may be partially or totally filled by minerals which can be dated isotopically, or whose stability fields suggest growth at elevated T-P conditions. The T-P condition implies a certain depth of burial at the time of mineral growth. If reasonable estimates can be made of the rate of erosional unloading, the time required to expose the minerals in question can be calculated.
4. Fault movement generates microcracks in mineral grains adjacent to the movement surface. New mineral growth might begin to heal or fill these microcracks as soon as they form. If mineral growth kinetics are known for the appropriate T-P condition, the volume of crack healing or filling is a direct measure of the age of the crack. If mineral growth kinetics are unknown it may still be possible to estimate age, by comparing the degree of healing or filling in the subject cracks to the degree of healing or filling in cracks associated with faults of known age and similar thermal history.

D. Relation of Seismicity to Surface Breaks

There are two curious aspects to modern seismicity in the Appalachian Orogen. First, the relation of intensity effects to epicentral distance suggests that there is less attenuation of seismic energy in the crust of the eastern and central U.S., than in the western U.S. (Bollinger, 1977). Presumably this reflects the lack of major discontinuities and general greater cohesiveness of the crust in the east.

Although ground breakage in the form of fissures, craterlets, and sand and water fountains, is well documented for the Cape Ann and Charleston events (Bollinger, 1977; Simmons, 1978) surface breakage is conspicuously absent for most modern seismic events. Thus, surface geology may be a relatively poor guide to the potential hazards of a specific site.

IV. DEFINITIONS OF KEY TERMS

The usual distinction between a fault and a joint is motion dependent. A joint is marked by separation normal to the plane whereas a fault undergoes shear displacement. Euphemisms for faults abound, including "shear zones", "zones of displacement", "dislocation zones", or "shear joints." All such structures, so characterized, are to be considered as faults.

A. Fault

A fault is a tabular or planar discontinuity characterized by motion parallel to itself. The discontinuity might be marked either by loss of cohesion or by extreme ductile deformation.

1. Ductile fault - A ductile fault involves continuous permanent strain without loss of cohesion normal to the fault at the time of last motion. Cohesion as used here refers specifically to the tensile strength of the fault surface or zone and the materials with it.
2. Brittle fault - A brittle fault is characterized by loss of cohesion normal to the fault at the time of last motion. Brittle faults may be subdivided into three categories.
   a. Unhealed - An unhealed brittle fault has remained essentially unchanged since its last motion.
   b. Filled - A filled brittle fault has been modified by new mineralization which partially or totally fills and cements open space along the country rocks enclosing the fault.
   c. Healed - A healed brittle fault has been modified by new mineralization and/or recrystallization so that the shearing strength of the fault zone is equal to that of the enclosing rocks.

The relationship between brittle and ductile faults is shown schematically in Figure IV-1.

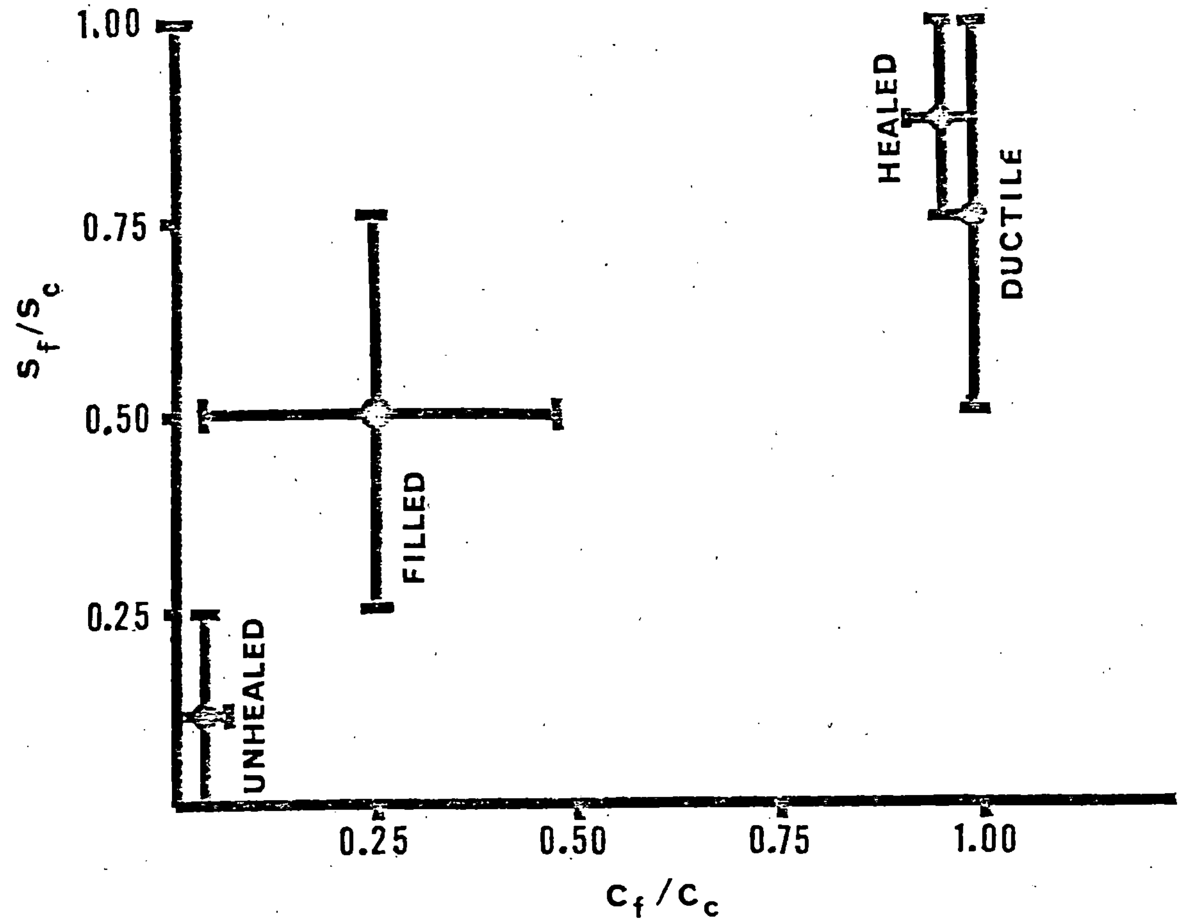


Figure IV-1. The vertical axis is the ratio of shearing strength for the fault (S_f) to shearing strength for the country rock (S_c); while the horizontal axis is the ratio of cohesion for the fault (C_f) to cohesion for the country rock (C_c). The error bars suggest the degree of variation in the ratios, but are approximations only.

B. Fault Motion

To describe the movement of any fault, it is imperative to distinguish between slip (actual relative motion) and separation (apparent relative motion) using the carefully defined terminology given by Reid and others (1913), Crowell (1959), Hill (1959), and Billings (1972, p. 174-198).

C. Fault Zone Materials

There is great confusion in the literature over the genetic interpretation of terms used to describe materials generated in a fault zone during movement. We accept the descriptions given by Higgins (1971) but reject many of his genetic interpretations, because we believe he fails to recognize the role of ductile processes in the formation of some fault zone materials.

1. Cataclasis - "The process by which rocks are broken and granulated due to stress and movement during faulting; granulation or comminution" (Higgins, 1971). Cataclasis is a brittle process and cataclastic rocks include: breccia, microbreccia, gouge, flinty crush rock, and pseudotachylites.
2. Mylonitization - A ductile process involving high ductile strain and incomplete recovery. "Mylonitic rocks are strongly foliated metamorphic rocks which may contain megacrysts flattened and extended in the foliation and/or ribbon quartz (which may now be microscopically recovered). Dimunition of grain size is characteristic of this process" (Hatcher, 1978a). Mylonitic rocks include: phyllonite, blastomylonite, mylonite, and ultramylonite.

V.

GROUP I: FAULTS WITH DEMONSTRABLE LATE MESOZOIC OR CENOZOIC MOVEMENT

A. Generalized description

Included in this class are all faults with displacement which can be demonstrated to post-date major Triassic-Jurassic block faulting; as such, these faults do no necessarily share a common genetic history. However, a very large majority of documented faults of this class appear to be high-angle and reverse in nature. These faults will be reviewed in detail under Section B (Description of fault group). Other fault types will be covered under a discussion by subgroup.

Recognition of faults of this group is usually dependent upon their association with faulted Cretaceous or Cenozoic sediments. In the absence of such material documentation of late Mesozoic or Cenozoic movement is very difficult. For this reason the distribution of these faults is uncertain, although they appear to be present in all the major geologic provinces of the southern and central Appalachians (figure II-2). Knowledge of the extent of faults of this class in the northern Appalachians is limited due to the absence of Cretaceous and Tertiary sediments.

Fault Subgroups

Thrust faults

Schäfer (1979) and Block et al. (1979) have recently described evidence for modern thrusting in the Valley and Ridge province and crystalline portions of the Appalachians [see chapter XVII]. Both studies justified the presence of modern thrusting by the presence of offsets in drill holes used for blasting operations during the construction of roadcuts. Similar structures have been observed in numerous quarry excavations in the Piedmont of the southern Appalachians (J.R. Butler, pers. comm., 1979). Schäfer (1979) described offsets in both sedimentary layers and in modern

(10 year-old) drill holes present in folded and thrusted Pennsylvanian shales and sandstones (figure V-1). He attributed the offset of drill holes to reactivation along previously existing fault planes. Block et al. (1979) described offsets in drill holes present in an interbedded sequence of quartz-biotite-plagioclase schist and calc-silicate gneiss. Offsets are along pre-existing foliation surfaces and fault planes which also display well-developed slickensides. Repeated measurements which were taken over an 8-year period indicated a relatively continuous rate of offset of 2.8 mm/year. The authors suggest that this motion was at least in part responsible for local microseismic activity and associated "Moodus noises."

Unfortunately these examples are completely based on sites where large-scale rock excavation has taken place. While the structures described are technically faults, their origin may be due to the local release of stress caused by unloading rather than regional tectonic stresses capable of producing macroseismic activity. Unitl additional studies can substantiate a macroscopic (map-scale) character for these structures they should be considered to be features analogous to "pop-ups" described under geomorphic faulting.

Conley and Drummond (1965) have described possible thrust-faulted Pleistocene or Pliocene alluvium, colluvium, and underlying gneiss located near the base of the Blue Ridge topographic escarpment is southwestern North Carolina. The presence of the structure near the base of a slope and the weathered nature of the bedrock suggest this may actually be a geomorphic feature produced by large-scale slumping.

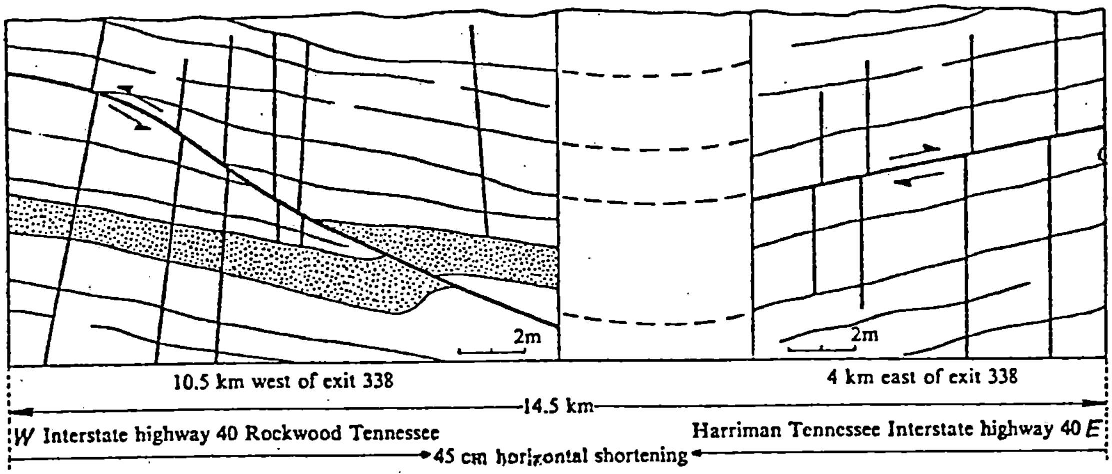


Figure V-1. Recent thrusting and folding of a syncline in Pennsylvanian sandstones and shales (stippled), between Rockwood, Tennessee and Harriman, Tennessee. More or less vertical lines indicate boreholes that are offset at a recently reactivated thrust-fault (left) and along a bedding plane (right). (from Schafer, 1979).

Block faults and growth faults

Late Mesozoic and Cenozoic faults of this type have not been documented within the Appalachians proper, but they may be present in the subsurface of the adjacent Atlantic Coastal Plain of Virginia (Cederstrom, 1945), North Carolina (Baum and Prowell, 1979), and Georgia (Cramer, 1969). Cretaceous and Tertiary faults of this type are well-documented in the Gulf Coastal Plain of Alabama (Copeland et al., 1977).

High-angle reverse faults

This type of fault is the only type in the Appalachians which has been shown to have well-documented post-Mesozoic displacement. The apparent localization of these faults along the Fall Line between the Piedmont and Coastal Plain (figure II-2) may be real (perhaps due to a "hinge-line effect") or more likely it is due to presence of a thin, relatively continuous veneer of Cretaceous and Tertiary sediments which allow ready identification of faults of relatively small displacement. Likewise, none of these faults have been identified north of the Coastal Plain of Maryland, probably due to the absence of suitable sedimentary cover over older crystalline and sedimentary rocks. Table V-I summarizes features for all recognized faults of this type.

Examples:

Stafford fault system - The Stafford fault system is located along the Fall Line and Potomac estuary of northeastern Virginia, approximately 40 kilometers southwest of Washington, D.C. (figure V-2). The fault system will be used as an example for the characteristic of faults of this group.

While the possibility of youthful faulting has been suspected for some time (McGee, 1888); the true extent of faulting has been only recently documented (Mixon and Newell, 1977 and 1978). Rocks in this region consist of a basement of crystalline schist and gneiss noncon-

TABLE 3

Map reference	Fault name or location	Strike orientation	Strike length	Age of Movement [1]	Vertical displacement	Comments	Reference
1	Brandywine fault system	Northeast	23 km	a. Cretaceous b. Miocene	75 m	Faults are upthrown on east side and are associated with Triassic rocks; they are not exposed at ground surface	Jacobsen (1972)
2	Washington, D.C.	-------	<1 km	a. Pliocene (?) or Pleistocene (?)	2 m	Faults displace river terrace gravels	Darton (1950)
3	Stafford fault system	Northeast	50 km	a. cretaceous b. early Miocene	30-50 m	En enchelon fault system; blocks upthrown on west side; faults aligned with Triassic faults; some faults may have Quaternary movement.	Mixon & Newell (1977, 1978)
4	Hopewell, VA	North	10 km	b. Pliocene	20 m	Fault blocks upthrown on east side	Dischinger (1979)
5	Wilson, NC	N50°E	<1 km	a. Post-Cretaceous	2 m	Fault dips 50°W, upthrown on east side	White (1952)
6	Stanley Co., NC	N40°E	<1 km	a. Pliocene(?) or Pleistocene(?)	4 m	Fault dips 50°W, upthrown on east side	White (1952)
7	Belair fault zone	Northeast	24 km	a. Cretaceous b. late Eocene	30 m	Fault zone consists of at least 8 en enchelon faults; many fault may have Recent (10,000 years b.p.) movement	Prowell & O'Connor (1978); O'Connor & Prowell (1976)
8	Warm Springs, GA	Northeast and NNW	<1 km	a. late Miocene(?) to late Pliocene (?)	3-10 m	Faults overlain by undeformed pre-Pleistocene or pre-Pliocene colluvium and alluvium	Reinhardt et al. (1979)
9	Albermarle Co., VA	------	<1 km	?	2 m	Faults cut high-level terrace gravels of Pleistocene (?) or Pliocene (?) age	White (1952) Nelson (1962)
10	Clifton Forge, VA	N30°W	<1 km	a. Tertiary (?)	5 m	Upthrown block on SW side	White (1952)
11	Raleigh, NC	East-West	<1 km	a. Pleistocene or Pliocene	3 m	Upthrown on south side, relatively low angle (40°) fault.	Parker (1979)
12	Cheraw, SC	N80°W	<1 km	a. Post-Cretaceous	1.2 m	Upthrown on NE side, relatively low angle (42°) fault.	Howell and Zupan (1974)
13	Stanleytown, VA	N12E	1 km	a. Holocene	6 m	dip is 62 SE; upthrown block on NW side; several faults present	Conley and Toewe (1968)

1 a. age of major movement
b. age of latest movement

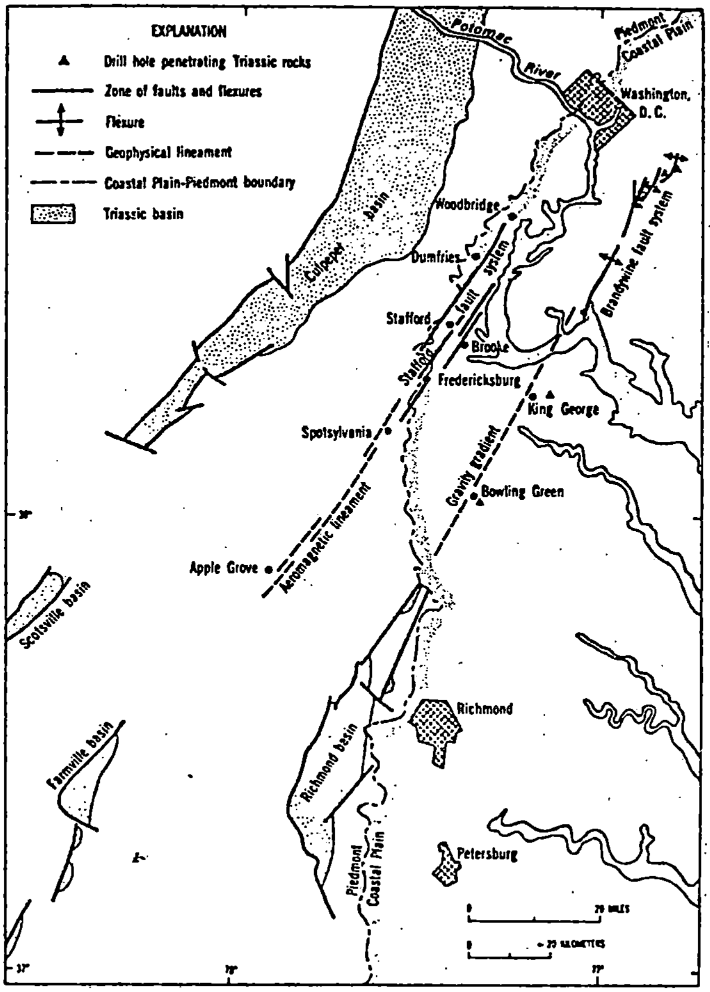


Figure V-2. Map showing alignment of Stafford and Brandywine fault systems, Triassic basins, and geophysical lineaments. (Mixon and Newell, 1977).

formably overlain by lower and upper Cretaceous coarse fluvial sediments of the Potomac Group which are in turn overlain by thinner units of Paleocene, Eocene, and Miocene marine sediments. The sequence is capped by thin units of uppermost Tertiary (?) or Pliocene-Pleistocene gravels.

Faulting is en echelon in nature, with faults being offset in a sinistral manner (figure V-3). Structural-contour maps of Cretaceous and Paleocene lithostratigraphic units show that displacement on faults increases downward, with the Cretaceous-bedrock contact having as much as 60 meters of displacement within Tertiary units is less than 20 meters (Mixon and Newell, 1967, 1968), indicating probable recurrent and penecontemporaneous movement. Units of the lower to middle Miocene Calvert Formation are not extensively affected by faulting. However,at one location the Fall Hill fault has displaced Pliocene-Pleistocene Rappahannock river terrace alluvium by approximately 0.5 meter. The apparent thickening of sediments across faults (figure V-4) is probably the effect of recurrent faulting and erosional truncation rather than original tectonic control of sedimentation.

Mixon and Newell (1977) suggest the alignment of the Stafford and adjacent Brandywine fault systems with the adjacent faults in the Farmville and Richmond Triassic basins may indicate reactivation of old, unhealed fault under a new stress regime.

B. Description of fault class

1. Basic geometry

a. strike length - Major fault systems have demonstrable lengths of 5 to 30 kilometers; in several cases these systems are en echelon in nature, individual faults may be less than one kilometer in length. Minor faults usually cannot be traced from a single exposure.

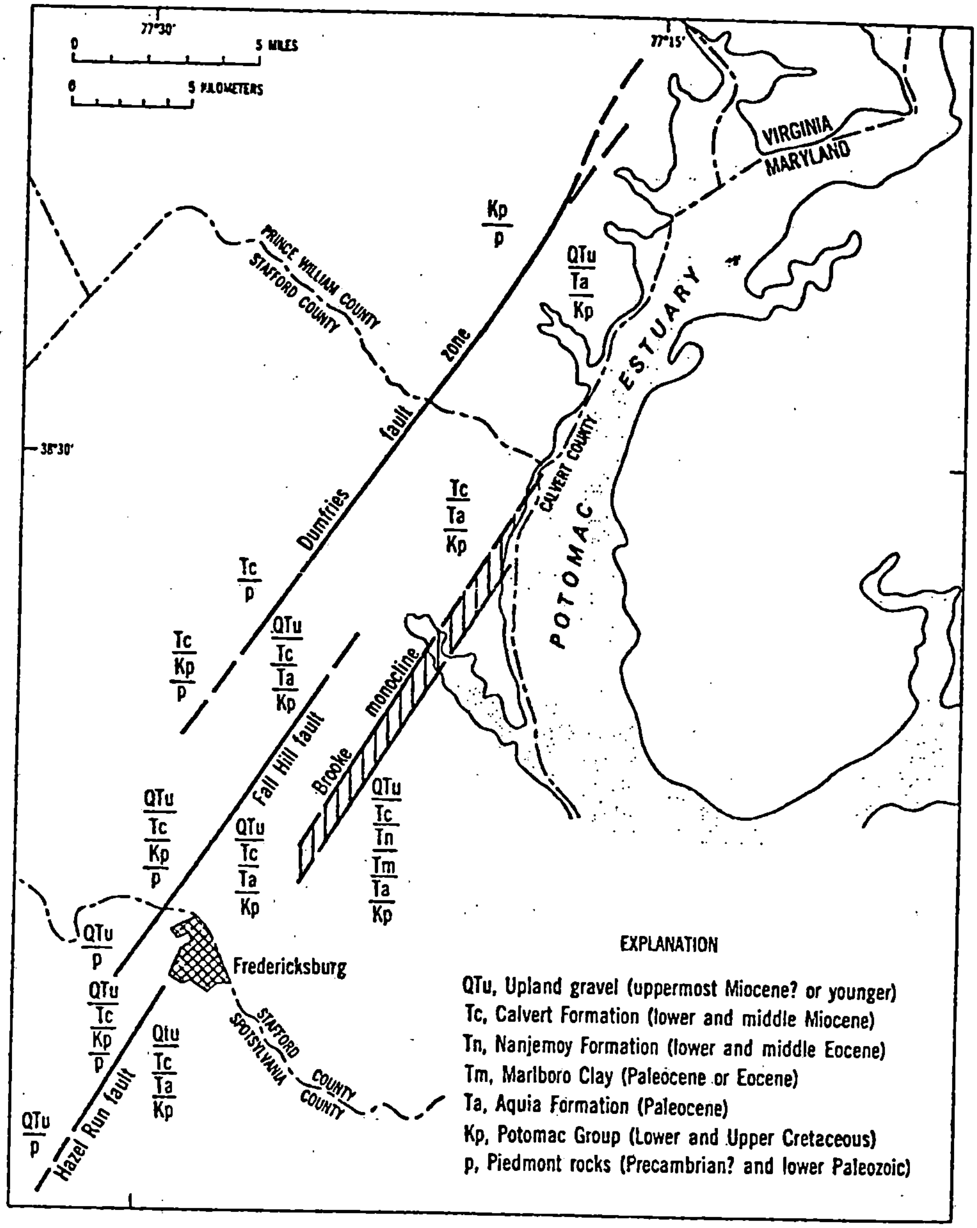


Figure V-3. Variation in stratigraphic section across structures of Stafford fault system as observed in outcrop. Northwest-southeast differences are due to down-to-the-coast displacement of Coastal Plain beds and westward onlap of Calvert Formation. Southwest-northeast differences are due to varying amounts of displacement along structural strike and relief on unconformities. (Mixon and Newell, 1977).

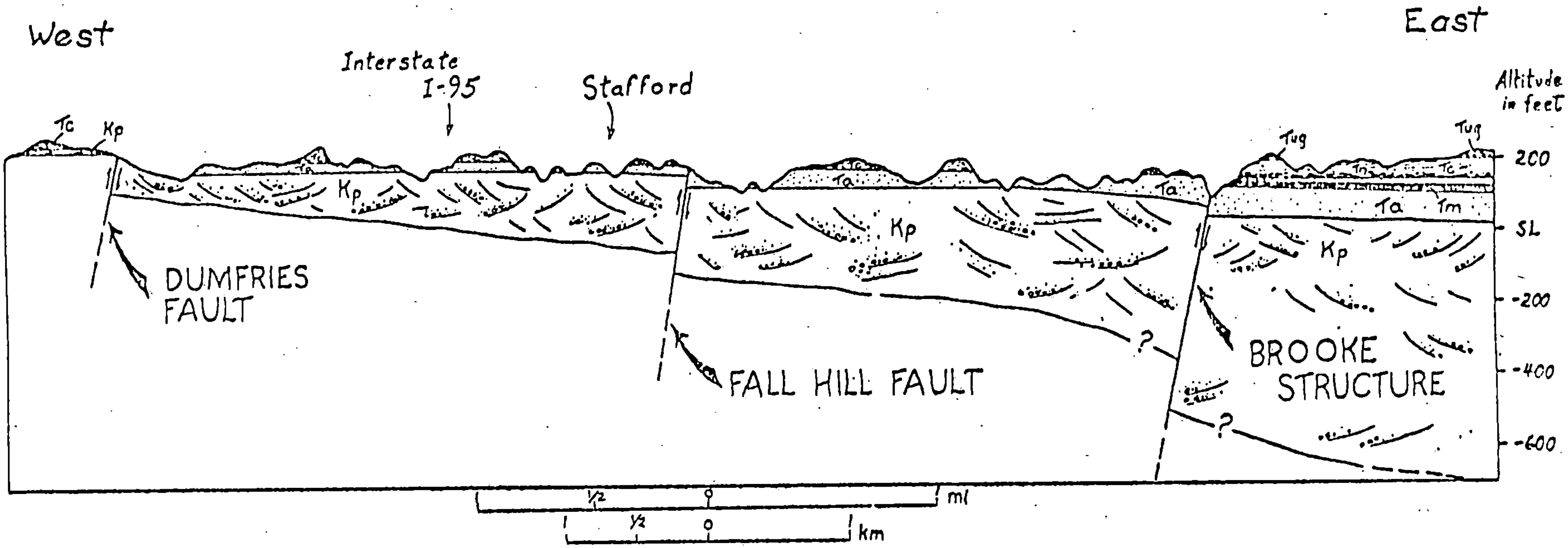


Figure V-4. Cross section across inner Coastal Plain in Stafford area showing steplike down-to-the-coast displacement of lower Cretaceous and Tertiary strata and Piedmont crystalline rocks. Kp = Potomac Group; Ta = Aquia Formation; Tm = Marlboro Clay; Tn = Nanjemoy Formation; Tc = Calvert Formation; Tug = upland gravel. (Mixon and Newell, 1978).

b. length perpendicular to strike - Uncertain. The high-angle of the faults, and their extensive length suggest they are deep seated in nature.

c. orientation - A majority of faults trend northeasterly, parallel to regional structural grain. Faults in the Pine Mountain belt near Warm Springs, Georgia (Reinhardt et al., 1979) trend northwest. Faults present in the Carolina slate belt (Parker, 1979; Howell and Zupan, 1979) trend east-west.

d. Displacement - Major faults have measured vertical displacements of 10 to 75 meters; usually displacement has been found to increase with depth in stratigraphic section, suggesting recurrent movement.

e. continuity - Many fault systems are en echelon in nature, individual faults may range from 0.5 to 15 kilometers. In some cases minor splays are present.

f. curvature - Faults exhibit very linear surface traces, curvature perpendicular to strike at depth has not been determined. Fault surfaces usually refract and decrease in dip when in unconsolidated sediments.

g. termination along strike - Faults terminate as splays with decreasing displacement or monoclinal folds. In many cases they can be traced into crystalline rocks where the actual termination cannot be mapped due to the lack of marker units.

2. Tectonic setting

Faults of this group occur in all major geologic provinces of the Appalachians (figure II-2). As previously stated, the localization of faults near the Fall Line is probably an artifact of ideal geologic conditions for mapping faults with small displacements. Several faults appear to be associated with Triassic basins or lie along strike from Triassic border faults.

3. Characteristics of the fault surface or zone

   a. Type of fault - All faults of this category exhibit brittle deformation except where faulted materials are composed of large quantities of clay minerals (i.e. saprolite and clay-rich sediment).

   b. surface texture - Faults have relatively sharp, planar boundaries. In unconsolidated sediments fault splays are present. Fault surfaces may not be obvious in massively bedded, unconsolidated, sandy sediments.

   c. character of zone - Faults have 1-10 centimeter wide zones of clay-like gouge. In some cases sand and gravel have been dragged into the fault zone. Slickenside surfaces are present in the gouge. Calcite fill is present in some.

   d. Metamorphism and mineralization - Due to the near surface nature of these faults no significant metamorphic effects are present. No low T-low P mineralization (quartz, calcite, and zeolites) have been reported in these fault zones. The absence of such minerals may aid in distinguishing younger faults from older, deep-seated faults with similar orientation and displacements.

   e. datable material - Organic material for ^{14}C dating. Paleontological, paleobotanical, paleomagnetics, and archaeological methods would be useful for dating relatively young material. Potassium-argon and rubidium-strontium dating of suitable materials (e.g. glauconite in marine sands) could provide limits for the maximum or minimum age of faulting.

4. Relation to country rock

   a. Parallel or cross-regional grain - Most faults subparallel regional structural grain.

   b. promontory or embayment - Many known faults (Table V-I) are adjacent to the Virginia promontory. However, there is no well-defined relation between faults and promontories and embayments. Likewise these high-angle reverse faults do not appear to be related to Coastal Plain structures such as the Cape Fear arch.

   c. thick-skinned or thin-skinned - Faults of this category appear to be thick-skinned in origin.

   d. relation to isopachs - Abrupt changes in the thickness of stratigraphic units across faults has been documented in the Stafford, Belair, and Brandywine fault systems. This is primarily due to preservation of the down-dropped block from subsequent erosion rather than growth fault sedimentation.

   e. stratigraphic interval - Faults cut rocks which range from Cretaceous to Holocene in age. For most faults the last major movement was pre-middle Miocene.

   f. relation to folds - Some faults terminate up stratigraphic section as monoclinal folds (e.g. Brooke monocline of the Stafford fault system, Virginia).

g. relation to s-surfaces - No penetrative s-surfaces are associated with faults of this category.

h. relation of fault character to rock type - Faulting appears to be independent of rock type. Faults indiscriminately cut all types of rocks (unconsolidated sediments, folded sedimentary rocks, low and high grade metamorphic rocks).

i. P-T conditions - Faulting occurred at near surface conditions.

j. isograds- Faults cut indiscriminately across metamorphic isograds.

k. relation to intrusions - There appears to be no direct relationship between faulting and the limited number of Tertiary plutons present in the Appalachians.

l. tectonic injections or forced intrusions - None have been observed.

5. History

a. age of inception - Many of the major fault systems (Stafford, Belair) appear to have had significant late Cretaceous movement prior to the deposition of early Cenozoic sediments.

b. recognition of syndepositional effects - Most faults have not produced significant local changes in original stratigraphic thickness or facies. However, erosion and truncation of strata subsequent to faulting has produced thickening and thinning of units. On a more regional scale, clastic sedimentation along the Atlantic Coastal Plain (Owens, 1970) roughly corresponds to the time of major faulting.

c. radiometric dating - Carbon 14 dating has been used in a study of the Belair fault zone of Georgia. Dating of organic material within a disrupted clay zone suggests some movement along the fault may be as young as Holocene (O'Connor and Prowell, 1976).

d. relation to loading - Faults are probably not related to loading-unloading effects but may be related to epiorogenic uplift of the Blue Ridge and Piedmont.

e. indications of last motion - Major fault systems appear to have ceased activity around Mid-Tertiary (middle Eocene to middle Miocene). Some faults, especially minor faults, have produced minor offsets in Pliocene or Pleistocene colluvial and alluvial sediments.

6. Stress field.

a. Orientation of principal stress - sigma max oriented normal to faults.

b. magnitude of stress and strain - Indeterminate. The relatively minor displacement of these faults suggest that total stress and strain were probably not as great as that associated with most Paleozoic faults

c. variation of stress and strain - Indeterminate.

d. in situ stress - Recent measurements of in situ stress in eastern North America (Sbar and Sykes, 1973) has delimited a large region of high horizontal compressive stress of variable orientation. The observed in situ stress is compatible with the production of high-angle reverse faults.

e. seismic first motion studies - Unavailable.

f. rate of motion - Indeterminate.

g. fluid pressure changes and effects - Indeterminate.

7. Geophysical and subsurface characteristics

a. seismic activity levels - Many of the high-angle reverse faults in Virginia located within or near the relatively active central Virginia seismic zone. Seismic activity has been reported near the Belair fault of Georgia but this is probably related to reservoir induced faulting along older structures.

b. subsurface offsets - Unknown.

c. relations to anomalies - Unknown.

d. geophysical lineaments. Faults of the Stafford fault system lie along an aeromagnetic lineament extending 80 kilometers to the southwest, and aligned with a border fault of the Farmville basin (Mixon and Newell, 1977). No information is available of other fault systems.

8. Geomorphic relationships

a. Abrupt changes in major river courses.

b. Fault-line scarps

c. Squared off spurs

d. Aligned ravines & gullies

e. Rapids and falls associated with upthrown blocks of crystalline rocks.

9. Methods of identification

These faults are easily detected near the Fall Line where unconsolidated sediments are overridden by crystalline rocks. Methods of fault detection include:

a. Detailed mapping of gently dipping sedimentary units and detecting departures from predicted elevation of contacts.

b. Utilizing drill and auger hole information as above; also determine basement surface configuration.

c. Utilize high resolution seismic reflection seismology to determine offsets of basement and stratigraphic surfaces.

d. Offset of strata and fault gouge and breccia

e. Offset of terranes and geomorphic features

10. Pitfalls in identification

a. Faults in areas where Cenozoic rocks are not present will be very difficult to recognize as Cenozoic.

b. Because of this, all high angle, brittle faults (particularly with reverse motion) in the Piedmont and attempts should be made to separate these from faults of Group 7. Where associated sediments are lacking attempts should be made to find suitable material for dating purposes.

c. Recent faults which actually are due to stress release by unloading (Group 12) could be misidentified as Group I faults. Consideration of causal mechanism is suggested.

d. Since the relationship between Appalachian faults and seismicity is not understood, seismicity along is not a valid means of identifying these faults.

11. Possibility of re-activation

Faults of this group should be given the highest consideration for potential re-activation.

12. Selected references

see table V-I.

VI

GROUP 2: WILDFLYSCH TYPE THRUST SHEETS

A. Generalized description

Included in this group are penecontemporaneous faults that cut through the sediment-water interface and along which large masses of rock were emplaced into an actively-filling marginal flysch basin (exogeosyncline). The allochthonous masses of rock, which include early Paleozoic deep-marine shale and greywacke sequences, rest on or are embedded within shelf sediments deposited northwest of the early Paleozoic continental margin. Many of the allochthons came to rest on a subsiding sea floor veneered by black mud, turbidites, and submarine slide breccias.

The group of faults is characterized by a spacial and temporal association with "wildflysch," a type of flysch facies first recognized in the Ultrahelvetic zone of the Alps. "Wildflysch" represents a mappable stratigraphic unit displaying irregularly sorted and frequently "exotic" blocks and boulders formed by tectonic fragmentation. Strata forming the matrix of the "wildflysch" normally are broken and severely contorted. A "wildflysch" forms by submarine slumping and sliding on the slope of a rising tectonic element or an advancing thrust sheet.

Elter and Trevisan (1973) distinguish three types of submarine slides (Figure VI-1) that may contribute to a "wildflysch": (a) slumping, where the materials are derived from the same formation, (b) olistostromes, where the materials are derived from diverse formations in the same sedimentary basin, and (c) precursory olistostromes, where the material is derived from the front of an advancing thrust sheet.

The Taconic allochthons belonging to this group of faults were probably emplaced as gigantic submarine landslides, but may have formed initially by tectonic mechanisms associated with crustal underthrusting. Following emplacement on the subsiding early Paleozoic continental shelf, the allochthons

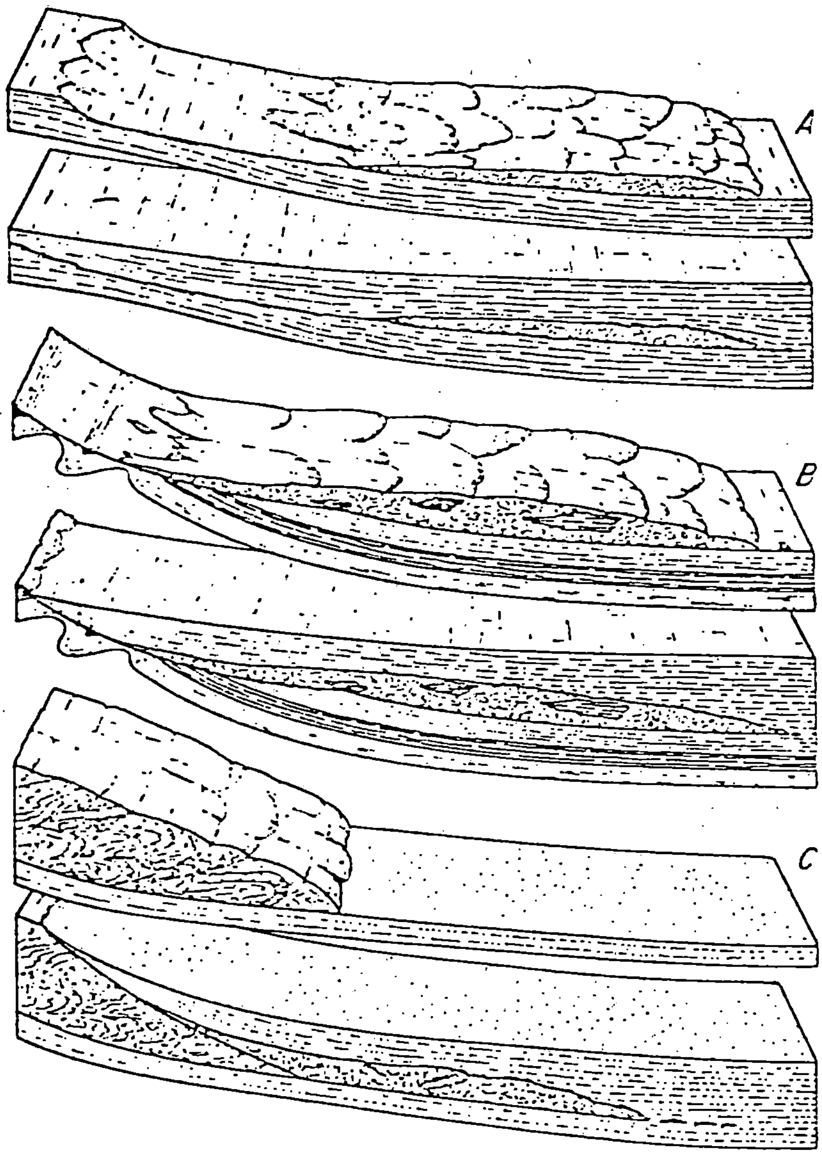


Figure VI-1.

Schematic representation of three different types of submarine slides. (*A*) Slumping (materials derived from same formation); (*B*) olistostromes (materials derived from other formations in the same sedimentary basin); (*C*) precursory olistostromes (materials derived from the front of an advancing allochthonous sheet).

(Elter and Trevisan, 1973).

were strongly deformed under conditions that permitted development of slaty cleavage, low-rank metamorphism, and ductile flow of the underlying shelf carbonates.

In the Appalachians, faults of this group appear to be restricted to Middle Ordovician age and are found only along the inner margin of the Valley and Ridge Province between central Pennsylvania and western Newfoundland (Figure VI-2). They are situated immediately west of the early Paleozoic shelf edge (Cameron's Line) and a belt of external basement massifs (e.g., Green Mountain anticlinorium). There are four principal occurrences of Taconic-type allochthons in the Appalachians: (1) western Newfoundland (Williams, 1975), (2) Quebec along the south shore of the St. Lawrence River (St. Julien and Hubert, 1975), (3) western New England (Zen, 1967, 1972), and (4) central Pennsylvania (Root and MacLachlin, 1978).

Examples:

Giddings Brook slice (Zen, 1967, 1972; Bird, 1969), the lowest major structural element in the Taconic allochthon of eastern New York State and southwest Vermont, which overlies a "wildflysch" (Forbes Conglomerate) intercalated with and, in part, incorporating the autochthonous, exogeosynclinal Normanskill Shale and Austin Glen Greywacke of Trenton (late Middle Ordovician) age. The Giddings Brook slice is overlain by several smaller thrust slices, which have been interpreted, in part, as younger (late Taconic or Acadian), basement-rooted thrust sheets (Ratcliffe, 1975; Ratcliffe and Bahrami, 1977) not belonging to this class. See Figures VI-3 and VI-4.

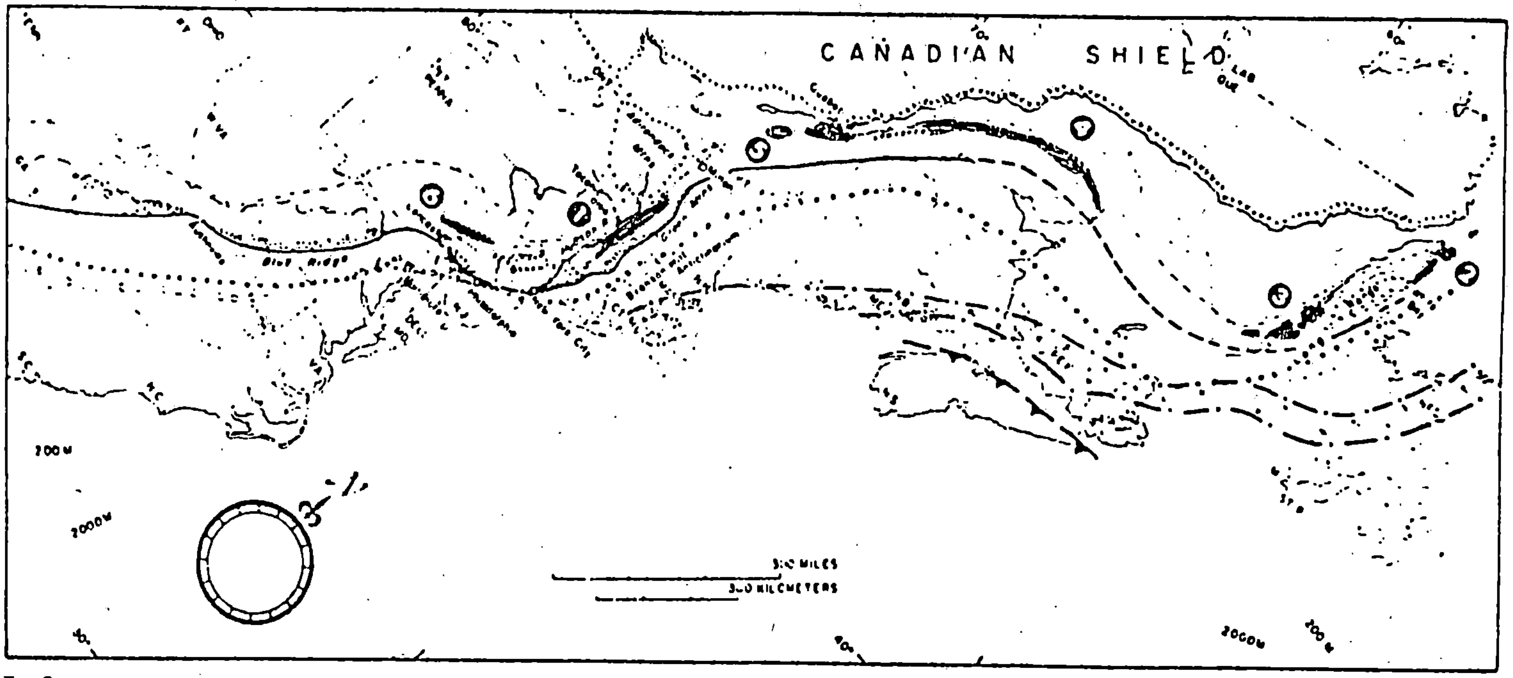


Figure VI-2. Eastern part of the North American continent during the Ordovician (modified from Rodgers, 1968). Ruled pattern: transported rocks of the Taconide zone; 1 = Taconic area; 2 = Hare Bay, and 3 = Humber Arm areas, Newfoundland; 4 = Gaspé peninsula, and 5 = southern Quebec; 6 = eastern Pennsylvania. Heavy solid line: eastern edge of carbonate bank (after Rodgers, 1968; Williams and Stevens, 1974). Heavy dotted line: continental margin (after Williams and Stevens, 1974). Heavy dash-dot line, with cross pattern: Avalon sub-continent (after Williams and Stevens, 1974). Heavy dashed line with carots: interpreted ancient margin of northwest Africa (after Schenk, 1971). Other patterns after Rodgers, 1968; check marks: edge of exposures of 1000 m.y. old basement, light dash-dot line: west limit of Appalachian deformed zone (Valley Ridge province and northeastern extension); circles: axes of zones of maximum Paleozoic volcanism; crosses: exposures of rocks supposed to be about 580 m.y. old (Avalonian Orogeny); light dashed line: overlap of Coastal Plain sediments (from Voight and Cady, 1980).

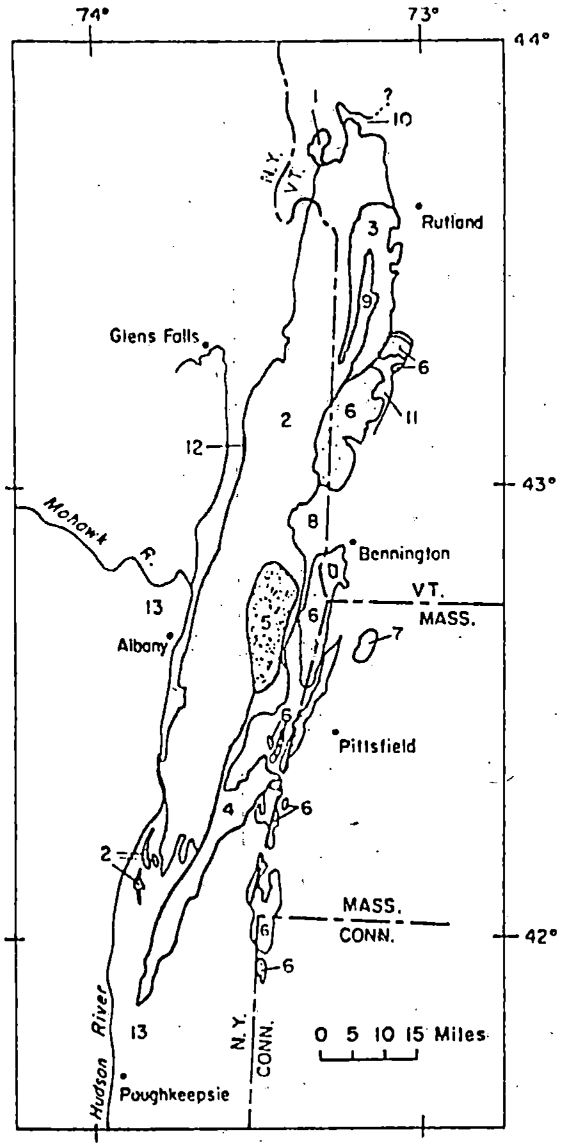


Figure VI-3. Principal tectonic units in and around the Taconic allochthon: 1- Sunset Lake slice, 2- Giddings Brook slice, 3- Bird Mountain slice, 4- Chatham slice, 5- Rensselaer Plateau slice, 6- Dorset Mountain slice, 7- Greylock slice, 8- Hoosick Falls embayment, 9- Edgerton half-window, 10- Sudbury slice, 11- carbonate sliver underlying Dorset Mountain slice, 12- Bald Mountain carbonate sliver, 13- autochthonous Taconic sequence. (from Zen, 1967).

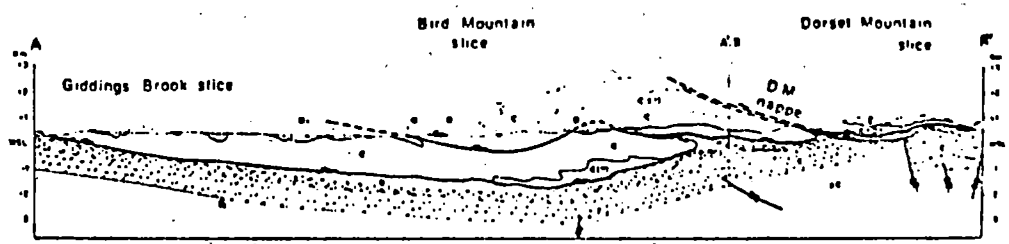


Figure VI-4. Cross-section of central Taconic Range (based on maps by Theokritoff, 1964; Zen, 1964; Shumaker, 1967; and Thompson, 1967). The Taconic allochthon complex is subdivided into, from left to right. Giddings Brook, Bird Mountain, and Dorset Mountain slices. The Dorset Mountain nappe is the highly deformed carbonate mass separating the Dorset Mountain slice and subjacent rocks of the autochthon and the Bird Mountain slice. The present imbricated structural form of the allochthon complex seems in large part due to late-stage (late Ordovician and Acadian) deep-seated deformation. Recumbent fold structure in the Bird Mountain slice reflects the interpretation of Zen. (from Voight and Cady, 1978).

Hamburg Klippe of central and east-central Pennsylvania (Stose, 1946; Platt and others, 1972; Root and MacLachlin, 1978), an extensive terrane in which the autochthonous, exogeosynclinal Martinsburg Shale of middle and late Ordovician age is supplanted along strike by an allochthonous complex of blocks and slabs of unknown dimensions, but of Taconic-type lithologic affinities. Many of the blocks have a Taconic-age structural fabric, but the entire allochthonous complex and the underlying autochthonous shelf sequence (Cumberland Valley sequence) were strongly deformed and foreshortened during the Alleghanian orogeny. The regional slaty cleavage, at least at the western end of the allochthon, is of Alleghanian age (Root, 1977). See Figures VI-5, VI-6, and VI-7.

B. Description of fault class

1. Basic geometry

a. strike length - Two of the longest allochthons, the Giddings Brook slice and the Hamburg Klippe, have lengths of 198 and 125 kilometers, respectively. Their original lengths may have been somewhat greater. However, the Hamburg Klippe is not a single, coherent sheet of rock, but rather is a complex of innumerable allochthonous slabs of uncertain dimensions (Root and MacLachlan, 1978; Alterman, 1971). The smallest of the principal Taconic allochthons, the Sunset Lake slice, is approximately 10 kilometers long.

b. length perpendicular to strike - The present width of the Giddings Brook slice is 26 kilometers, although the original width probably exceeded 35 kilometers (Voight and Cady, 1978). The minimum width of the Hamburg Klippe is 22 kilometers, but

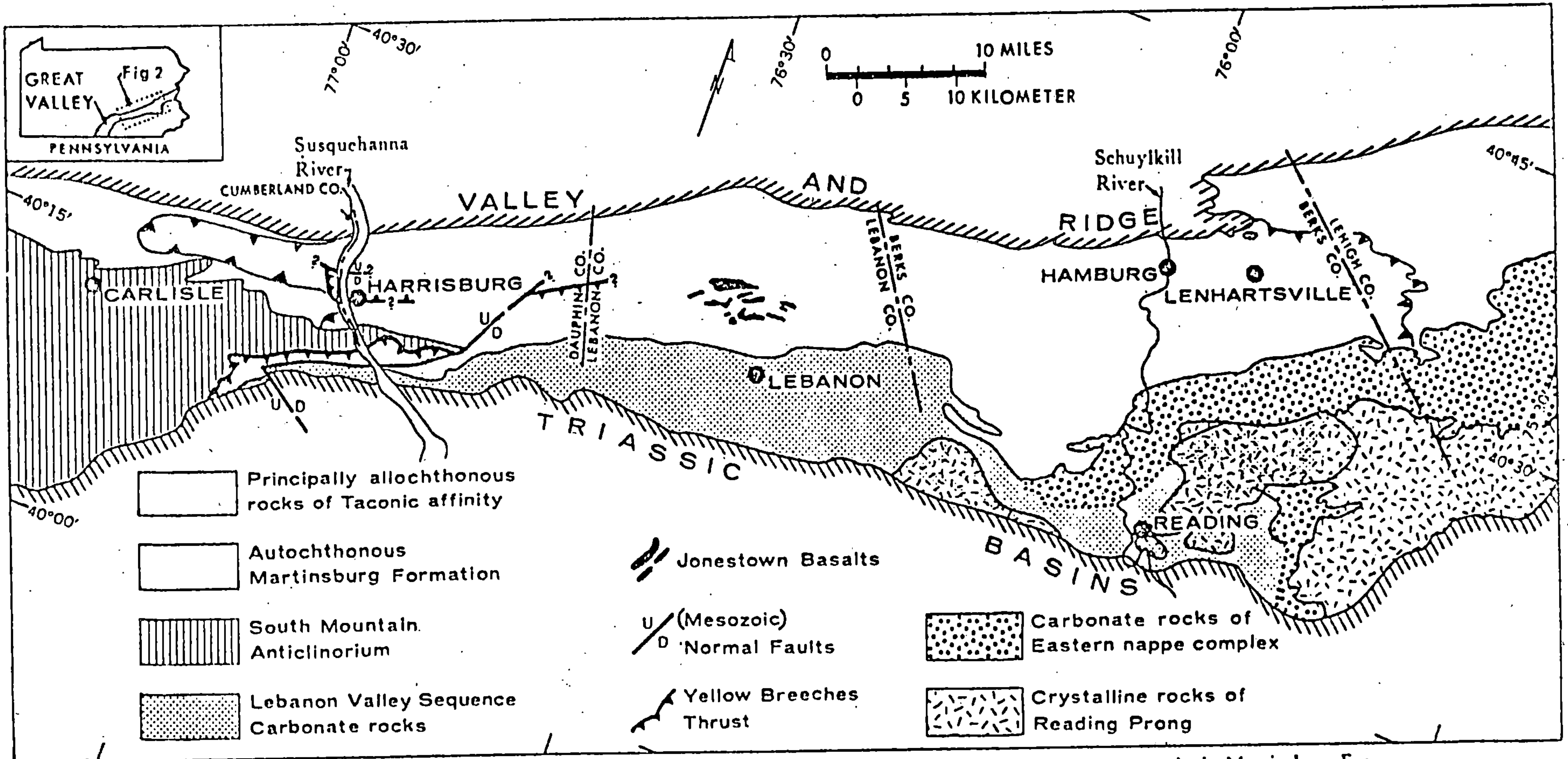


Figure VI-5. Generalized geologic map of Pennsylvania Great Valley, showing distribution of allochthonous rocks in Martinsburg Formation. Eastern limit after Alterman (1971) (from Root and MacLachlin, 1978).

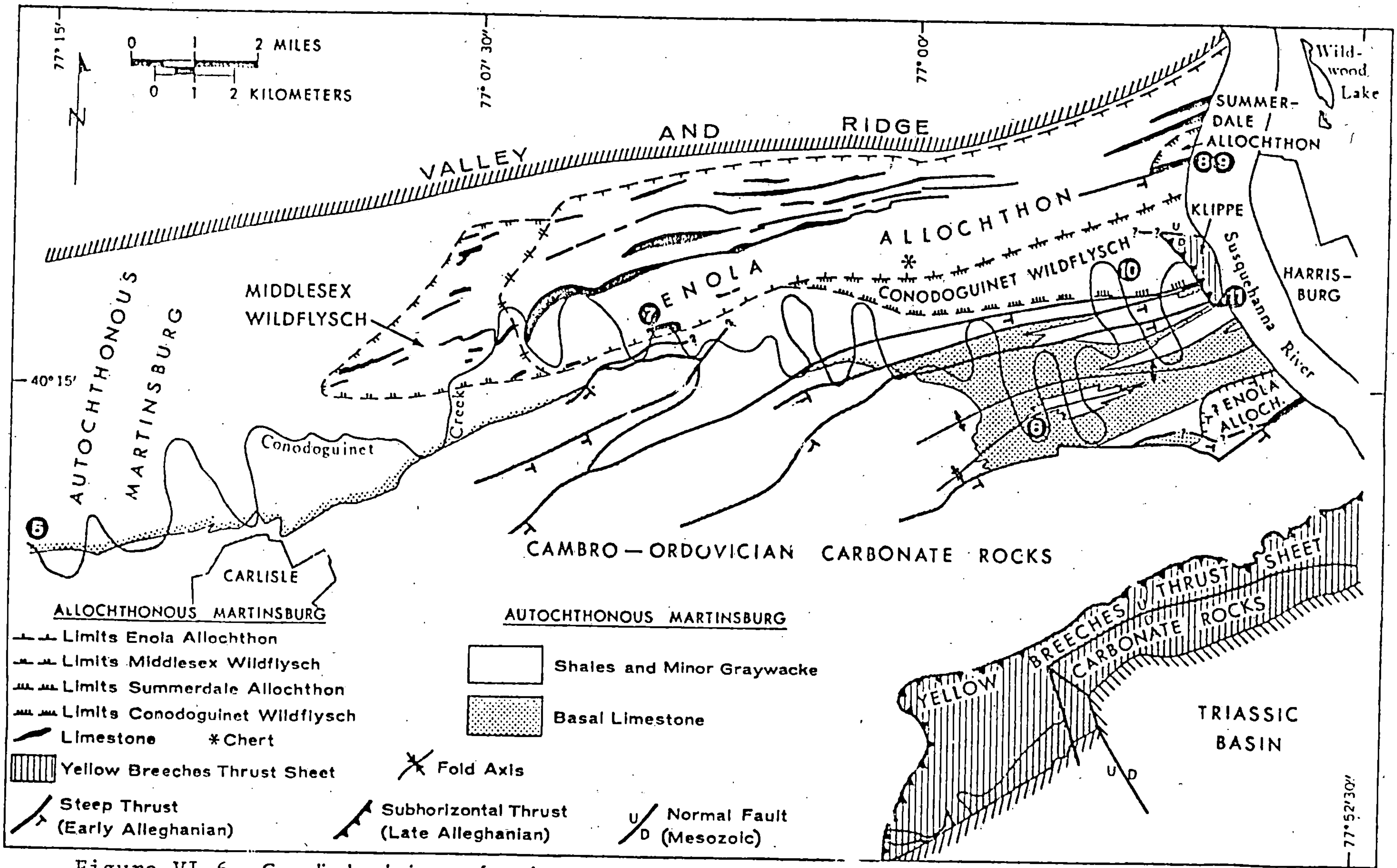


Figure VI-6. Generalized geologic map of area between Harrisburg and Carlisle, showing distribution of allochthons in Martinsburg Formation. (from Root and MacLachlin, 1978).

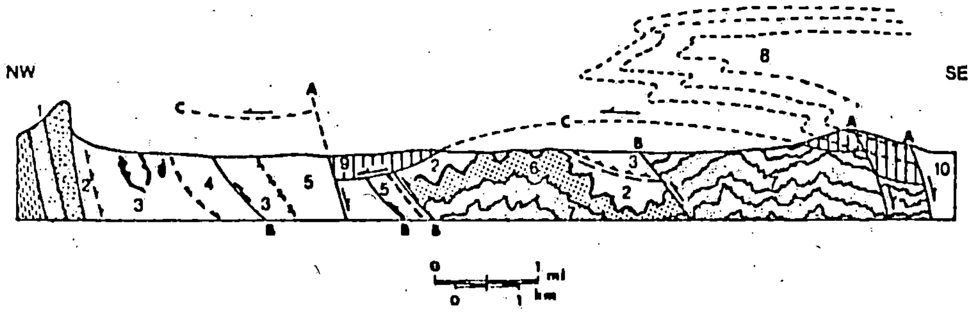


Figure VI-7. Generalized geologic cross section along west bank of Susquehanna River from Triassic basin to Valley and Ridge province (considerable vertical exaggeration). 1 = near-vertical beds of Valley and Ridge; 2 = shales in Martinsburg Formation; 3 = Enola allochthon, including limestones (shown in black); 4 = Summerdale allochthon; 5 = Conodoguined wildflysch; 6 = basal limestone of Martinsburg Formation; 7 = Cambrian-Ordovician carbonate rocks in South Mountain anticlinorium of Alleghanian age; 8 = Lebanon Valley nappe of Taconic age; 9 = klippe of Yellow Breeches thrust sheet; 10 = Triassic basin. A = Mesozoic normal faults; B = early Alleghanian steep thrusts; C = late Alleghanian Yellow Breeches thrust. (from Root and MacLauhlin, 1978).

the northern edge of the allochthon is buried beneath the upper Martinsburg Formation or younger strata and post-Taconic thrusting obscures its southern edge. All other allochthons are considerably narrower.

c. orientation - The allochthons are normally parallel to the regional structural grain, except where they have been strongly redeformed by superimposed structures. Motion of the allochthons was not necessarily perpendicular to their present strikes.

d. displacement - The Taconic allochthon appears to have moved approximately 100 kilometers westward from a site east of the Cheshire-Dalton shelf facies boundary, the early Paleozoic shelf edge Ratcliffe, 1975; Ratcliffe and Hatch, 1979). This site lay east of the palinspastic position of the Green Mountain and Berkshire massifs. The original site of the Hamburg Klippe rocks probably was southeast of the Baltimore gneiss domes (Platt and others, 1972); they have been transported a minimum distance of 70 kilometers to the north and northwest.

e. continuity - The thrusts along the base of the allochthons are continuous through the entire length of the allochthon, however, the thrusts are not known to be rooted. Present exposures are erosional remnants of originally more extensive sheets. Late folding and erosion may give rise to separated portions of the same allochthon slab (Zen, 1972).

f. curvature - The fault surfaces may be strongly curved, especially at the ends of the slices and along the trailing margins where the allochthons have been folded and cut by later thrusts.

g. termination along strike - Erosion appears to have removed the original terminations of the allochthon slabs.

2. Tectonic setting

Faults of this group are associated only with the Taconic-type allochthons, which are restricted to the inner margin of the Valley and Ridge Province, but must have originated in the Piedmont Province, where remnants may still be recognized. The lower allochthonous slices, those first to arrive, were emplaced onto and became embedded in Middle Ordovician shales (Normanskill and Martinsburg Formations) deposited in a rapidly subsiding foreland trough (exogeosyncline) which began to develop on the continental shelf at the end of early Ordovician time. The allochthons are continental rise and slope deposits coeval with the shelf sequence onto which they were emplaced by gravitational gliding (Bird and Dewey, 1970; St. Julien and Hubert, 1975) or continental margin-trench collison (Chapple, 1979; Rowley and Delano, 1979).

The events associated with emplacement of the Taconic-type allochthons may be generalized as follows:

- beginning in the late early Ordovician time, block faulting and subsidence of a portion of the continental shelf to form a rapidly subsiding longitudinal trough, a marginal basin,
- deposition of black shale in the trough and across the shelf accompanying the rapid westward migration of the carbonate-shale boundary towards the craton,
- deposition of "wildfylsch" in the trough immediately followed by emplacement during the Middle Ordovician (graptolite zone 13) of the early (structurally lower) allochthons as thrust sheets or as gravity slides,

- emplacement of later allochthons by gravitational and/or tectonic mechanisms followed in New England by intense deformation and regional low-rank metamorphism,
- subsequent (Acadian in New England and Alleghanian in Pennsylvania) deformation and metamorphism of the internal margins of the allochthons.

Bird and Dewey (1970) relate the emplacement of the lower, "wildflysch-type" allochthons to gravitational gliding of continental rise strata into a newly formed exogeosynclinal basin, developed in response to the initial stages of contraction of the early Paleozoic continental margin (Figures VI-8 and VI-9). They postulate that continued continent-ward migration of deformation and metamorphism in the late Ordovician eventually lead to (a) the telescoping of Piedmont sequences against the shelf edge, (b) the destruction of the area of provenance of the early allochthon, (c) the emplacement of the higher Taconic slices as conventional thrust sheets, and (d) the intense deformation and metamorphism of the entire Taconic allochthon.

Voight and Cady (1978) discuss a variety of alternative gravitational detachment and emplacement models for the Taconic allochthon (Figure VI-10) and suggest that, in general, a hybrid gravitational-tectonic mechanism is required, involving an early phase of thrusting prior to gravitational gliding.

3. Characteristics of the fault surface or zone:
   a. type of fault - Normally ductile, low angle, old-on-young thrusts, but rarely true-bedding thrusts.

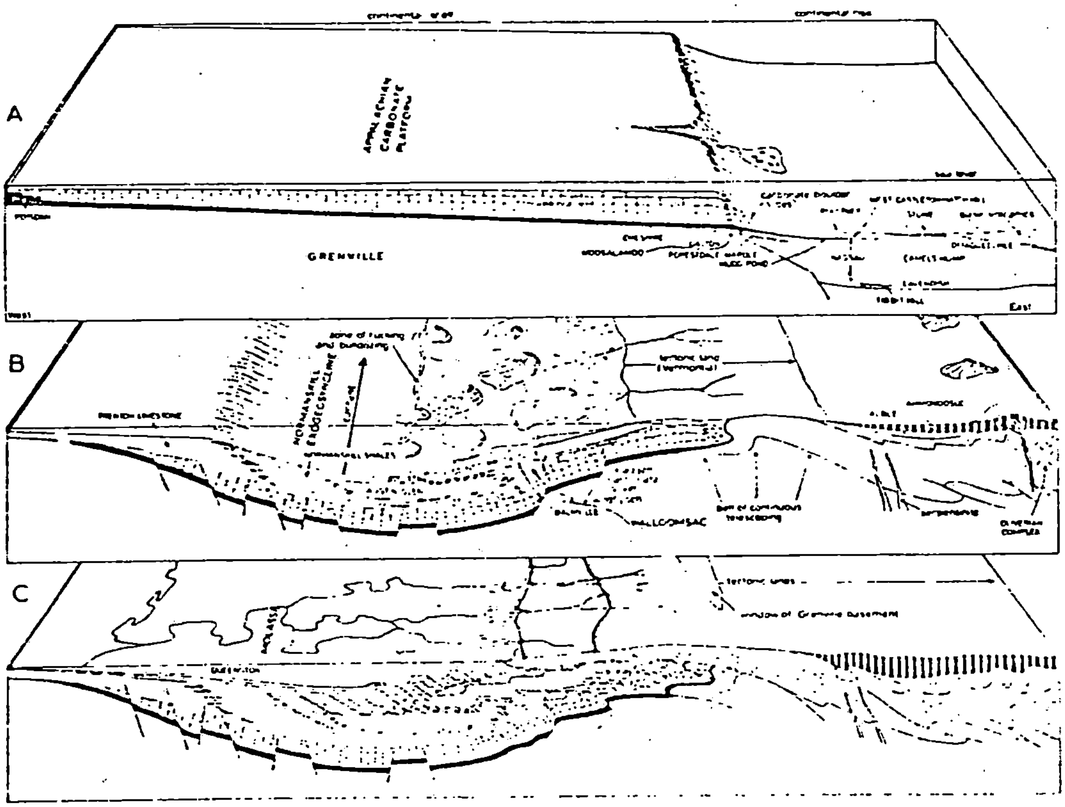


Figure VI-8. Schematic block diagrams illustrating the pre-Taconian and Taconian evolution of the continental margin of North America in western New England: A. pre-Taconian; B. early Taconian; C. late Taconian; (from Bird and Dewey, 1970).

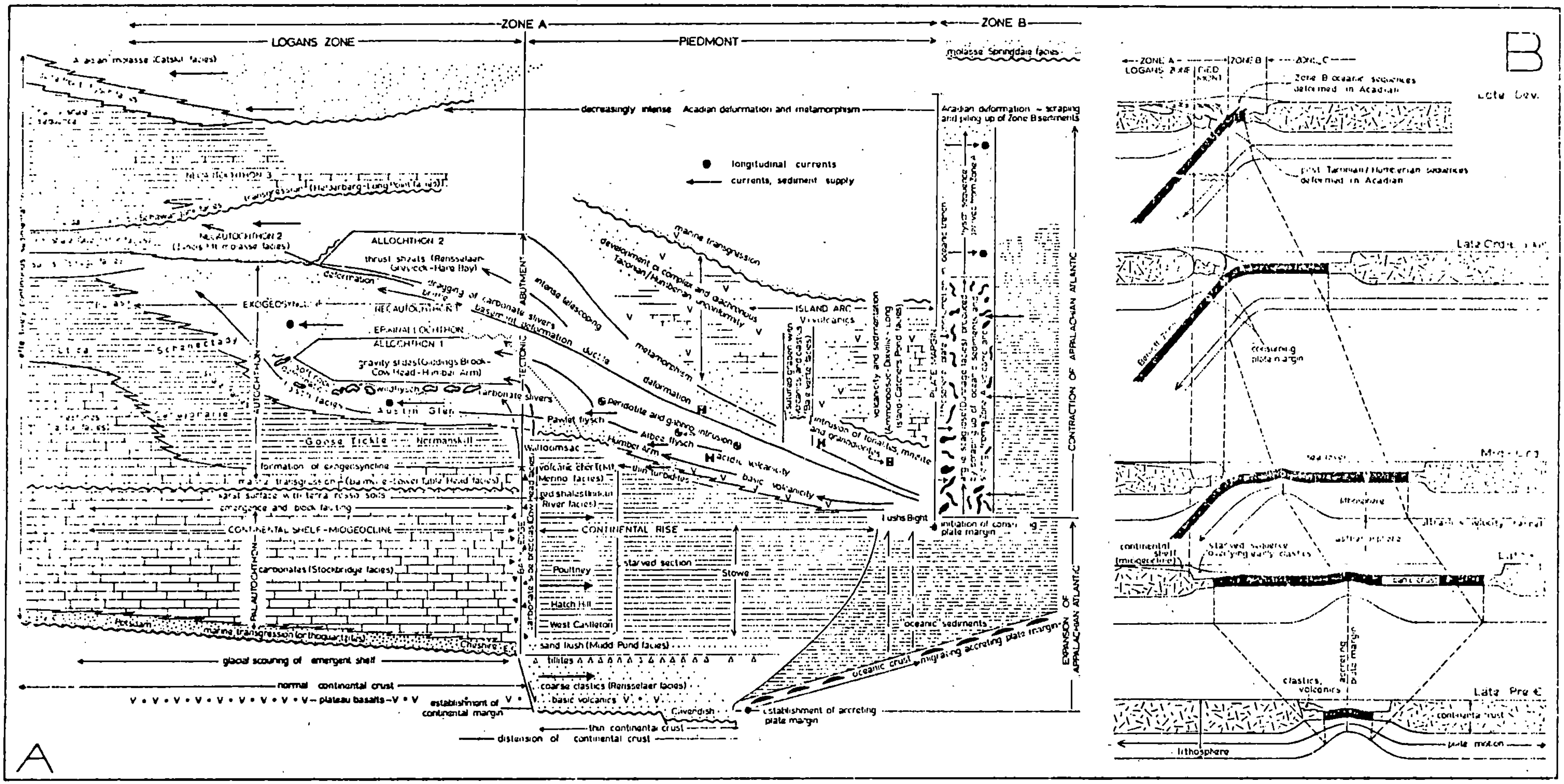


Figure VI-9. Model for the evolution of the Appalachian orogen, showing the positions of Wildflysch type allochthons. (from Bird and Dewey, 1970).

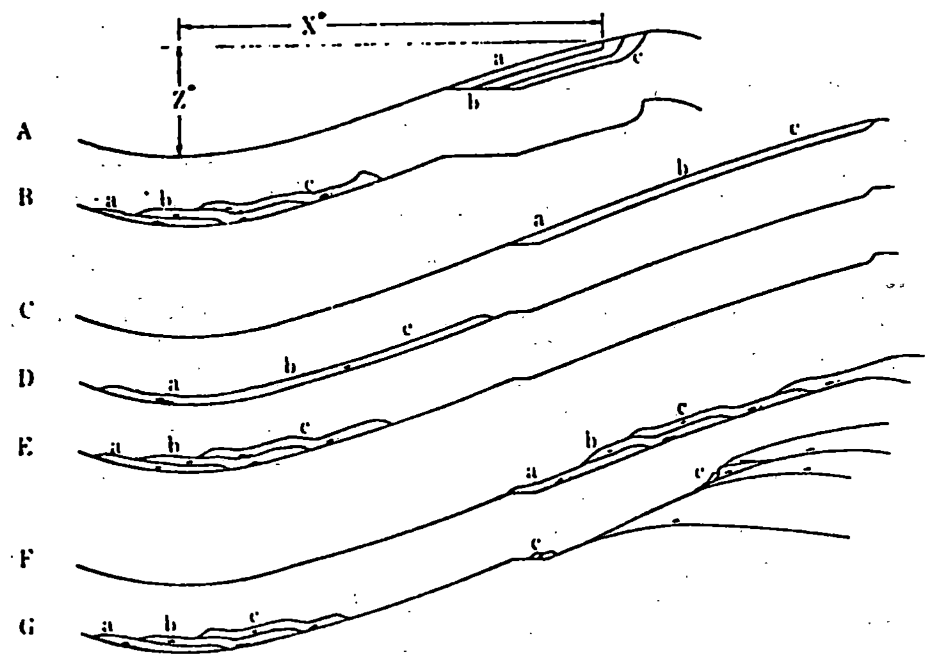


Figure VI-10.
Schematic diagram of alternative gravitational emplacement models. The *diverticulation* model is given by profiles A and B, which respectively indicate the initial and final positions of allochthons (*diverticulates*) *a*, *b*, and *c*. The stacking order *a*-*b*-*c* represents the order of emplacement, *a*-*b*-*c*, and is in general also related to the age of rocks (with *a* containing the youngest rocks and *c* the oldest). The horizontal distance between trough and rise is given by X^*; the (vertical) amplitude is Z^*. In an alternative model the allochthon segments are laterally connected, *a*-*b*-*c* (profile C). These segments could be simultaneously emplaced in a single, giant allochthon (profile D). Alternatively *retrogressive detachment* could occur, in which event segment *a* is detached and emplaced, to be followed in succession by segment *b* and finally by segment *c* (profile E). Case E could, however, also be produced by stacking of segments *c* and *b* on segment *a*, prior to detachment of *a* (*progressive detachment*); emplacement of the *stacked assemblage* could then reproduce the geometric arrangement shown in E. Profile E could also be reproduced by *late-stage imbrication* of the giant allochthon shown in profile D, with the late-stage faulting due to significant change in environmental or boundary conditions. A geometric arrangement similar to profile E could, as a fourth possibility, be produced by the game of leapfrog whereby segment *c* is first detached and emplaced, passing over depositional segments *b* and *a*; detachment of segment *b* follows, then *a*, producing the same geometry as in profile E but with segments *a* and *c* interchanged. Finally, a hybrid mechanism is shown in profile F and G; initial detachment and surmounting of the toe is caused by direct tectonic action, followed by downslope gravitational movement of some segments. In the case shown the stacked assemblage is produced by tectonic action prior to gravity sliding. Other hybrid mechanisms could be specified; e.g., so-called gravitational spreading associated with inclined topographic surface slopes, arbitrary basal slopes, and rear compression of deformable rock masses. (from Voight and Cady, 1978).

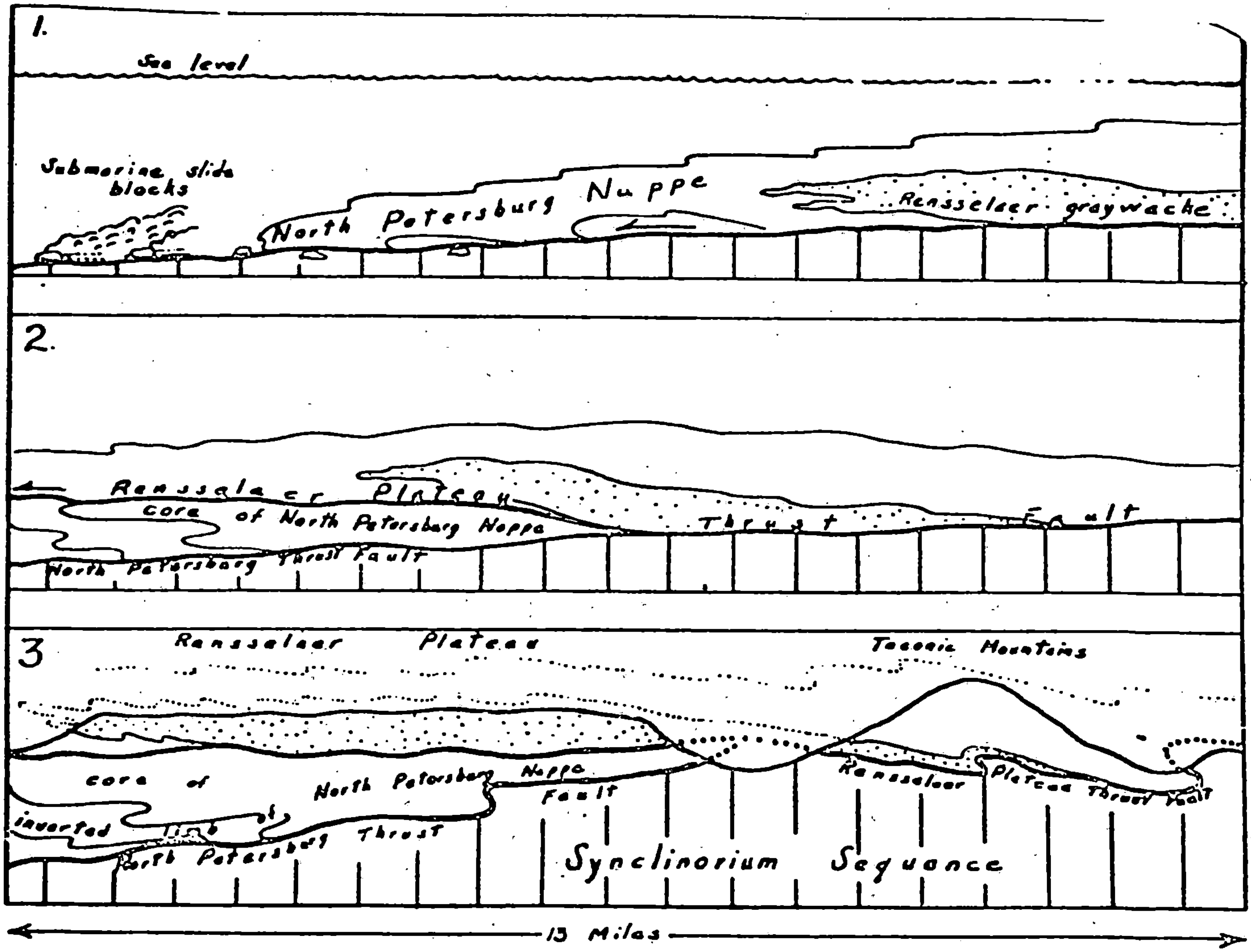


Figure VI-11. Schematic section showing emplacement of thrust sheets. (from Potter, 1972a).

b. surface texture - Except for thrusts at the base of the higher Taconic slices, which are probably not of this group, the faults lack slickensides and mineralized surfaces.

c. character of the zone - The actual fault surfaces may be cryptic, uneven boundaries between different colored shales or shales and greywackes of different ages. Commonly the boundaries are welded or are marked by highly sheared shale that breaks into small, polished, lozenge-shaped fragments (scaly shale or "argille scagliose").

Within the Taconic allochthon, wildflysch-like zones are generally not recognized associated with the slices above the Giddings Brook slice; the thrusts associated with the higher slices are more brittle in character. Potter (1972a) describes "crushing, shearing, and mineralization" along the Rensselaer Plateau Thrust (Figure VI-11). Carbonate slivers derived from the underlying autochonous shelf sequence are distributed along this thrust.

d. metamorphism and mineralization - Emplacement of the Hamburg Klippe and the lower slices of the Taconic allochthon pre-dates the regional slaty cleavage and greenschist facies metamorphism, which is Taconic (Zen, 1972) in New England and Alleghanian in Pennsylvania (Root and MacLachlan, 1978). Zeolite or prehnite-pumpellyite facies metamorphism may have accompanied emplacement of the allochthon.

e. datable material - None.

4. Relationship to Country Rock

a. parallel or cross-regional grain - The faults approximately parallel the local regional structural grain, except around the ends of the slices.

b. promontory or embayment - Preservation of the thrust slices is better in the straight segments between embayments and promontories (figure VI-2). Taconic-type rock masses are absent from the New York promontory.

c. thick-skinned or thin-skinned - The thrust slices are definitely thin-skinned structures. They involve only sedimentary cover (never basement slices) and do not exceed two kilometers (Giddings Brook slice) in thickness.

d. relationship to isopach - The thrust slices lie in regions of maximum thickness of the Upper Ordovician clastic sequence, the axial zone of the Late Ordovician exogeosyncline (Bird and Dewey, 1970).

e. stratigraphic interval - Strata within the thrust slices range in age from Eocambrian to middle Ordovician (Graptolite zone 12). The Giddings Brook slice is overlain by epikinallochthonous strata of Graptolite zone 13 age.

f. relation to folds - The emplacement of the thrust slices normally pre-dates the earliest regional folding, but accompanies local slump folding. The North Petersburg nappe (Giddings Brook slice) was emplaced as a huge recumbent anticline (Potter, 1972a).

g. relation to S-surfaces - In the Taconic allochthon, the earliest regional foliation, normally a slaty cleavage, post-dates and is superimposed on the allochthons (Zen, 1972). Allochthon slabs in the Hamburg Klippe complex, however, commonly contain a slaty cleavage that had formed prior to their emplacement into the Martinsburg basin. The orientation of the S_1 cleavage varies from slab to slab and is strongly overprinted by the regional S_2 cleavage of Alleghanian age (Root, 1977).

h. relation of fault character to rock type - none described.

i. P-T conditions - The thrust slices were emplaced onto or near the seafloor at relatively low temperatures and pressures.

j. isograds - Regional metamorphic isograds (up to biotite and garnet-isograd in the western Taconic allochthon) are superimposed across the allochthons and post-date their emplacement.

k. relation to intrusions - Large blocks of basaltic and andesitic pillow lavas (Jonestown volcanics in Pennsylvania and Starkes Knob in New York) are incorporated in the wildflysch complex (Platt and others, 1972; Bird and Dewey, 1970) and pre-date emplacement of the allochthons.

Near West Rutland at the northern end of the Taconic allochthon, late, post-tectonic lamprophyre dikes cut the allochthon. Hornblende from one such dike was dated by the K-Ar method as 105± 4 m.y. or late Cretaceous (Zen, 1972).

l. tectonic injections or forced intrusions - Although clastic dikes are known to exist within the Taconic sequence, they have not been linked with specific movement horizons (Voight and Cady, 1978).

5. History

a. age of inception - The Giddings Brook slice contains rocks as young as middle Ordovician (graptolite zone 12) and is emplaced into and across Normanskill Formation of late middle Ordovician (zone 13) age (Bird, 1969). The slice is overlain by epikin-allochthonous and neoautochthonous strata of zone 12 and 13 age.

The Hamburg Klippe contains rocks as young as zone 11 (early Middle Ordovician) or zone 12 and was emplaced into its present position in middle and/or late Ordovician time (Root and MacLachlin, 1978).

b. recognition of syndepositional effects - "Wildflysch" developed in advance of and was subsequently overriden by the allochthonous sheets. A "wildflysch" developed as scree off the toes of advancing allochthons and by the bulldozing, rucking, and overriding of the moving allochthons (Bird and Dewey, 1970).

c. radiometric ages - The early cleavage/schistosity superimposed on the Taconic allochthon has been dated radiometrically as 420-440 m.y. B.P. (see discussion in Zen, 1972, p. 2585).

d. relationship to loading - none.

e. indications of last motion - The Taconic allochthon and the Hamburg Klippe are both overlain by small remnants of a molassic deposit of late Ordovician age at Illinois Mountain, New York (Bird and Dewey, 1970) and Spitzenberg, Pennsylvania (Stephens and others, 1979) that establish a minimum age for motion of the allochthonous sheets.

Several of the higher Taconic slices were emplaced during the Acadian event (Ratcliffe, 1975), but those slices are not bounded by thrusts of this group.

6. Stress field

The stresses operative within the Taconic-type allochthons at the time of emplacement are not known, but they would be highly dependent upon the mechanism of emplacement, gravity gliding versus underthrusting. Voight and Cady (1978) present a detailed discussion of the mechanics of gravitational gliding applied specifically to the Taconic-type allochthons. It is argued that the difficulty of transmitting horizontal compressive stress through a thin sheet of weak rock establishes gravity as the dominant transport mechanism. However, the model developed by Chapple (1978) for the mechanics of thin-skinned fold-and-thrust belts driven solely by lateral compression also can be applied to emplacement of the Taconic-type thrust sheets. Regardless of which mechanism of emplacement was operative, anomalous fluid pressures within the zone of detachment would have greatly facilitated movement of the thrust sheets (see Voight and Cady, 1978, p. 532).

7. Geophysical and subsurface characteristics
   a. seismic activity levels - There is no known modern seismicity associated with any of these faults. For a discussion of the areas of recent seismic activity in the eastern United States, see Sykes (1978).
   b. subsurface offsets - None observed.
   c. relations to anomalies - The Taconic allochthon and the Hamburg Klippe are co-extensive with a linear region of strong negative Bouguer anomaly; values are as low as -70 mgals.
   d. geophysical linements - None observed.
8. Geomorphic relationships - The Taconic-type thrust sheets exhibit no special or notable geomorphic relationshps.
9. Methods of identification - Faults of this group are identified principally by stratigraphic and paleontologic means. The allochthon slabs commonly contain "exotic" rock types and/or fauna, such as green and maroon slate, ribbon-limestone, mafic and ultramafic blocks, arkosic turbidites of pre-Olenellus age, chert, and conodonts and shelly fauna of Baltic affinity. Faults may be merely disturbed contacts of gray with colored pelites, but more commonly the boundaries are difficult to define with the problem being one of differentiating two dark slates.

   Autochthonous strata may be truncated beneath the lower thrust slices (Potter, 1972). Faults of this group normally pre-date regional folding, foliations, and metamorphism. Problems involved with locating the boundaries of the allochthon are discussed by Zen (1961).

10. Pitfalls in Identification - Where exposure is poor, the thrust slices may be mistaken for blocks in "wildflysch." The original orientations and shapes of the thrust slices most places have been modified by post-Ordovician deformation. Younger high- and low-angle faults (principally Acadian and Alleghanian thrusts) displace Taconic allochthon and Hamburg Klippe rocks, yet they are not of this group.

11. Possibility of Reactivation - There is virtually no possibility for reactivation except by landsliding or other mass wastage processes under unusual and clearly recognizable circumstances.

12. Selected References

Elter and Trevisan (1973)

Root and MacLachlin (1978)

Voight and Cady (1978)

Zen (1967, 1972)

VII

Group 3: BEDDING PLANE THRUSTS - DECOLLEMENTS

A. Generalized Description

Bedding plane (Fig. VII-1) and decollement thrusts (Fig. VII-2) are the characteristic fault phenomena of "thin-skinned" deformation. The faults are one of the principal structural features of foreland deformation and are characterized by having most of their displacement on surfaces which parallel bedding. The spacing of their ramps generally controls the locations of the major anticlines which they apparently initate by splaying or climbing stratigraphic section (Fig. VII-3).

Although bedding plane and decollement thrusts are best known from the forelands of orogens, recent work in the Moine of Scotland and the Grandfather Mountain Window, North Carolina, has demonstrated that thrusting in the more internal metamorphic terranes has the same thrust geometry as the foreland. Apparently any set of rock types which contains any appropriately oriented large-scale planar mechanical anistrophy, fail in similar ways.

Typical bedding plane and décollement thrusts (as shown in Figs. VII-I and VII-2) have the following properties:

1) Thrusts cut up section in the direction of tectonic transport.

2) The faults tend to parallel the bedding in "units" behaving as the weaker layers and cut up section in the buttressing layers. In general, weak layers are units such as evaporites, shales or coals; however, localities are known in the Cordillera (Burchfield, personal communication, 1979) where the thrusts parallel bedding within the apparently competent units (limestones) and appear to ignore weaker shale interbeds.

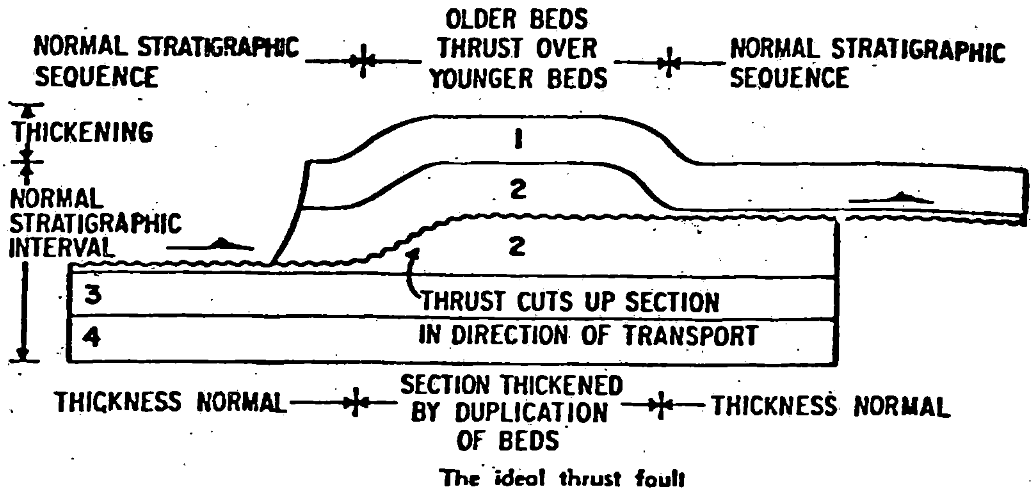
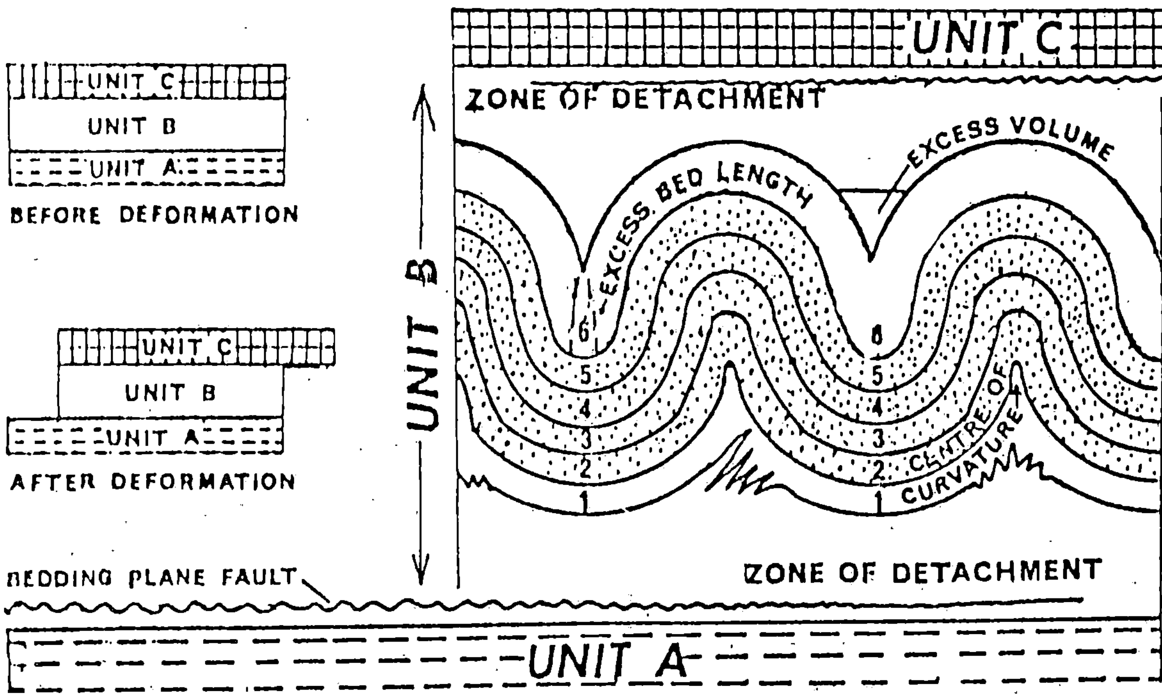


Figure VII - 1. Bedding plane fault climbing section by ramping. (Dahlstrom, 1970.).



This distance is the amount which folding shortens Unit B and is also the amount of bedding plane motion in the detachment zone elsewhere Unit C will be shortened while Unit B is not and the detachment plane motion may decrease to zero.

Concentric folding fails in bed 6 because it cannot accommodate the full length and volume of beds beyond the centre of curvature.

Length and volume problems illustrated for bed 6. Above are accommodated in bed 1 by faulting and/or crenulation with consequent detachment from Unit A below. Note that the change in structural shape between the upper and lower surface of bed 1 requires a minor discontinuous detachment within it.

Figure VII - 2. Bedding plane fault climbing Section by "decollement." (Dahlstrom, 1970).

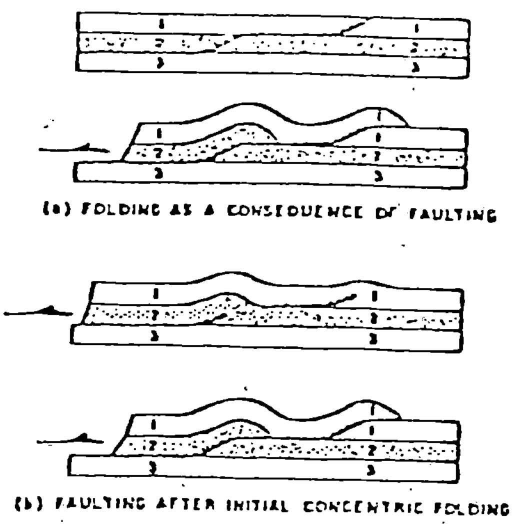


Figure VII-3. Relationship between folding and faulting sequence (2) Faulting precedes folding; sequence (b) folding precedes faulting. (Dahlstrom, 1970).

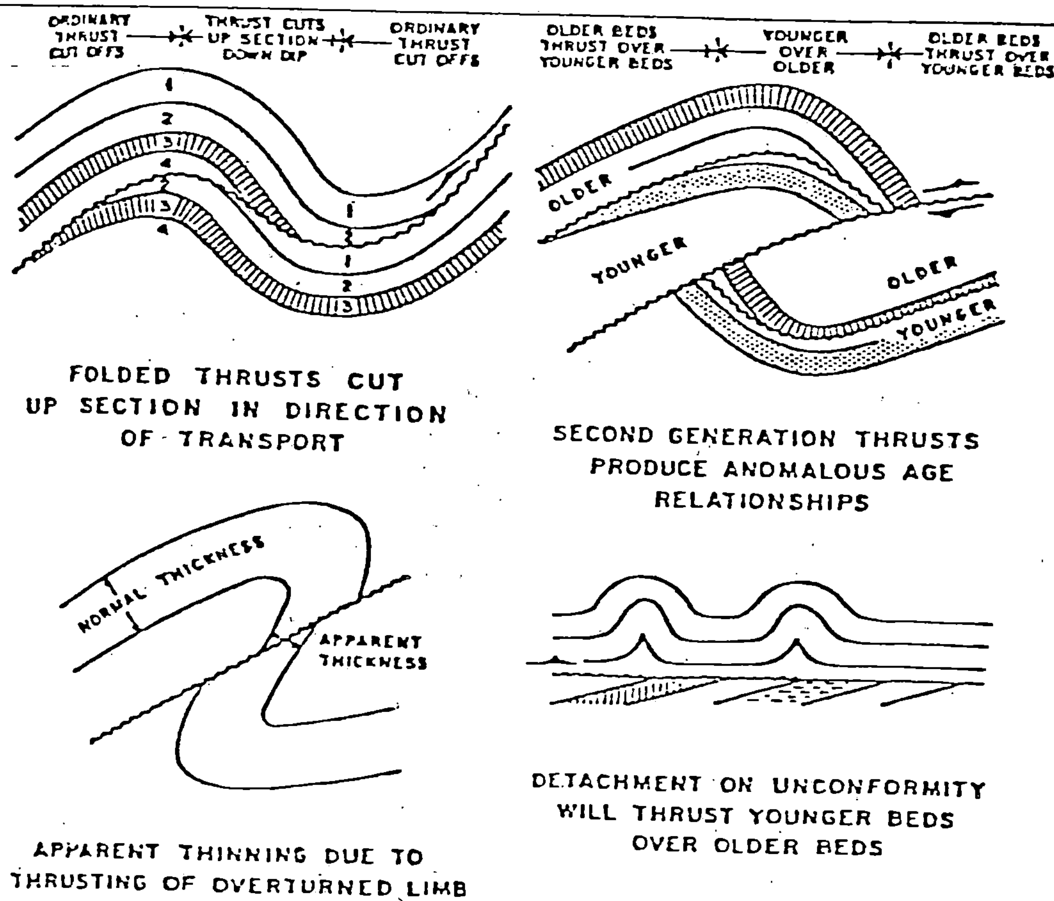


Figure VII-4. Apparent violations of Dahlstroms (1970) "Rules" of thrusting, due to structural complexities predating thrusting.

3) Thrusts need not change the overall thickness, but, if they do, they thicken the section by repetition of strata. These thrusts do not cause bed omission except in anomalous cases (see Fig. VII-4).

4) Thrusts place older beds on younger except in anomalous cases (Fig. 7).

The terminology which has been applied to thrust faults is shown in Figs. VII-5 and VII-6. Complications which add complexity to bedding plane thrust fault geometry typically occur in the region of ramps and at the trailing and leading edges of the thrusts. These effects are shown in Figs. VII-7 and VII-8. An additional element of complexity is added during late stage tightening of folds and folding of thrusts. Documentation and analysis of these complications is given by Perry (1978a,b).

Syndepositional effects of foreland thrusting tend to be associated with molassic sedimentation (e.g., Price and Montjoy, 1970). Syndepositional thrusting in more internal areas is associated with flysch and wildflysch sedimentation, where the location of the emergent thrust may be marked by precursory olistostromes (Elter and Trevisan, 1973).

Typical Examples. The classic example of a bedding plane thrust is the Pine Mountain fault of Tennessee, Virginia and Kentucky (Rich, 1934; Harris and Milici, 1977). Other major faults of this type in the Appalachian Valley and Ridge are the Pulaski thrust of Virginia and Tennessee and the Little North Mountain fault of Virginia and Maryland. Perry (1978a,b) has compiled an extensive description, relating bedding plate thrusts to fold development in the central Appalachians. Thrust faults are not restricted to the Valley and Ridge Province but also extend well out into the Plateau; the Burning Springs Anticline is located 180 km from the Alleghany front. On the New York Plateau, Prucha (1968) has

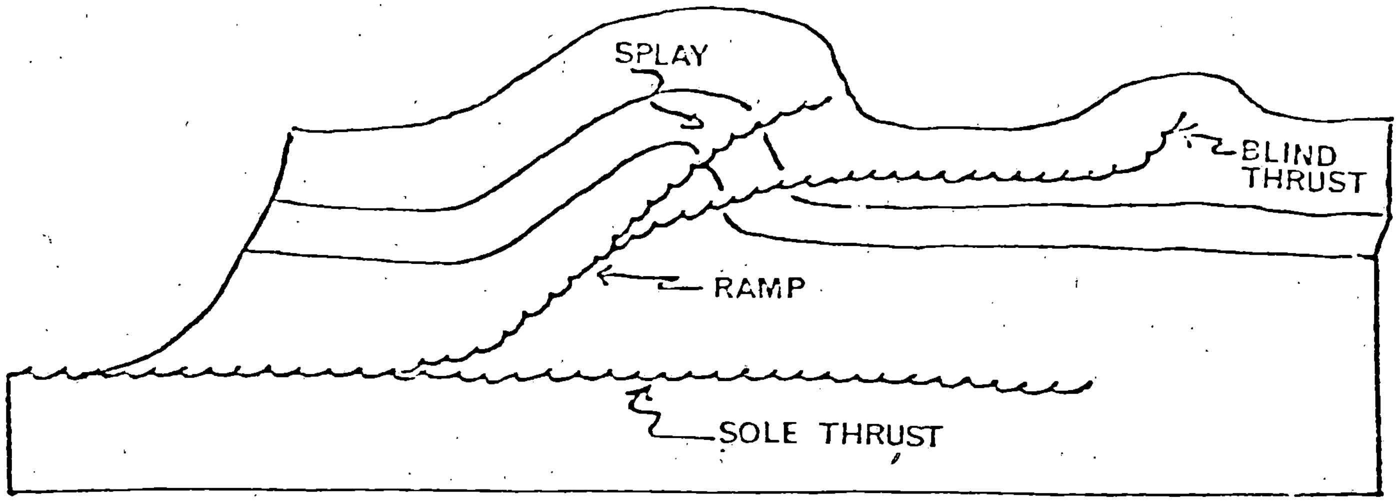


Figure VII-5. Thrust fault anatomy. (Dahlstrom, 1970)

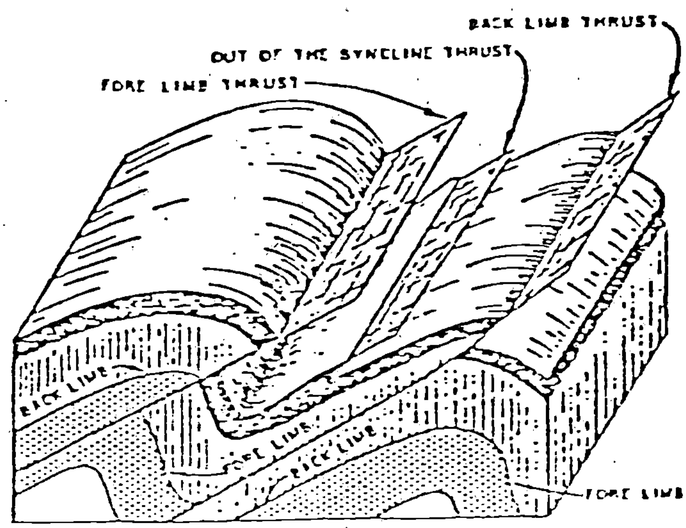


Figure VII-6. Thrust-fault terminology describing the geometric fold-fault relationships. (Dahlstrom, 1970).

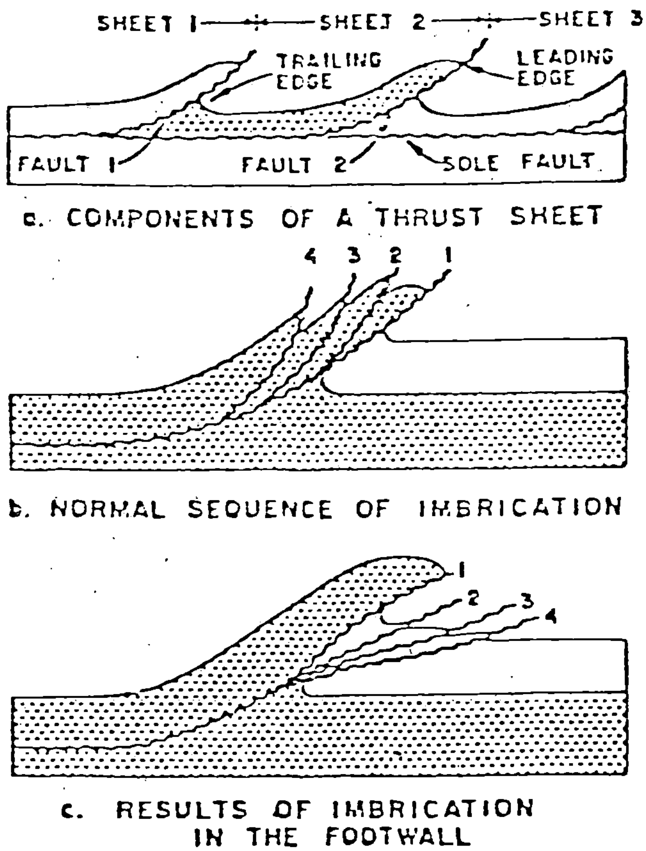


Figure VII-7. Imbrication. Complications of thrust faulting geometry; leading edge. (Dahlstrom, 1970).

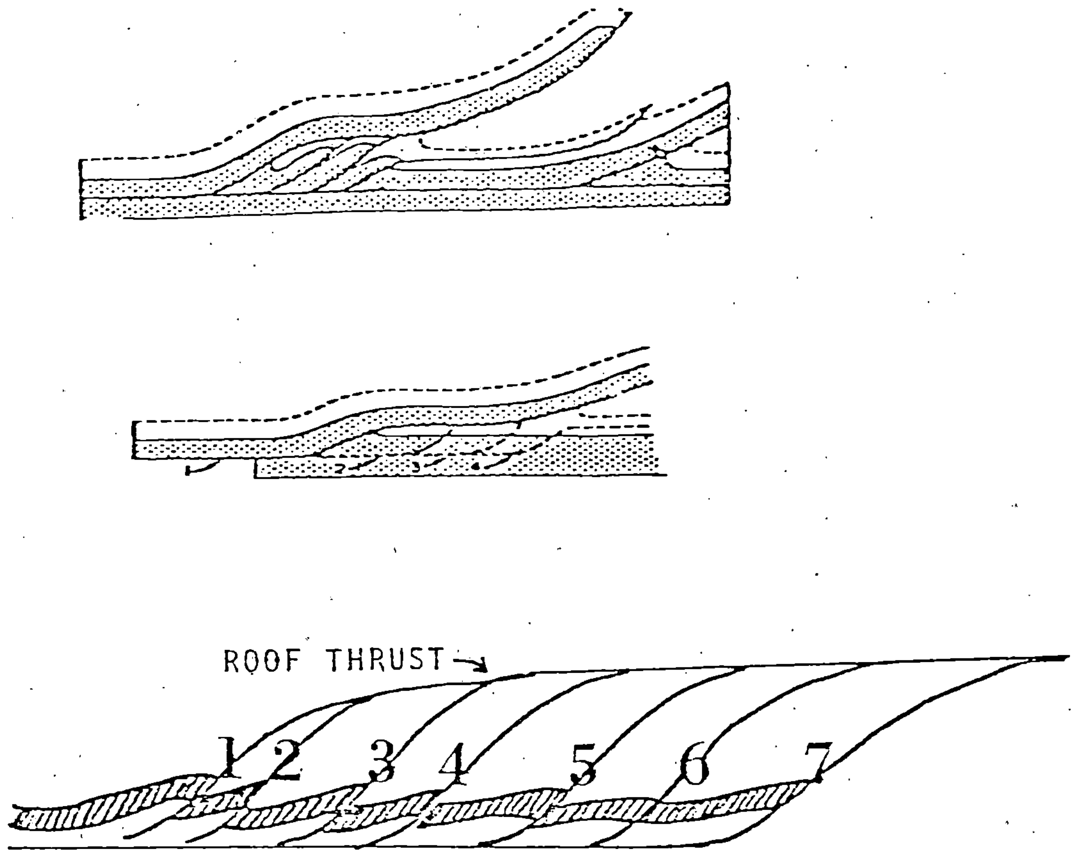


Figure VII-8. Complication of thrust fault geometry; trailing edge imbrication showing sequence of inbricate development and development of duplex. (a) imbricate stack, (b) sequence of imbricate development, (c) development of duplex. (Dahlstrom, 1970).

recognized the presence of a decollement surface beneath the northernmost anticline some 150 km north of the Alleghany front, while Engelder and Geiser (1979) show that this decollement extends to the Helderberg escarpment some 80 km beyond the outermost fold of the Plateau.

B. Description of Fault Group

1. Basic Geometry

a. Strike length - Kilometers (e.g., McConellsburg thrust, Pennsylvania≃ 15 km) to hundreds of kilometers (e.g., Pulaski thrust ≃325 km).

b. Width - Kilometers to hundreds of kilometers from leading to rear edge; for example, the minimum width for the decollement to the Burning Springs anticline as measured from the Blue Ridge is 200 km. The trailing edges of thrust sheets may be truncated by more internal thrusts, e.g., see the Pulaski-Blue Ridge thrust relations (Milici, 1975). The leading edge may end by splaying (e.g., Fort Ridge and associated faults) in small-scale features accomodating lateral compaction (New York Plateau, Engelder and Geiser, 1979) or in blind thrusts (Figure VII-5; also see Thompson, 1979).

c. Orientation - To a first approximation the faults parallel the regional grain of the Appalachian foreland fold and thrust belt. However, in regions such as the Pennsylvania Reentrant and the Virginia Promontory, intersecting deformation trends may obscure this property.

d. Displacement - Characteristically sheets move toward the craton with respect to the underlying basement rocks. Displacement vectors are essentially normal to strike for the Appalachians. Subsequent folding of bedding faults may tilt the surface such that the hanging wall seems to have moved up or down, giving a false impression of the real sense of slip such that the use of the terms normal and thrust faults are misleading and, therefore, not appropriate. However, late stage thrusts, called up-limb thrust faults (Perry and deWitt, 1977), or symmetrical thrusts (Gwinn, 1964), may locally move in a direction opposite to that of the main detachment, as well as having an identical dip opposed to that of the main fault.

An additional component of horizontal displacement due to layer-parallel shortening must be added to that due to slip on the fault surface. This component has only been partially documented in the Appalachians, primarily in the New York and Pennsylvania Plateaus (Nickelsen, 1966; Engelder and Geiser, 1979) and the Central Appalachian Valley and Ridge (Faill, 1977). In this region, Engelder (1979) has shown that this component may almost double the total lateral shortening.

e. Continuity -

i. Parallel to strike; faults of this class are continuous surfaces at the time of inception; may follow a single bedding surface (individual horizon) for hundreds of km or may climb section to new detachment horizon subsequent to folding and erosion may isolate segments of the sheet.

ii. Normal to strike (profile section) - Bedding plane thrusts characteristically climb section (ramp) in the direction of tectonic transport, forming anticlines in the ramp area (Fig. VII-5). Numerous complications develop in the ramp areas, among these are:

1. Imbrication: (Fig. VII-7b) and (Fig. VII-7c) Break back imbrication refers to imbricates which develop in a sequence where the younger faults are closer to the trailing edge, while break forward imbricates develop in a sequence in which the youngest imbricate is closest to the leading edge.

ii. Duplexing (Fig. VII-8).

iii. Thrusts may terminate in ramp areas either as splays (Fig. VII-7) or as imbricate stacks (Fig. VII-8).

f. Curvature -

i. Map view - Two types of outcrop patterns are found: Bow shaped (Fig. VII-9) and rectangular (Fig. VII-10). Fault terminations in these two patterns are distinctly different. Bow-shaped traces terminate in anticlines while rectangular ones terminate in tear faults. The bow shaped types dominate in the Appalachians. Elliott(1976a) presents evidence that displacement on bow shaped faults is directly proportional to their length, with maximum displacement expected near their mid-point. It has been suggested that the bow shape may represent either the shape of the sedimentary basin, geometry of the loading mass, or geometry of the detachment horizon.

ii. Local curvatures - Ramps occur where thrusts cut sharply up section from one décollement plane to another, with local anticlines created above the ramps (Fig. VII-5). Splaying is common at leading edge, ramps, and trailing edge (truncated rear end). Slices are common in the vicinity of ramps and splays.

g. Termination along strike - Bedding thrusts may terminate abruptly in strike-slip faults (tear faults) (Fig. VII-11). They may gradually lose displacement along their length and terminate in folds or in a series of en echelon thrust or folds called transfer zones (Fig. VII-12) which converse the displacement by carrying it to the next major thrust.

Tear fault termination may be a single large fault or multiple faults. Tear faults are sometimes manifested at the surface by en echelon folds or a region of fold terminations (Fig. VII-13).

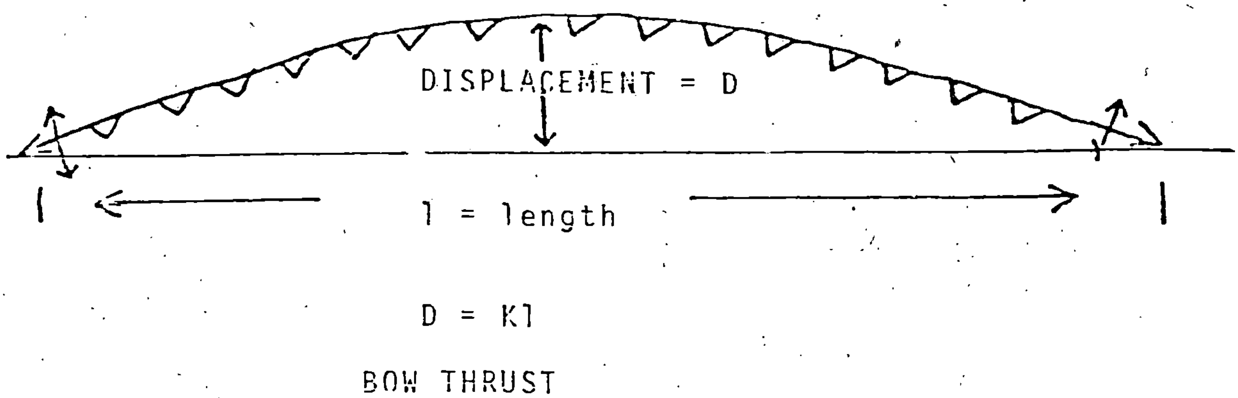


Figure VII-9 Bow Thrust
(Dahlstrom, 1970).

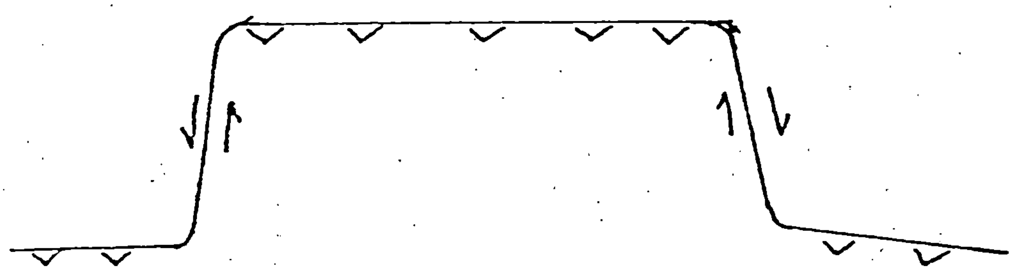


Figure VII-10 Retangular Thrust
(Dahlstrom, 1970).

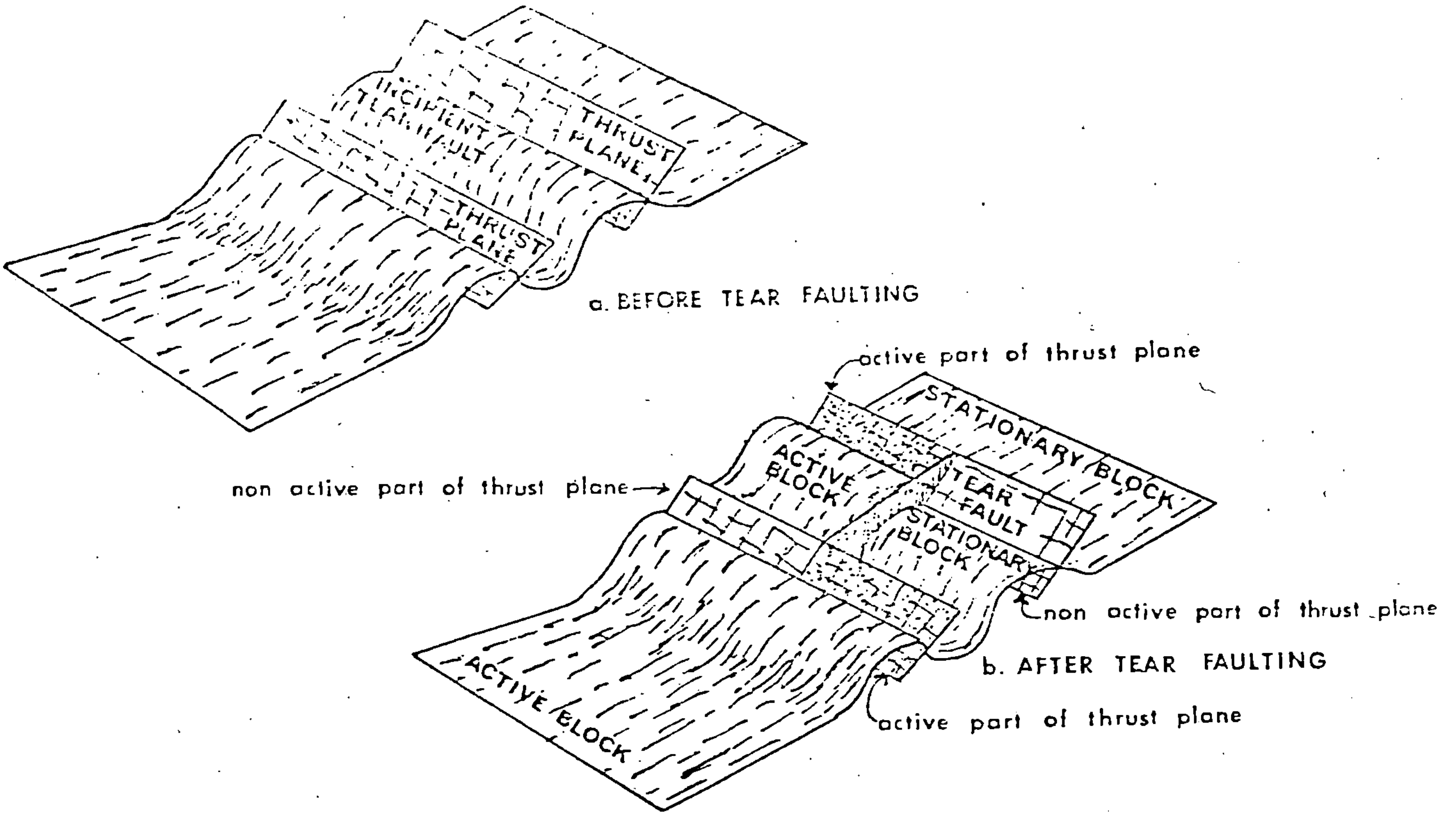


Figure VII-11 Secondary transverse tear faults. (Dahlstrom, 1970).

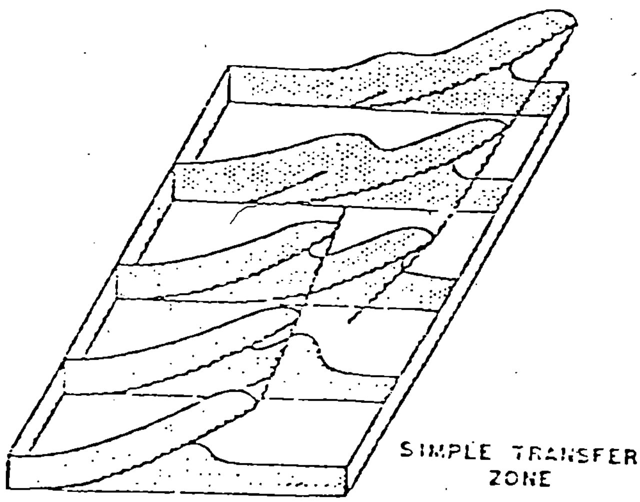


Figure VII-12 Termination of bedding plane thrust into folds. (Dahlstrom, 1970).

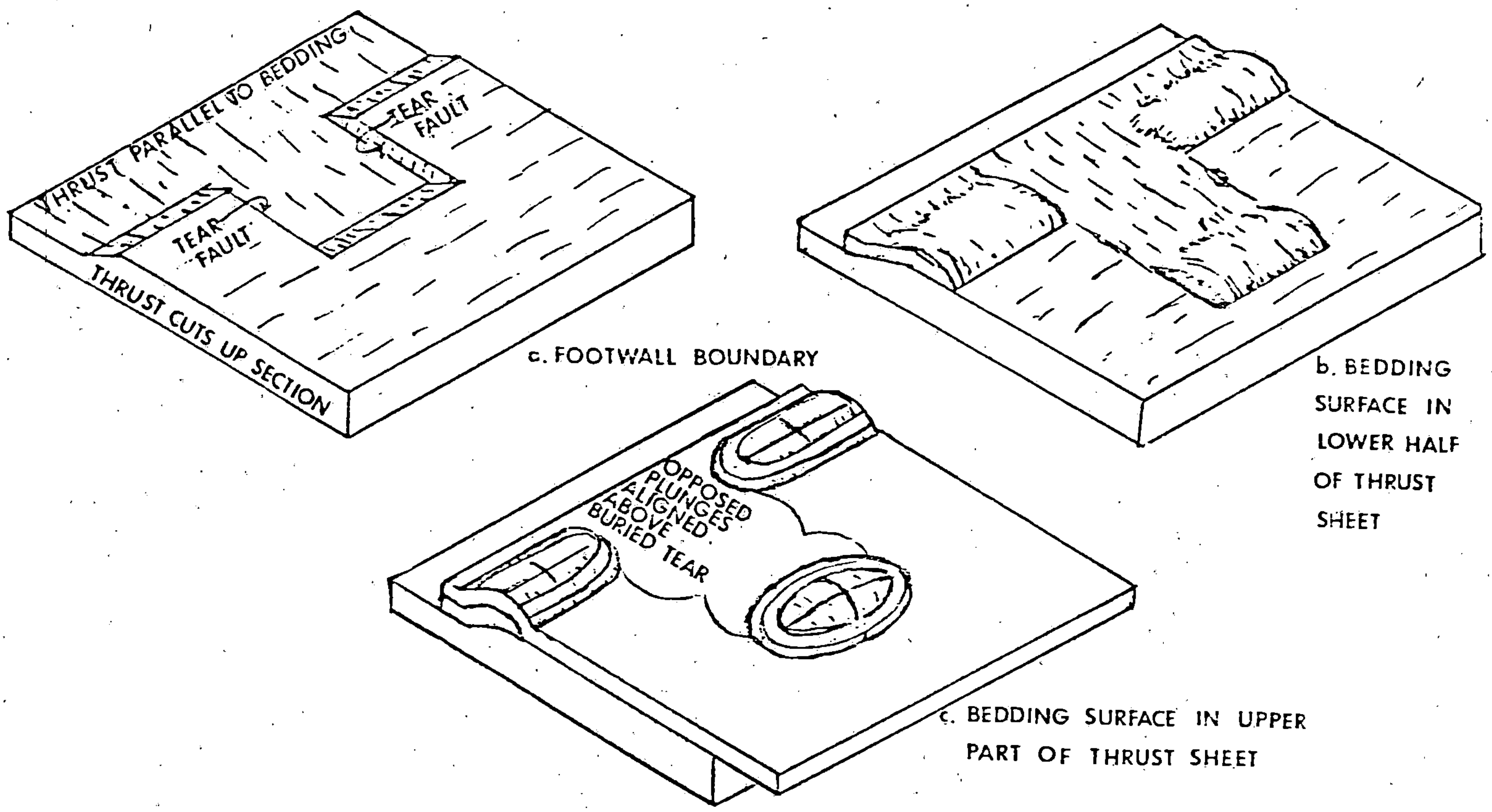


Figure VII-13 Terminations of bedding plane thrust. (Dahlstrom, 1970).

2. Tectonic Setting

This style of faulting occurs in the thick miogeoclinal wedge and cratonic foreland. However, recently Harris and Bayer (1979) have suggested that a thrust fault terrane may also characterize the Blue Ridge of the southern Appalachians. Displacement decreases toward craton; some early stages of Piedmont thrusting could conceivably involve a bedding plane thrust (e.g., Safe Harbor fault, Pennsylvania, Wise, 1970), but evidence of these thrusts has probably been obscured. Dips flatten eastward with depth and then disappear under the frontal zone of the Blue Ridge and related thrusts: master décollements are best developed in ductile horizons such as Rome Shale. Master thrusts rise to the west or northwest and either emerge or go into blind folds and die normal to strike. Many do not extend through the mid-Appalachian salient.

In most mountain belts, the timing of thrusting is generally associated with Molasse and Flysch sedimentation. However, in the Appalachians this has been a matter of considerable controversy, as this would extend the development of the foreland back to the Taconic and implies the presence of syndepositional thrusting and folding. Although scattered evidence for such activity has been reported from the Appalachian foreland (e.g.,Lowry, 1957; Cooper, 1964; Lowry and Cooper, 1970) the main thrusting and fold events in the foreland are still regarded as primarily late Carboniferous (e.g., Van der Voo, 1979).

It should be noted that until recently the basic tectonic framework of the Appalachians has been a matter of some debate, often referred to as the "thick skin-thin skinned" controversy. Proponents of the thick-skinned school held that deformation in the Appalachians was largely due to vertical motions of portions of the basement beneath major folds. These concepts were primarily supported by sedimentologic and stratigraphic evidence that the folds were growing during deposition (Cooper, 1964; Rodgers, 1970). Thus, "thick-skin" ideas held that the deformation of the Appalachian orogen (particularly the Valley and Ridge) had been very long-lived.

"Thin-skinned" proponents (see Rodgers, 1970), pointing to the example of the French Jura and geophysical evidence that the basement beneath the Valley and Ridge and Appalachian Plateau was almost completely flat, held that the deformation of these regions was one of bedding-plane thrusting above detachment surfaces. In general those supporting these ideas have held that the deformation of the Valley and Ridge and Plateau occurred as a single late Paleozoic event, rather than as an ongoing process throughout much of the Paleozoic.

Although the structural and geophysical evidence have overwhelmingly supported thin-skinned ideas and even extended them into the Blue Ridge and Piedmont, now also known to be allochthonous, evidence for syndepositional deformation is still extant. Geiser (1977) has noted that thin-skinned tectonics and syndepositional deformation are not incompatible phenomena. Numerous cases of this relationship are well-known from the European literature. Thus, the possibility still remains open that the deformation of the Appalachian foreland may extend back considerably further than the late Paleozoic.

The structural behavior of the southern and central Appalachian foreland shows a marked contrast in style, changing from dominantly thrusting in the Southern Appalachians to dominantly folding in the central Appalachians inasmuch as the major anticlines are apparently cored by thrusts (Gwinn, 1970) and décollement surfaces can be traced far out onto the Plateau (Prucha, 1968; Engelder and Geiser, 1979). The thrusting ending by going "blind" in the north rather than emerging on the surface as they do in the south.

The northern termination of the Valley and Ridge Province is characterized by an abrupt narrowing of the fold thrust belt into a belt of apparently monoclinally-dipping beds on the east side of the Poconos and Catskills. However, Geiser (1980) has interpreted this area as a narrow zone of imbricated thrusts where the leading edge of a master décollement terminates. This zone has been mapped along the Helderburg Escarpment north of Rosendale, New York. The presence of the zone of imbrication north of the Delaware Water Gap implies that: 1) the Hudson River Valley - Great Valley sequence contains unidentified thrusts, 2) that the western margin of this region from the Delaware Water Gap to Albany marks the site of an imbricated footwall at the leading edge of a major east-dipping thrust sheet emerging from the Normanskill Formation.

3. Characteristics of Fault Surface or Zone

a. Type of fault. Although little is known from direct observation of active bedding plane faults, textural features of fault surfaces in the central Appalachians suggest that they are largely the product of aseismic creep. However, southern Appalachian faults seem to have surface textures more characteristic of frictional sliding (see Harris and Milici, 1977 and Milici, 1978 for locations and examples).

b. Surface Texture -

i. Mineralization generally sparse; quartz and calcite may deposit on surface.

ii. Fault surface usually identified in ramp areas where fault zone crosses (jumps) sections.

iii. Typically motion is concentrated on a few stratigraphic surfaces in a major sedimentary pile but minor motions can be distributed on hundreds of fault surfaces. Flexural-slip during folding may be responsible for some slip; Cloos was able to separate flexural slip from decollemnt by calculating the total possible displacement from flexural slip or the wrong sense of displacement on a fold. Within major zones, slice on slice on slice may be created to produce sections up to several hundreds of meters thick consisting largely of chaotic lensoidal slickensided or polished pieces.

iv. Some horizons may involve more ductile deformation and form tectonic injections. These major involve shales and evaporite horizons.

v. Slickensided surfaces and wear grooves may develop.

c. Character of zone - The most common characteristic of the fault zones is fibrous and slickensided surfaces, the product of pressure solution and diffusion controlled phenomena characteristic of creep (see Appendix B). However, some studies of fault surface textures (Pierce and Armstrong, 1966; Brock and Engelder, 1977) indicate that features indicating frictional sliding are present on some faults.

Although not common, gouges and breccias are found associated with thrusts. These structures are known to occur where thrusts emerge at the surface, thus their presence probably indicates a shallow depth of development for that portion of the fault. Pierce and Armstrong (1966) identified what they termed a "mylonite" marking the surface of the "Tuscorora fault." The interpretation of this "mylonite", however, is still an open question.

d. Metamorphism and mineralization - Mineralization is primarily restricted to calcite, quartz, and chlorite. No metamorphism is known to be associated with these faults.

e. Datable materials - Datable materials are rare; Pierce and Armstrong (1966) succeeded in obtaining a K/Ar whole rock date from what they interpret to be a carbonaceous shale contained within the fault zone. Other than this, there have been no attempts to date material within bedding plane fault zones. With the emergence of more sensitive dating tools, however, it may now be possible to more accurately date the faults.

4. Relation to Country Rock

a. Bedding plane thrusts parallel the regional tectonic trends but may locally cut obliquely across them.

b. Major changes in structural style occur at both the Virginia and New York Promontories. Deformation in the Valley and Ridge changes from thrusting in the southern to folding in the central Appalachians changes to thrusting again shown by the Anthracite Basins and the narrow belt of imbrication which replaces the folding of Valley and Ridge Province north of the Delaware Water Gap.

c. Thin-skinned

d. Relation to Isopachs - No clear relationship has been shown between individual faults and gross isopachs of entire stratigraphic columns, although there are theoretical reasons for believing such may exist. However, Engelder and Geiser (1979) and Slaughter (1980) have found evidence that regional detachments can be related to isopachs in the detachment zone (Fig. VII-14).

Pinching out of decollement horizons can be the cause of ramping, as for example, the Burning Springs anticline. While the change in the relative thicknesses of the Carboniferous clastic vs. carbonate sections has been suggested as a possible cause for the south-central change in the structural style of the Valley and Ridge.

e. Stratigraphic interval - Bedding thrusts are directly controlled by the stratigraphic interval of the detachment surface. The faults follow given intervals, with ramps developing as shear stresses build in the overlying stiff layer. The causes of ramping are not well understood

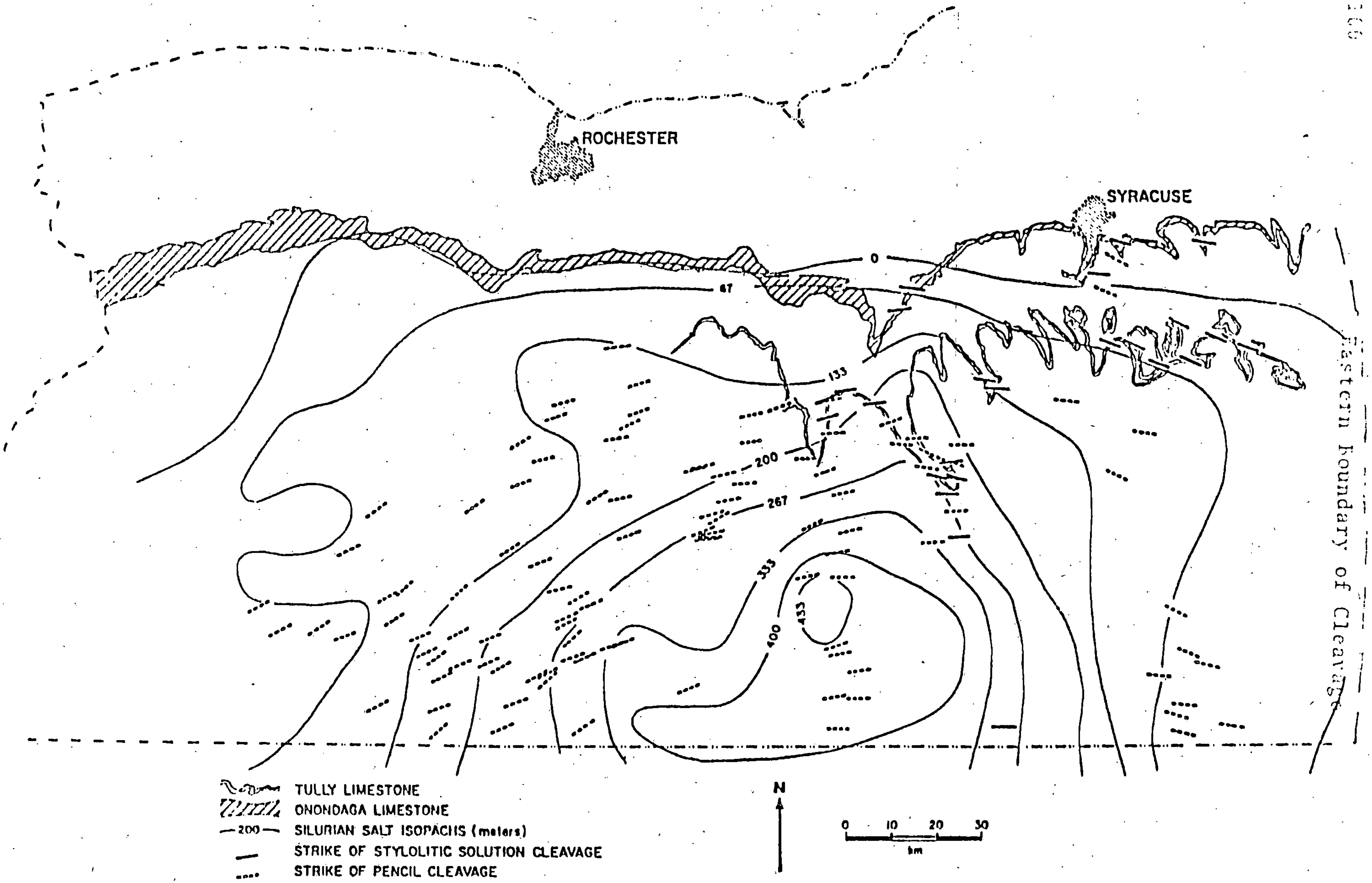


Figure VII-14 Relationship between detachment surface as indicated by layer parallel shortening (CLPS) and silurian salt horizon. The solution and pencil cleavage are a minifestation of LPS.

but such controls as lateral facies changes, changes in strain rate during fault growth, change in décollement horizon dip, and changes in pore pressure have all been suggested.

f. Relation to Folds. Present evidence from field studies (Elliott, 1976a; Engelder and Geiser, 1979) indicates that thrusting probably precedes major folding. Thus Appalachian folds with wavelengths on the order of kilometers are thought to be largely the result of ramping of thrust faults rather than buckling. The presence of a detachment surface over 60 km outward of the most external fold on the New York Plateau (Engelder and Geiser, 1979) clearly demonstrates that thrusting preceded folding throughout this region and possibly throughout the central Appalachians as well. However, this subject is still a matter of considerable controversy as the formation of concentric buckle folds may generate local thrusts due to accomodation problems in the core. These thrusts may then merge do form the sole thrust (Dahlstrom, 1970). A more complete analysis and field examples of this process whereby a thrust propagates has been given by Thompson (1979). An alternative model has been suggested by Wiltschko and Chappel (1977) whereby a décollement develops due to underflow of a thick layer of low viscosity. Complications may arise where early thrusts become locked by folding. Continued shortening of the section can result in renewed faulting which may then cut the earlier folds.

g. Relation to s-surfaces - The development of local cleavage surfaces along bedding-plane thrusts has been documented by Alvarez et al. (1978) in the Apennines and discussed by Elliot (1976b). Alvarez et al. (1978) have suggested that thrust tips may migrate by utilizing "damage" zones created by cleavage development.

h. Relation of fault character to rock type - There are two controls on the fault character by the rock type:

i. Ramping. Ramping generally occurs in more competent units, e.g., sandstones and limestones.

ii. The deformation textures along the fault surface generally change with rock type; in thick weak units (shales, salts, etc.) slip is distributed in a wide zone, in some cases hundreds of meters wide; in strong units, slip is restricted to narrow zones.

i. P-T conditions - Bedding-plane thrusting characteristically occurs under the conditions of the low temperature (≤ 100 C) and low (≃ 1 kb) pressures of the foreland. Since active thrusts are known to emerge at the surface, it is apparent that the process can occur at surface conditions. The independence of thrusting and temperature in the southern and central Valley and Ridge has been demonstrated by Harris et al. (1978) through use of the Conodont Alteration Index (CAI) isograd data (Harris et al., 1978). A similar independence is suggested for the New York Plateau where cleavage related to a décollement surface in the Salina Group is independent of the CAI isograds (see Fig. VII-15).

j. Relation to isograds - The root zones of these thrusts may cut and displace isograds and paleo-isotherms. This behavior is classically demonstrated by the Blue Ridge thrust in Virginia and Tennessee (Bryant and Reed, 1970), while a few, such as the Greenbrier have isograds superposed on them (Bryant and Reed, 1970).

k. Relationship to intrusions - none.

l. Tectonic injections or forced intrusions - Tectonic injections of gouge and highly ductile units such as shales, occur locally along the thrust surface.

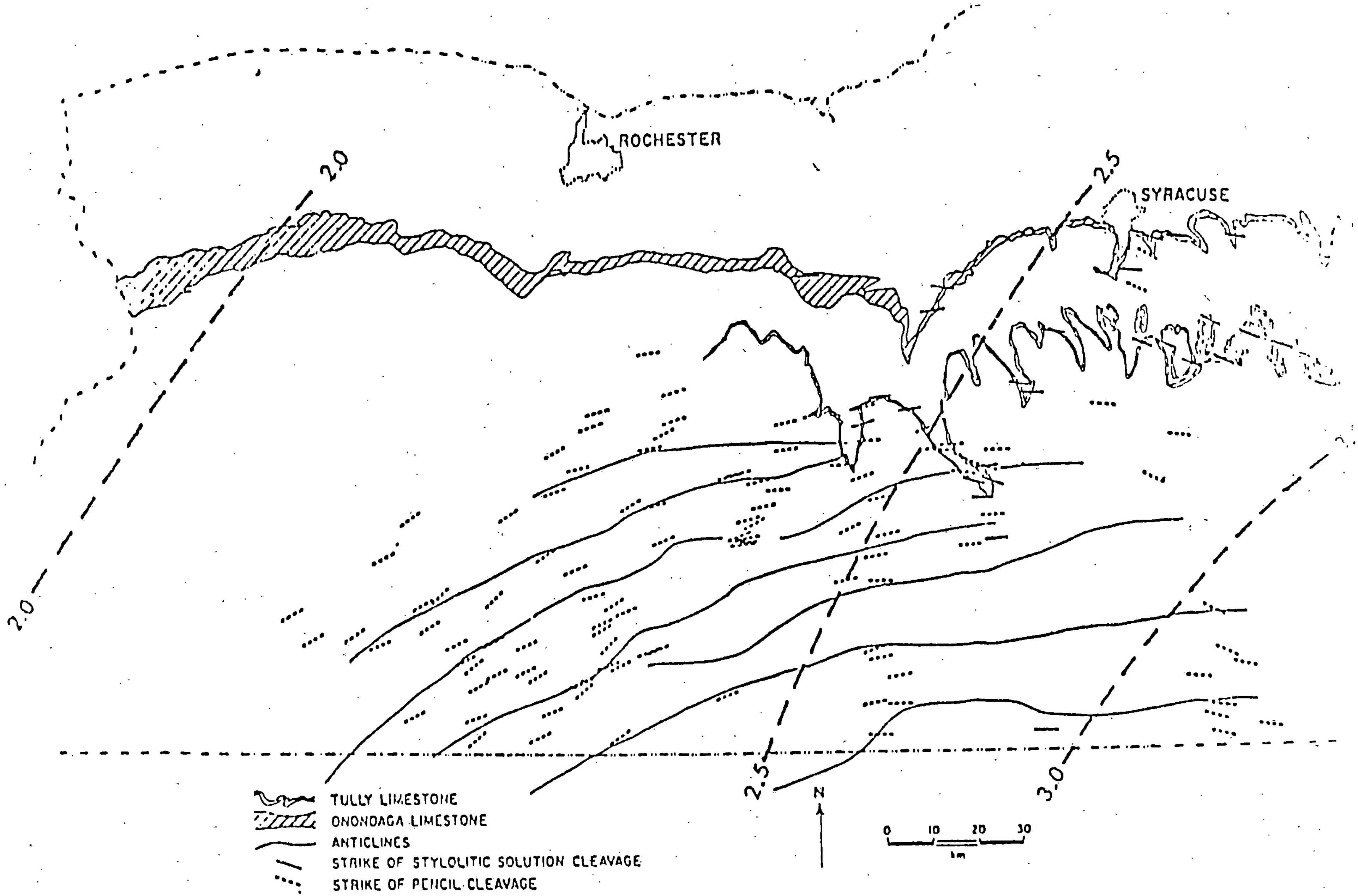


Figure VII-15 Demonstration of independence between paleo-isotherms and detachment surface at the Silurian Salt horizon in the N.Y. Plateau. Paleo-isotherms are indicated by Conodont Alteration Index (CAI) taken from Epstein (1975).

5. History

a. Age of inception -

The age of thrusting in the Appalachians is a subject of some dispute, since the age of inception is not necessarily indicated by the age of the youngest rocks cut. Most of the foreland thrusting in the Appalachians is probably Carboniferous or younger in age. However, there is some evidence in the form of age dates (Pierce and Armstrong, 1966) and possible unconformities (Frexlen et al., 1961) which suggest Devonian deformation. In addition,there is a variety of evidence for syndepositional folding extending back as far as the Ordovician (Lowry, 1957) and continuing through much of the Paleozoic (e.g., Tillman, 1963; Cooper, 1964; Thomas, W. A., 1966; Lowry and Cooper, 1970; Jacobeen and Kanes, 1974). Thus folding and thrusting may have been initiated considerably before the terminal Alleghanian event.

b. Recognition of syndepositional effects: As indicated in section a., there is considerable evidence for syndepositonal deformation in the Appalachians, most of which has been identified with folding. The evidence for this behavior is primarily in the form of structurally controlled stratigraphic thickening and thinning (e.g., Tillman, 1963; Cooper, 1964) as well as auto-conglomerates occupying synclinal basins (e.g., Lowry and Cooper, 1970). Additional unpublished evidence for current and sedimentologic control by structure has been found by Steinen (in the Keefer formation in central Pennsylvania (R.P. Steinen, personal communication, 1980). It seems likely that other evidence of this type may be found elsewhere in the Appalachians, where stratigraphic and sedimentologic studies are performed in the context of the local rather than the regional setting of basin analyses which have been the characteristic form of study in the Appalachians.

c. Radiometric ages - Pierce and Armstrong (1966) give the only known age determination; a whole rock K/Ar date of 390 ± 50 my from the Tuscarora fault of central Pennsylvania.

d. Relationship to unloading - As far as is known, these faults are unaffected by unloading.

e. Indications of last motion - No bedding-plane thrust is known to have moved since the end of the Paleozoic. However, there are no good indicators which demonstrate a definite time of last motion, except locally where overlain by Quaternary alluvium.

6. Stress Field.

a. The regional stresses approximate Anderson's (1951) theoretical model where σ_1 is approximately normal to the structural grain, σ_2 is approximately parallel and σ_3 is vertical.

b. Magnitude of stress and strain-

i. Deviatoric stress values in thrust sheets are a controversial subject, with a wide range in values being cited. For example, Jamison and Spang (1976) have found evidence that differential stress values within the McConnell thrust were between 1120 and 1430 bars. Whereas Groshong (1975) has pointed out that in the more external parts of the New York Plateau décollement differential stress values were less than the yield strength of calcite (≃ 75 bars). The wide variations in stress values observed may be a function of the type of flow law which applied to the thrust surface. Those thrusts controlled by diffusion creep would follow a linear viscous law and thus would be expected to show low values of deviatoric stress, whereas those governed by frictional sliding (i.e., brittle failure) would be expected to have high values.

ii. Strain - Body strain within the thrust plate varies from 1-2% shortening at the leading edge to greater than 100% at the trailing edge. This strain is partitioned among finite amplitude folding, solution loss, intra- and intergranular strain, jointing, wedging and recoverable elastic strain.

c. Variation in stress and strain -

i. Stress - The highest stress levels are developed along the fault surface; possible local stress concentrations may exceed 1 kb; however, maximum mean values within a sheet undergoing ductile creep are probably less than 200 bars (Elliott, 1976). On the other hand, Jamison and Spang (1976) indicate that the trailing edge of thrust sheets may experience values of deviatoric stress close to 1.5 kb. The deviatoric stress levels attenuate towards the tip where current evidence indicates they are on the order of a few 10's of bars (Groshong, 1975).

ii. Strain - The distribution of strain magnitudes associated with thrusting may follow the distribution of stress magnitudes; however, only the most preliminary quantitative data are avilable on this (Dean and Kulander, 1972; Alvarez et al., 1978; Engelder and Geiser, 1979). An added problem is that virtually nothing is known about the distribution of strain partitioning within thrust sheets.

d. *In situ* stress - Not known.

e. Seismic first motion studies - No seismicity has been directly connected with the Appalachian bedding-plane thrusts.

f. Rates of motion - When active, the thrusts are believed to move at rates of 10^{-12} - 10^{-14}/sec. (Elliott, 1976a). However, neotectonic seismic data from present-day mountain belts (Seeber et al., 1980) suggests that seismic activity may be common along some of these faults; unfortunately, the data are not of sufficient quality to provide unambiguous answers.

g. Fluid pressure changes and effects - Not known; however, changes in fluid pressure should affect behavior of fault (see Hubbert and Rubey, 1959).

7. Geophysical and Subsurface Characteristics

a. Seismic activity levels - Although no seismicity has been definitely connected with any particular thrust fault, the present stress regime of the East Coast of the United States is dominantly one of compression directed approximately normal to the structural grain (Rankin, 1977; Yang and Aggarwal, 1980). In addition, most of the fault plane solutions available for the east coast indicate that high angle reverse faulting or thrusting forms the present mode of motion (Yang and Aggarwal, 1980). Consequently, thrust fault terranes may have a distinct potential for seismic activity. This potential is apparently realized during loading, as indicated by Talwani et al. (1979) who discuss induced seismicity beneath Lake Jocassee, South Carolina.

b. Subsurface offsets - Commonly offsets both stratigraphy and structure above the detachment zone. Not known to produce any effects in the crystalline basement, although irregularities may control the location of offsets.

c. Relations to anomalies - Produces local gravity anomalies where imbricate thrusting develops "stacking" of dense section, while addition of low density material to core may also produce anomalies

(Kulander and Dean, 1978). Should have no effect on magnetic anomalies unless thrust package contains a magnetically susceptible unit which is offset.

d. Geophysical lineaments - May produce linear gravity anomaly parallel to regional grain over zones of imbrication or perpendicular to strike due to transverse ramps.

8. Geomorphic Relationships

In general, thrust faults have little geomorphic expression unless the entire plate is exposed at the surface like the Pine Mountain sheet. In this case the contrasting lithologies and the exposed bounding tear faults produced marked differences in drainage patterns within and without the sheet. Topographic expression might develop as the result of thrusting juxtaposing strata of contrasting susceptibility to erosion.

9. Methods of Identification

Bedding plane faults are identified by:

a. The tendency for the fault to have most of its surface restricted to one or two stratigraphic horizons.

b. By following the set of "rules" as described by Dahlstrom (1970) and as briefly summarized at the beginning of this section.

10. Pitfalls in Identification

a. Bedding-plane thrusts may be different to identify in highly deformed terrane where they may be folded or may transect pre-existing structures causing apparent "violations" of Dahlstrom's rules.

b. Local thrusting due to tighening of folds may be confused with major thrusts (e.g., Gwinn, 1964; 1970).

c. The width of the fault surface cannot be used as a measure of displacement. Sole thrusts surface with large (km) displacements can be restricted to a zone a few centimeters thick.

d. In regions where fault complexity commonly develops (i.e., at the toe and over ramps), there may be considerable difficulty in identifying the major fault.

e. Wedging (Cloos, 1964) may be mistaken for major bedding plane thrusts. Although the geometry of wedging is identical to that of bedding plane thrusts, the scale differs by orders of magnitude. Wedges have maximum displacements of 30-60 meters (unusual) but typically are only on the order of centimeters to meters.

f. Flexural slip along bedding due to folding is easily mistaken for a thrust surface. The problem is further complicated by the occurrence of folded thrusts. Further mapping and determination of fold wavelengths and layer thickness can be used to determine whether the flexural slip is due to folding or thrusting.

g. Bedding plane thrusts can be easily missed since they may become very narrow and show almost no sign of movement in the form of deformation textures, and because such faults are usually conformable to strata.

II. Possibility of Reactivation - These faults have almost no possibility of reactivation by their original driving mechanisms. However, man-made loading, injection of fluids and/or in situ stress may cause reactivation in appropriately oriented faults. Unfortunately at the present we have no data for the strength of these older thrust surfaces.

12. Selected Reference List

Chapple, W. M. (1978)

Gwinn, V. E. (1964)

Harris and Milici (1977)

Rich, J. L. (1934)

Rodgers, J. (1953)

VIII

GROUP 4 FAULTS: PRE- TO SYNMETAMORPHIC THRUSTS IN HIGH GRADE TERRANES

A. Generalized Descriptions

Thrusts of Group 4 consist of brittle (including imbricate) thrusts, which possibly exhibited bedding plane-type behavior, that were emplaced and subsequently were overprinted by metamorphism. All the characteristics of bedding thrusts (Group 3) may apply to these. Most were completely annealed by the thermal event; some were reactivated later during or after the thermal peak producing mylonites along faults. Probably most Group 4 faults formed as early compressive features as a result of the initial stages of the thermal/metamorphic event with which they were associated. However, there were probably a variety of faults, thrusts, strike-slip, and normal faults, which formed in the early Paleozoic orogen. Some of these may have been reactivated as synmetamorphic thrusts. Several faults of this group are transitional into recumbent basement-cored nappes as well as into late to post-metamorphic thrusts in high grade terranes (Group 5). Those, such as the Honey Hill fault of eastern Connecticut, include metamorphic reactions as part of their strain mechanism. Some, like Cameron's Line in Connecticut (Rodgers, 1970), may be sutures with ultramafic associations. These are typically the synmetamorphic thrusts and exhibit a ductile, rather than a brittle, strain histroy. Faults of Group 4 are recognized by telescoping of stratigraphic successions, metamorphic overprinting with no disruption of isograds, aligned ultramafic bodies and juxtaposition of markedly different stratigraphic and/or petrologic suites. The movement of most of these faults in the Appalachians occurred during the Ordovician or Devonian and as such present no hazard today.

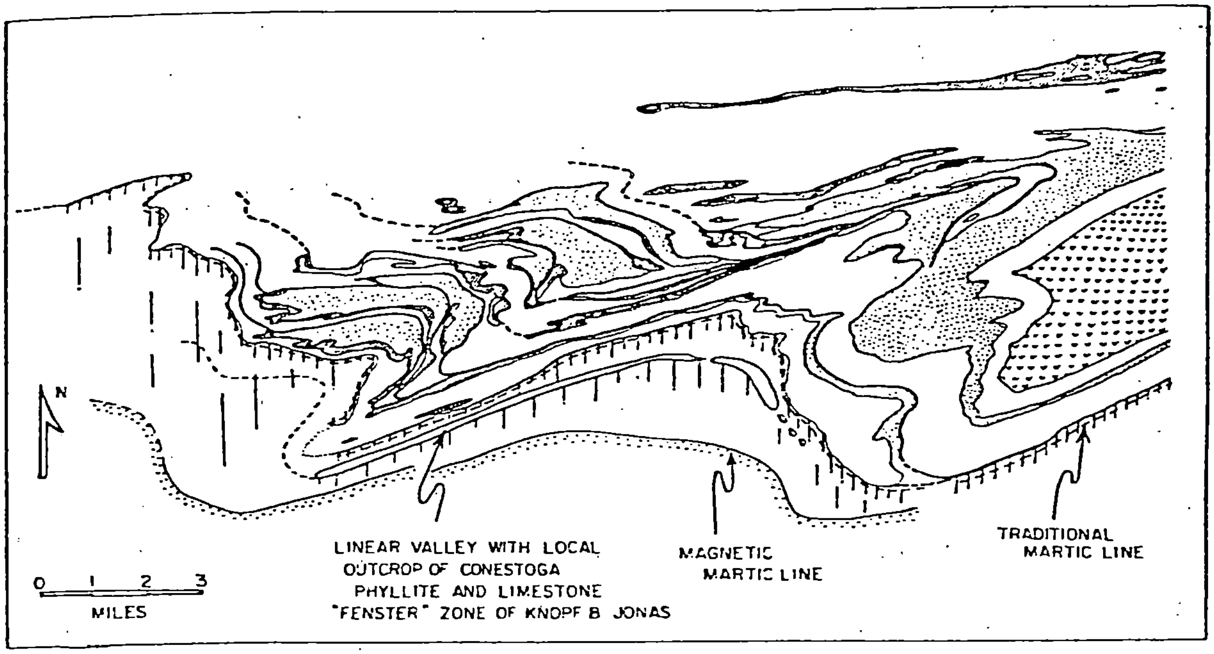
Typical Examples

Typical examples of Group 4 faults may be grouped into two subgroups: (1) brittle premetamorphic bedding thrusts which were for the most part healed and not reactivated, but were severely deformed later; and (2) synmetamorphic thrusts exhibiting a ductile history, were probably reactivated, but were also severely deformed later. Subgroup (1) faults include the Martic thrust of Maryland and Pennsylvania (Fig. VIII-1) (Wise, 1970), Hayesville thrust of North Carolina and Georgia (Hatcher, 1978b; Hatcher and others, 1979), Greenbrier fault of North Carolina and Tennessee (Hadley and Goldsmith, 1963; King, 1964; Hadley and Nelson, 1971) and Peach Bottom faults of Pennsylvania. The Baltimore Gabbro ophiolite thrust sheets of Maryland and Bay of Islands ophiolites in Newfoundland may fall into this subgroup as well, but may fit better into Class 2 in terms of timing. Subgroup (2) faults include the Rosemont in New York (Armstrong, 1941), Coatesville - Doe Run Pennsylvania, New Jersey and New York (Bailey and Mackin, 1937) and Honey Hill fault in Connecticut (Fig. VIII-2) (Dixon and Lundgren, 1968; Wintsch, 1979).

B. Basic Geometry

Subgroup (1) - Premetamorphic

If these faults are still recognizable as such after metamorphism and have involved predominantly sedimentary sequences, the geometric characteristics of bedding thrusts (Group 3) are applicable here. There is an association of some faults of this group (e.g., Cameron's Line) with ultramafic rocks, bringing forth the possibility that several of these faults may be sutures and former plate boundaries. Generally, metamorphic isograds extend across these faults and they have been sufficiently annealed that subsequent motion is unlikely but may occur in the brittle realm on properly oriented segments.



VIII-I. Geologic map of folded imbricate Group 4 thrusts of the Martic Region. Geology modified from Cloos and Hietanen (1941) (from Wise, 1970).

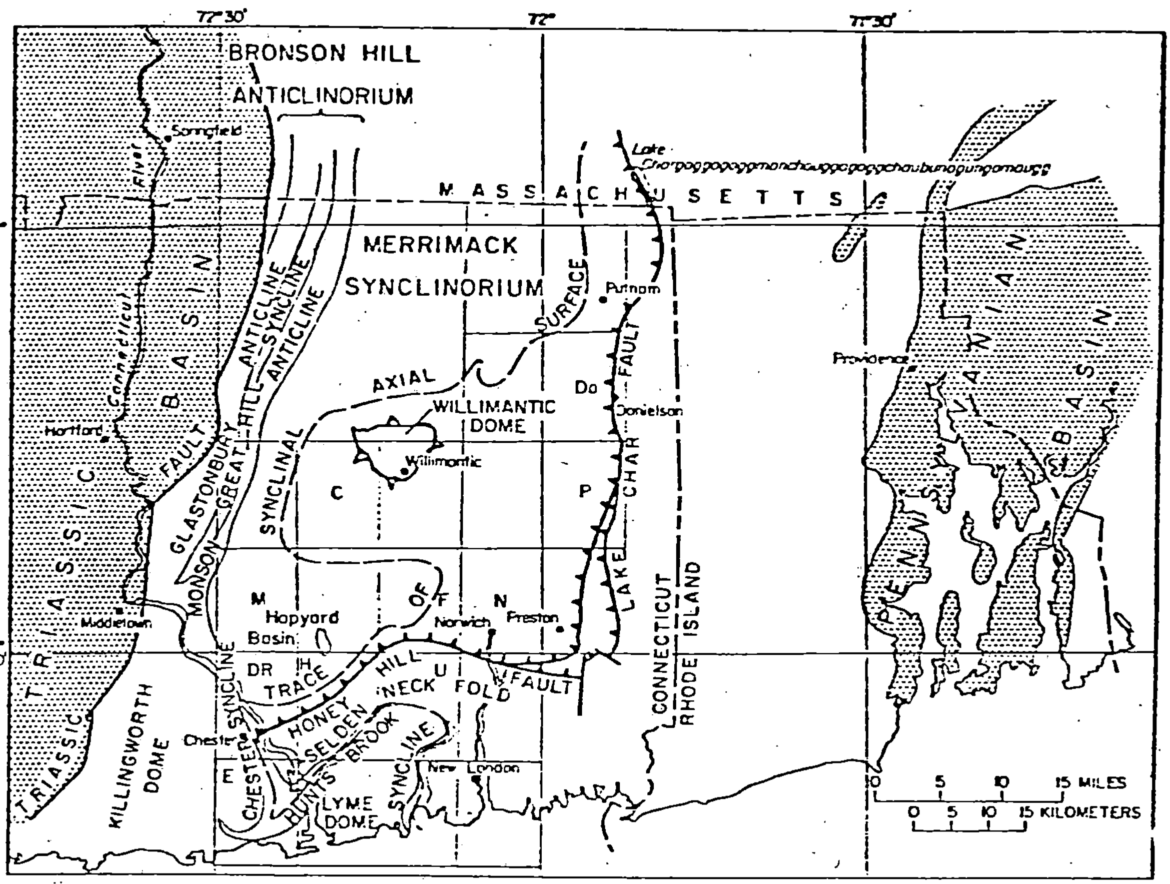


Figure VIII-2. Map of eastern Connecticut, showing major structural features (after Dixon and Lundgren, 1968). The Honey Hill and Lake Char faults and the fault encircling the Willimantic Dome (after Wintsel, 1979) are Group 4 faults.

They are recognized by telescoping of stratigraphic successions, locally aligned ultramafic bodies and/or juxtaposition of two or more markedly different stratigraphic/petrologic suites.

Subgroup (2) - Synmetamorphic

a. Strike length - Tens to hundreds of kilometers.

b. Width - Generally recognizable width of fault zone is on the order of cm to meters, may be "knife-sharp" contact.

c. Spatial Relations - Strikes of faults of this class are subparallel to the dominant grain of the Appalachians. Refolded segments may have any orientation.

d. Displacements - Minimum displacements of tens of km are demonstrable from surface data. COCORP seismic data (Cook and others, 1979) and magnetic/gravity data (Hatcher and Zietz, 1978) raise the possibility of displacements of a much greater magnitude, several hundred km in the southern Appalachians.

e. Continuity - Traceable by mylonitic rocks along contacts in some and by stratigraphic relationships, the latter being most important.

f. Curvature - Dependent upon nature of synchronous to subsequent folding. Some Group 4 faults may exhibit constant strike for long distances, then turn abruptly, as in the Lake Char - Honey Hill fault (Dixon and Lundgren, 1968). These faults typically flatten down dip, but subsequent folding may interrupt this uniformity. The Towaliga - Goat Rock and Willamantic - Lake Char - Honey Hill faults are good examples of this property.

g. Terminations along Strike - Mostly ill-defined. Faults of this group frequently merge with complexly folded zones or with other fault zones of differing styles and frequently later histories of movement. For example, the Lake Char fault merges northeastward with the Clinton-Newberry fault in Massachusetts and the Honey Hill passes westward into a zone of complex folds.

C. Tectonic Setting

Premetamorphic faults formed by thrust sheets riding up and out of a series of shelf sediments, perhaps along the edge of a closing former marginal basin. Synmetamorphic faults forms at considerable depths under conditions of greenschist, amphibolite or even granulite facies metamorphism. They may merge with recumbent nappes.

D. Characteristics

a. Premetamorphic thrusts were formed under brittle conditions; synmetamorphic thrusts exhibit ductile behavior for the principal movement event. However, later brittle deformation is evident along some faults of this group. For example, pseudotachylite in the Honey Hill fault zone is indicative of later brittle movement.

b. Texture of zone - Premetamorphic thrusts have knife-sharp contacts with brittle or no deformation along them. Synmetamorphic faults may involve knife-sharp boundaries but most tend to have mylonitic and associated fabrics (see for example Lundgren, 1972).

c. Materials Present - Premetamorphic thrusts may have no discernable materials along contacts, but thin zones of recrystallized gouge may be present. Synmetamorphic faults may contain the entire spectrum of plastic flow (ductile) materials, but later movement can superimpose brittle materials, generally at low oblique angles to the mylonitic foliation or sometimes precisely parallel to it.

d. Metamorphism - Any rank of metamorphism may overprint the premetamorphic thrusts. Synmetamorphic thrusts have been observed in association with greenschist facies (Hadley and Goldsmith, 1963) amphibolite facies (Hadley and Goldsmith, 1963; Dixon and Lundgren, 1968; Hatcher and others, 1979) and granulite facies (Watterson, 1978; Hatcher and others, 1979) conditions.

e. Datable Materials - Abundant datable materials exist in association with these faults, but frequently the event dated is not faulting but time of cooling of the rock mass or the age of metamorphism. Some mylonites have been successfully dated (Odom and Fullagar, 1973; Russell, 1976).

E. Relationships to Country Rocks

a. Dominant metamorphic foliation commonly defines the regional grain. Premetamorphic faults exist at any angle to the dominant foliation. Synmetamorphic faults generally relate to and may be aligned parallel to one or more major S-surfaces.

b. There are no obvious relationships of these faults to salients and re-entrants.

c. The premetamorphic thrusts may exhibit thin-skinned behavior in part but generally basement or other crystalline rocks are involved. Synmetamorphic thrusts involve crystalline rocks and behave as thick slabs. Faulting in the latter occurs at considerable depths, therefore great thicknesses of rock materials must be moved.

d. Relationships to Isopachs - There are only possible indirect relationships of these faults to isopachs in the Appalachians. They could effect sedimentation which was taking place more or less coevally to the west of the metamorphic core: the stacking of pre- to synmetamorphic thrust sheets could have effected uplift of the core which supplied clastics to the foreland shelf beginning in middle Ordovician time.

e. Stratigraphic Interval Affected - The interval affected in both pre- and synmetamorphic thrusts includes rocks as deep as the crystalline basement (either continental or oceanic) and whatever cover rocks may have been present. Some premetamorphic thrusts may in places involve only cover rocks, such as along portions of the Greenbrier fault (Hadley and Goldsmith, 1963).

f. Relationships to Folds - Faults of this group may develop synchronously with folds. Faults developed in this relationship would be subparallel to the axes of these folds. In many instances the faults represent the excised cores of folds which became closed during formation and movement continued on the resultant thrust. They are commonly overprinted by later folds.

g. Relation to S-surfaces - S-surfaces overprint premetamorphic thrusts. Synmetamorphic thrusts have a mylonitic foliation along them which is the dominant s-surface inside and outside the fault zone.

h. Change in Fault Character with Changing Lithology - Premetamorphic thrusts would exhibit the detachment - ramp properties of thin-skinned thrusts, if confined to cover sequences. The fault character of synmetamorphic thrusts would change according to lithology as well, particularly with regard to the type of mylonitic material present along the fault with varying protolith.

i. P-T Conditions - Premetamorphic thrusts affect unmetamorphosed rocks to rocks metamorphosed during a previous thermal/deformation cycle during their movement histories. Synmetamorphic thrusts form under conditions ranging from greenschist to granulite facies conditions (300 - 700°C) and at depths corresponding to pressures of 1-5kb (5 - 20 km). They are generally associated with Barrovian metamorphic conditions.

j. Relationships to isograds - Premetamorphic thrusts are overprinted by isograds. Synmetamorphic thrusts are generally subparallel to isograd surfaces. Late stage movement may produce truncation of isograds, but this is not widespread in faults of this class.

k. Relationships to Intrusion - Generally there is no known or clearcut relationship to intrusions.

l. Relationships to Tectonic Injections - It is likely that some faults of this group brought with them masses of ultramafic rocks and/or pieces of oceanic crust. The ophliolite sheets of the Bay of Islands in Newfoundland (Williams, 1973) probably escaped metamorphism by being thrust onto the foreland. Those of the Baie Verte area in Newfoundland were not so fortunate. The latter may be the history of many of the ultramafic bodies of the central and southern Appalachians.

E. History

a. Age of Inception - The recognizable premetamorphic thrusts were generated immediately prior to the metamorphic/thermal peak, while the synmetamorphic thrusts formed during the thermal event. Timing of thermal events is different in different parts of the orogen. The Greenbrier and Hayesville faults are probably pre-middle Ordovician; the Honey Hill is probably Devonian.

b. Syndepositional Effects - Generally not applicable. However, there may be a correlation between the time of movement of these thrusts and the appearances of clastic wedges to the west of the metamorphic core in the Ordovician and Devonian.

c. Radiometric Ages - No age dates have been determined from this class of faults. However, mylonite from the Bartletts Ferry fault of Alabama and Georgia (subclass (2)) yielded a Devonian Rb/Sr whole rock age (Russell, 1976).

d. Relationships to Unloading - These faults, to some degree, predate the time of arrival of sediments making up the Ordovician and Devonian clastic wedges. However, the lag in time between the inferred time of movement of the faults and the formation of the clastic wedges could be a function of distance from where the sediment originated and its sites of deposition.

e. Time of Last Motion - Premetamorphic thrusts were annealed by the metamorphic event with which they were associated. Some synmetamorphic thrusts may have brittle deformation superimposed indicating later, probably Paleozoic reactivation. Older ductile faults at Cherokee Nuclear Site are reactivated by brittle deformation, these were cut by quartz-feldspar veins which yielded age dates (minimum ages) of 210 Ma. For more information, the reader is directed to the Preliminary Safety Analysis Report for the Cherokee, South Carolina, Nuclear Power Plant. This document may be examined in the Public Document Room of the Nuclear Regulatory Commission at 1717 H Street NW, Washington, D.C.

5. Stress Field -

a. Orientation - Stress field orientations in premetamorphic thrusts involving cover rocks would be similar to that of thin-skinned thrusts with σ_1 oriented toward the northwest. A similar condition prevailed during formation of synmetamorphic thrusts with σ_1 oriented toward the northwest or west.

b. Magnitude of Principal Stresses and Strains - Stresses and strains for premetamorphic thrusts are considerable. At elevated temperatures the constitutive relationships between stress and strain are a function of strain rate. Therefore no legitimate assessment of principal stress magnitude of synmetamorphic thrusts is possible. Strains associated with synmetamorphic thrusts are huge. For discussion of the problems and methods of determination of finite strain in highly strained rocks, see Ramsay (1967) and Mitra (1978).

c. Variations of Stress and Strain Through Time - Stress and strain magnitudes probably varied considerably throughout the movement histories of these faults. They probably move incrementally; synmetamorphic thrusts move with formation of mylonites.

d. Present <u>in situ</u> stress - since these are pre- to synmetamorphic thrusts, there should be little relationships to present stress fields.

e. Seismic First Motion Studies - Not applicable.

f. Rates of Motion - Essentially unknown. See discussion under c. above

g. Fluid Pressure Changes and Effects - Classical fluid pressure relationships, as deduced by Hubbert and Rubey (1959), could be applied to premetamorphic thrusts in cover rocks. In synmetamorphic thrusts fluid pressure changes would be a function of metamorphic conditions and the availability of water in the system. Dehydration reactions probably play a part in the movement of synmetamorphic thrusts. For example, serpentine is altered easily until it begins to dehydrate.

6. Geophysical and Subsurface Characteristics

a. Seismic Activity - No clearcut association of seismic activity and these faults has been documented.

b. Subsurface Displacement - Seismic reflection studies in the southern Appalachians (Cook and others, 1979) have not revealed clearcut examples of known faults of this class, although the Hayesville fault may be discernable in the seismic section.

c. Relationships to Gravity and Magnetic Anomalies - Geophysical signature is particularly inadequate with this class of faults as it is dependent upon the rock types brought into juxtaposition by faulting. The fault zones of this group (except perhaps the Goat Rock) do not have a characteristic magnetic signature. Other magnetic or gravity relationships are actually obscure, unless two distinctly different terranes are brought together. This is true with portions of the Hayesville fault. Thrust sheets juxtaposing two terranes of markedly different rocks would likely produce contrasting or characteristic magnetic signatures.

d. Relationships to Geophysical Lineaments - No obvious genetic relationships.

7. Geomorphic Relationships - Faults of this group are generally not well expressed in the topography. Expression depends upon the nature and weathering characteristics of rocks on opposite sides of these faults. Very subtle topographic expression may exist, as small notches in ridges, slightly aligned tributary streams and subtle differences in erosional character of rocks on either side of faults.

8. Methods of Identification - Faults of this group are best identified by differences in rock type across these faults. Mylonites and other mylonitic rocks in some synmetamorphic faults may help, along with cataclasites where they occur. Overprinting by metamorphism and no offset of isograds along the boundary may be used carefully but one must be able to discern otherwise that a contact in question is a fault.

9. Pitfalls in Identification

a. Failure to identify subtle differences in stratigraphy on either side of faults.

b. Failure to recognize mylonites along synmetamorphic faults.

c. In a high grade, highly deformed area, the most homogeneous, planar, fine-grained rock is most likely to be the most highly deformed.

d. Age dating of cooling rather than motion.

e. Mistaking the age determined for a superposed brittle event for the age of mylonite or faulting in premetamorphic faults.

f. Tendency to link vaguely defined epicenters with faults of this group.

g. Brittle deformation zones are likely to be missed (except in drill cores) because they are generally very thin, on the order of 100 times less than the thickness of mylonite zones.

h. Much money and time can be wasted trying to prove isotopically that the metamorphism and movement in question is Paleozoic, whereas the basic problem may be a premetamorphic event or, in the case of cataclastically reactivated faults, younger than the metamorphic event.

i. Change in character of protolith with metamorphic overprinting.

10. Possibility of Reactivation

a. Premetamorphic thrusts are unlikely candidates for reactivation. Synmetamorphic thrusts are not a major cause for concern in the citing of critical facilities, but given a choice they would be good to avoid.

b. Mylonitic foliation in synmetamorphic thrusts is the most prominent planar feature and commonly has a lower shear strength. Hence this is the most likely material for reactivation.

c. Younger cataclasis does occur on some of these faults indicating reactivation has occurred in the past. However, the cataclasis is a very localized phenomenon indicating local offsets. Doming, cooling, differential stresses, uplift are all possible causes. There is no concentration of seismic activity along these zones at present.

d. Some Group 4 faults occur along province boundaries, as possible crustal boundaries in some instances (e.g., the Hayesville thrust), therefore stress concentrations may occur here.

11. Selected References List

Armstrong (1941)

Dixon and Lundgren (1968)

Hadley and Goldsmith (1963)

Hatcher (1978a)

Hatcher and others (1979)

King (1964)

Lundgren (1972)

Roper and Dunn (1973)

Wise (1970)

IX

Group 5: LATE-TO POST-METAMORPHIC THRUSTS IN MEDIUM TO HIGH GRADE TERRANES (PALEOZOIC CYCLE)

A. General Description

Thrusts of this group are generally thrusts of crystalline rocks in which there has been enough motion (minimally) to juxtapose metamorphic isograds (Fig. IX-1). However, to accomplish this a considerable amount (at least a few kilometers) of either horizontal or vertical transport, or a combination, must have occurred. These faults may or may not involve basement rocks.

Contacts may be knife-sharp, like those of many décollement thrusts, or have relatively thin mylonite zones along them indicating time of formation was probably late stage synmetamorphic. Cataclastic and/or retrograde zones along these faults or portions thereof may indicate recurrent movement at a later time when the rock mass had cooled sufficiently to exhibit brittle behavior. Some of these therefore could be grouped as complex faults.

Some Group 5 faults reside beneath extensive continuous sheets with defineable roots, while others may occur beneath erosional remnants as dismembered allochthons and klippes. Splays are seldom observed along faults of this group. All are faults of the metamorphic core of the Appalachians.

Subgroups of Group 5 include: (1) those faults with abundant mylonites which juxtapose Paleozoic isograds; (2) faults without mylonites; and (3) erosional remnants of allochthonous sheets.

Examples of Group 5 faults include the Linville Falls fault, subclass (1), in the Grandfather Mountain window in North Carolina (Bryant and Reed, 1970a, 1970b), the Hollins Line fault of Alabama, subclass (2), (Tull, 1978), the Alto allochthon of Georgia and South Carolina, subclass (3),

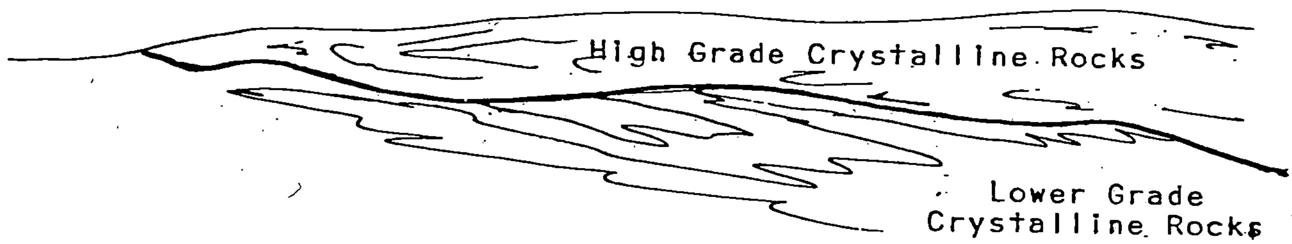


Figure IX - 1. Typical Group 5 thrust. It justaposes high grade rocks over low grade. It may truncate folds formed earlier and may itself be folded.

(Hatcher, 1978b), the Bowen Creek-Ridgeway faults of Virginia and North Carolina, subclass (1), Conley and Henika, 1973), Inner Piedmont nappes, subclass (2), (Griffin, 1971, 1974) and possibly faults along the west side of the Berkshires (Ratcliffe and Harwood, 1975). Faults of the Pine Mountain belt of Georgia and Alabama (including the Towaliga and Goat Rock faults) contain extensive mylonites. They juxtapose high (sillimanite?) grade terranes of the Inner Piedmont and Uchee belt against the slightly lower (kyanite) grade rocks of the Pine Mountain belt (Clarke, 1952; Bentley and Neathery, 1970). Until the metamorphic grades of these respective terranes have been accurately determined, the proper group of these faults will remain unknown. The Ammonoosuc fault of New Hampshire and Maine is another candidate for Group 5 fault.

B. Description of Fault Group

1. Basic Geometry

(a) Strike Length - 10 s to 100 s of kilometers (Hollins Line fault), may have klippes (Alto allochthon).

(b) Width - Less than a meter to tens of meters.

(c) Orientations - Parallel to subparallel to the dominant structural grain. Traces bounding the ends of klippes and folded faults of this group may cut across the regional strike (e.g., Linville Falls fault). They generally have a low angle of dip.

(d) Displacement - A few kilometers of tens of kilometers have been generally accepted. Larger displacements have been suggested (Hatcher, 1978a). Geophysical data supports the latter (Hatcher and Zietz, 1978).

(e) Continuity - May be demonstrated along their lengths. These faults rarely splay.

(f) Curvature - Commonly folded, so this is reflected in outcrop patterns. Subhorizontal segments exist in some. Have outcrop traces strongly influenced by the topographic contours.

(g) Termination along Strike - Allochthons are terminated (in some cases enclosed) by erosion, some, e.g., Inner Piedmont nappes, may be terminated by overlap by other nappes. Linville Falls fault is terminated down dip by the Brevard zone (Fig. IX-2) (Bryant and Reed, 1970a, 1970b). Some Piedmont nappes may terminate into recumbent folds from metamorphic phase.

2. Tectonic Setting - These thrusts were formed in the metamorphic core during the waning stages of the metamorphic-thermal peak. A generally northwestward push has occurred but multiple thermal maxima have occurred at different times in different places in the orogen. Geophysical data (Hatcher and Zietz, 1978; Cook and others, 1979) suggest that they may be rooted at least as far to the southeast as the Kings Mountain belt in the southern Appalachians (Fig. IX-3).

3. Characteristics of Faults of Group 5

(a) Most faults of this group are ductile, having formed during the waning stages of metamorphism.

(b) Texture - Can be knife sharp, indicating possible annealing of some faults.

(c) Character of Fault Zone - Thicknesses range up to a few meters with an abrupt transition to country rock. Veins and breccias are rare but mylonites are common and are locally coarse grained. Cataclastic features are rare but may be present (e.g., in the Linville Falls fault zone).

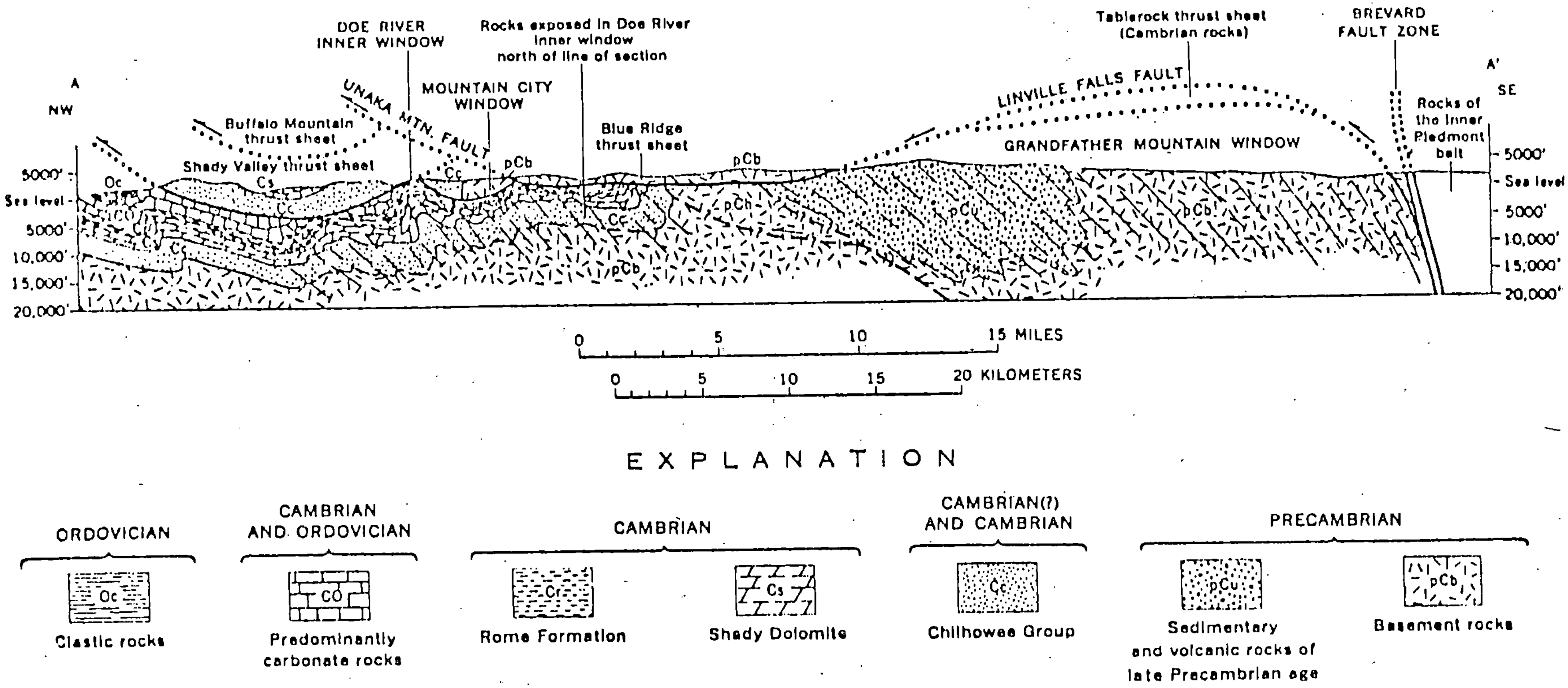


Figure IX-2. Geologic section of the Blue Ridge province in northwestern North Carolina and northeastern Tennessee, showing relationships between structural layers of the Unaka belt, the Blue Ridge thrust sheet, and The Grandfather Mountain window (from Bryant and Reed, 1970a). Vertical scale same as horizontal.

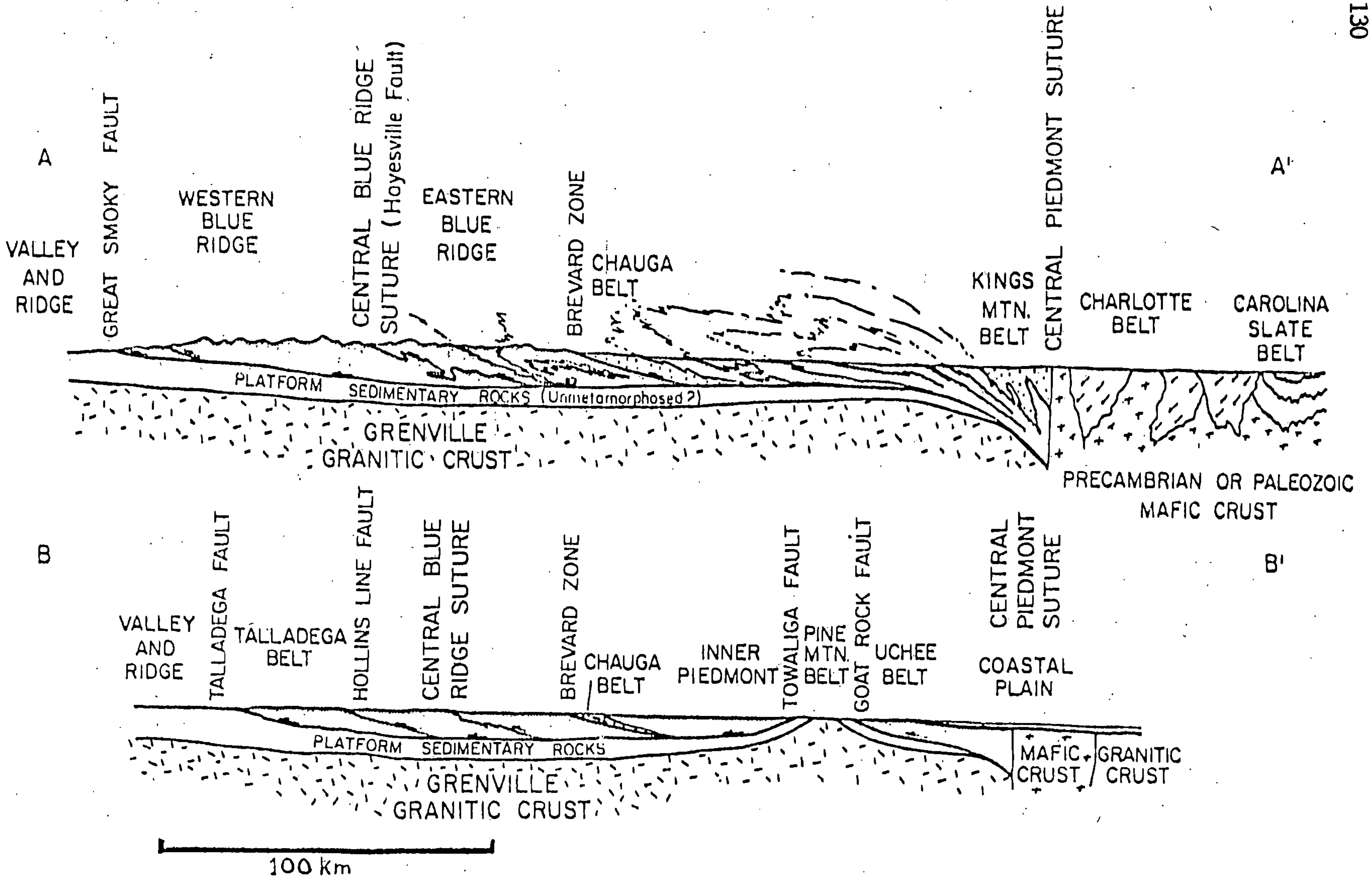


Figure IX - 3 Cross-sections through the southern Appalachians showing the large amount of horizontal offset on post-metamorphic thrusts (from Hatcher and Zietz, in press).

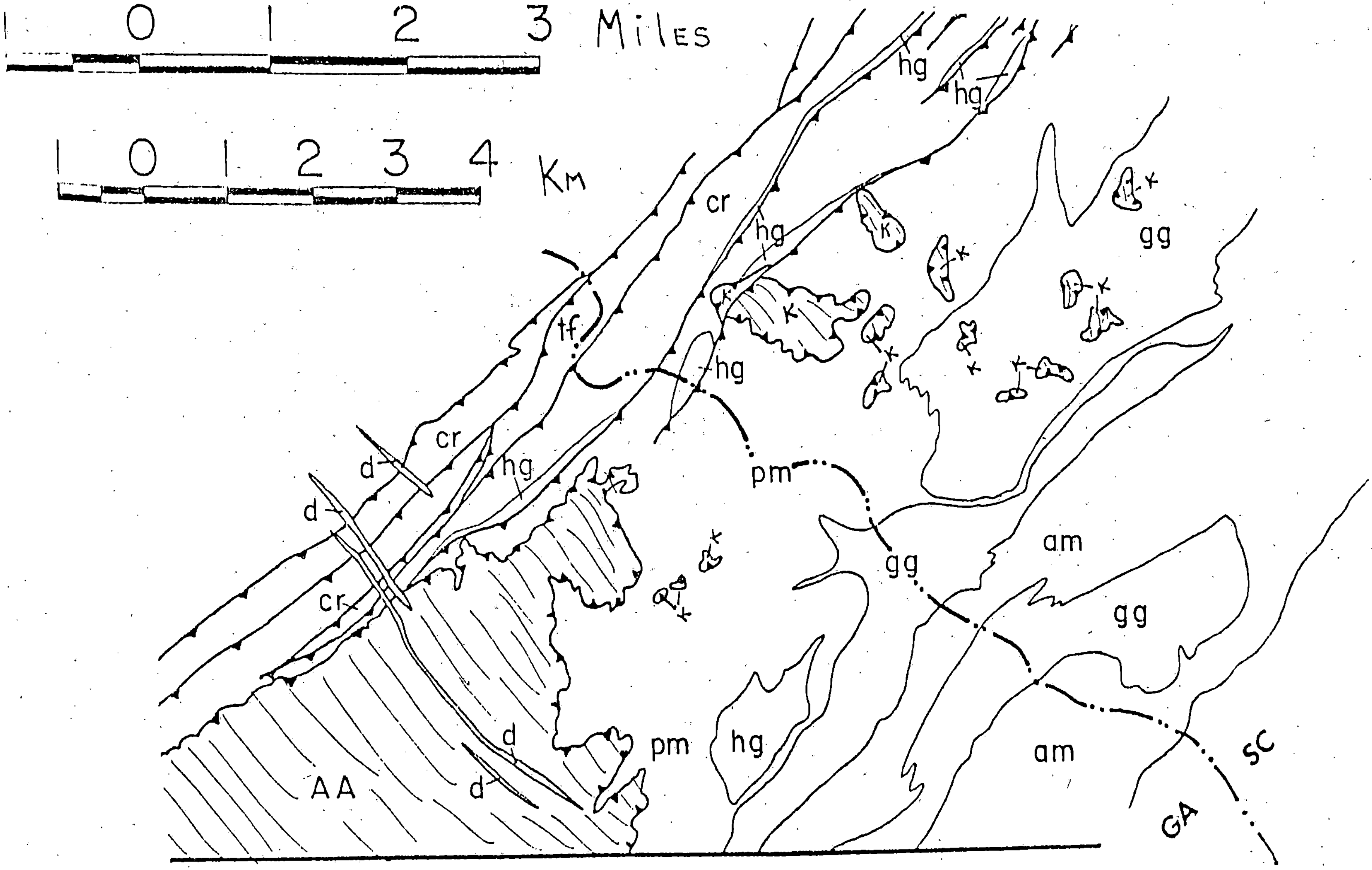


Figure IX - 4
Detailed geologic map of the northeast end of the Alto allochthon (AA and K) showing its sinuous outcrop pattern. Some of its pattern is caused by later folds. Brevard zone faults cut the allochthon. pm-Poor Mountain Formation rocks. cr-Chauga River Formation rocks. hg-Henderson Gneiss. gg-granitic gneiss. am-amphibotite. d-Mesozoic diabase (Hatcher and Butler, 1978).

(d) Metamorphism - These faults may retrograde higher grade units to the greenschist facies. Some, e.g. Alto allochthon, may have very minor or no retrogressive zones. They also juxtapose isograds.

(e) Datable Materials - Sericites and feldspars may be present as part of the retrogressive assemblage.

4. Relationships to Country Rocks

(a) Parallel or Cross Grain - Regionally parallel to orientations (dip and strike) but locally may be at high angles.

(b) Promontory or re-entrants - Generally none obvious.

(c) Thin or Thick-skinned - Geometry is suggestive of thick slabs emplaced during the cooling history of the chain.

(d) Relationship to Isopachs - Clastic wedges of the foreland may be associated with emplacement of these thrusts.

(e) Stratigraphic interval - May or may not involve crystalline basement rocks. Probably involve late Precambrian to Eocambrian metasedimentary and metavolcanic rocks as well as early to middle Paleozoic plutons and possible metasedimentary and metavolcanic rocks in some parts of the orogen.

(f) Relationships to Folds - Some thrusts of this group die into recumbent folds; all are refolded to a greater or lesser degree. They are most commonly refolded by very late open folds but may be locally tightly folded.

(g) Relationships to S-surfaces - Most of these faults are sub-parallel to the dominant s-surface, which probably reflects a continuation from the peak of metamorphism. Many late-stage lower grade S-surfaces can be superimposed.

(h) Relationships of Fault Character to Rock Type - These faults may follow schistose layers or may become localized along a contact between more and less competent materials.

(i) Pressure-Temperature Conditions - Group 5 faults form in the transition from high grades down through greenschist facies conditions (>1 kb, 350 - 400°C).

(j) Relationships to Metamorphic Isograds - The hallmark of this class of faults is truncation of metamorphic isograds.

(k) Relationships to Intrusions - Earlier plutons may be transported as rootless masses (e.g., granites of the eastern Blue Ridge, Leatherwood granite within the Smith River allochthon). Inner Piedmont nappes deform plutons as they are being emplaced. Mesozoic diabase dikes cut through all thrust sheets and are not offset.

(l) Tectonic Injections - Tectonic injections associated with this group of faults are unknown to the authors.

5. History

(a) Age of Inception - Most of these thrusts are slightly younger than and can be related to a local metamorphic peak. However, the timing of movement differs in different parts of the chain but probably began during the waning stages of metamorphism. Most southern and central Appalachians thrusts of this group begin moving in the Taconic event (∿450-480 Ma, Butler, 1972; Dallmeyer, 1975). Considering the structural chronology, it has been suggested that the Linville Falls fault is pre-Alleghanian, but post-Taconic metamorphism, perhaps Acadian (Hatcher, 1978b). Earlier movement has not been documented on the latter.

(b) Syndepositional Effects - Not applicable.

(c) Radiometric Ages - Few, if any, faults of this group have been dated directly by radiometric techniques. Odom and Fullagar (1973) obtained a 350 Ma Rb/Sr ischron on mylonite of the Brevard zone at Rosman, North Carolina. This date may or may not be related to movement on the Linville Falls and S-surfaces related to Brevard zone movement post-date dominant inner Piedmont and eastern Blue Ridge S-surfaces. It also probably post-dates movement on Inner Piedmont nappes. Spruce Pine pegmatites have been interpreted as having ages of ∿420 Ma (Butler, 1972).

(d) Unloading - Not applicable.

(e) Indicators of Last Motion - Pegmatites which cut the Smith River allochthon (Conley and Henika, 1973) post-date last movement of this structure. K/Ar ages generally indicate time of uplift (e.g., Harper, 1967). Those of Stonebreaker (1973) may indicate something about time of last major movement on the Brevard and related faults. Timing of the late minor cataclasis on some segments of faults of this class is unknown. Diabase dikes of Mesozoic age cut faults of this class. Therefore movement must predate emplacement of these bodies.

6. Stress Field

(a) Orientation of Principal Stress - Orientation(s) of principal stress during the phase of mylonitization is debatable. The classic argument of pure versus simple shear in the formation of mylonites would be brought to bear (Johnson, 1967; Hobbs, Means and Williams, 1976; Hatcher, 1978b). Associated folds yield a shear sense with a northwest-directed σ_1. The late stage of movement likewise involves a northwest-oriented σ_1.

(b) Magnitude(s) of Stresses - Total strain in mylonites is locally huge. This coupled with the fact that the slabs which were moved have volumes of hundreds of km^3 imply stresses must have been very high but levels would have varied with strain rate (see Appendix A).

(c) Variations of Stress and Strain - Doubtless movement of these thrusts was episodic, spanning a considerbale period of geologic time. Large variations in stress and incremental strain would therefore have existed, but the exact variations are essentially unknown.

(d) In Situ Stresses - Unmeasured and therefore unknown.

(e) Seismic First Motion Studies - Not applicable.

(f) Rates of Motion - Unknown, see comments in (c) above.

(g) Fluid Pressures - Values of P_{H_2O} are unknown and can only be surmised indirectly and qualitatively. Hydrous phases formed retrogressively occur in most of these fault zones, indicating fluid pressures sufficient to form these phases existed at the time of movement.

7. Geophysical Data

(a) Present-Day Seismicity - None recognized on this group of faults.

(b) Subsurface Offsets - Essentially unmeasured, but probably in the range of tens to hundreds of km. For example, the Amonoosuc fault probably formed beneath the Connecticut Valley synclinorium (Thompson and others, 1968).

(c) Relationships to Anomalies - The Alto allochthon in northeast Georgia is very well expressed in aeroradioactivity data (Higgins and Zietz, 1975). Some faults of this group reside close to the Brevard zone magnetic anomaly, but are actually not expressed by either regional magnetic or gravity patterns. They are not expressed in regional gravity patterns.

(d) Geophysical Lineaments - None obvious.

8. Geomorphic Relationships

Fault zones of this group tend to be narrow and well healed, hence there is generally little geomorphic enhancement. However, the rocks transported by the thrusts may be sufficiently different from the overridden rocks to be expressed in the topography. The Alto allochthon forms a plateau in northeast Georgia. Klippes of the allochthon occur on hilltops in northwestern South Carolina (Hatcher, 1978b). The Hollins line fault of Alabama was originally recognized by its topographic expression. Inner Piedmont nappes may likewise carry resistant units which become expressed in the topography. The Six Mile nappe (Griffin, 1969; Hatcher and Griffin, 1969) carries sillimanite schists which hold up a plateau area in northwestern South Carolina. Portions of a similar structure are topographically expressed in the Bat Cave area of North Carolina (Lemmon, 1973).

9. Methods of Identification

(a) The principal means of recognition of Group 5 faults is by observing offsets, inversions and juxtaposition of metamorphic isograds and zones. The best techniques available to bring out these features is detailed geologic mapping and thin section studies.

(b) Stratigraphy and the truncation, repetition and deletion of rock units provide the principal means for tracing these faults.

(c) Most faults of this type have been identified during the course of areal geologic mapping, particularly during detailed geologic mapping, commonly at the quadrangle scale.

10. Pitfalls in Identification

(a) Group 5 faults overlap with faults of the synmetamorphic (Group 4) and compound (Group 10) types, both in mechanics of formation and timing; therefore classification problems may arise. But the distinction between Group 4 and Group 5 faults is not important for NRC purposes.

(b) Detailed geologic mapping coupled with thin section studies of metamorphic assemblages, mineral paragenesis, and deformational chronologies is generally necessary to detect isograd/facies offsets.

(c) Thrusting of high grade rocks onto high grade rocks makes identification very difficult, even though the chronology of deformation and mechanics may be identical to that of other faults of this group.

(d) Planes or zones of prograde or retrograde low grade metamorpism within a high grade terrane should be treated with suspicion.

(e) Variations in the properties of a given contact might cause misclassification or interpretation as a simple stratigraphic contact.

(f) Dating retrogressive mineral assemblages may be possible but determination of exactly what is being dated requires very careful study of mineral paragenesis.

11. Possibilities for Reactivation

Reactivation of Group 5 faults is unlikely, except along high angle segments.

12. Best References on Group 5 Faults

Bryant and Reed (1970b)

Conley and Henika (1973)

Griffin (1974)

Hatcher (1978b, 1978c)

Ratcliffe and Harwood (1975)

X

GROUP 6: THRUSTS ROOTED IN LOW GRADE TO UNMETAMORPHOSED CRYSTALLINE BASEMENT

A. Generalized Description

Thrusts of this group are generally large low angle thrusts which transport basement rocks (Fig. X-1). Yet they behave as thin-skinned thrusts where they involve and carry cover rocks. They are associated with either low grade or no metamorphism. Where Palezoic metamorphic rocks have been involved the grade is generally no higher than greenschist facies. They may or may not have associated with these a regional penetrative cleavage. Faults if this group characteristically occur along the foreland/metamorphic core boundary as transported external massifs. Such structures may be found in similar position in any of the world's major thrust mountain chains. At the base of these thrust sheets, the fault zone is ductile marked by greenschist mylonites and/or brittle cataclasites. Thicknesses of these zones range from 1-2 m , rarely to more than 10 m.

1. Thrusted fold nappes with basement cores (Fig. X-2) - Reading Prong type (Musconetcong nappe system; Drake, 1978). Thrust nappes of this subclass consist of detached fold nappes deformed initially by a shear mechanism with ductilly deformed cover.

2. Blue Ridge type - Thrusts of this subgroup consist of large thrust sheets which transport basement rocks (King and Ferguson, 1960). A fold mechanism is not involved. Most have been subsequently deformed by folding and some later faults. They occur along the western edge of the Blue Ridge (Fig. X-3).

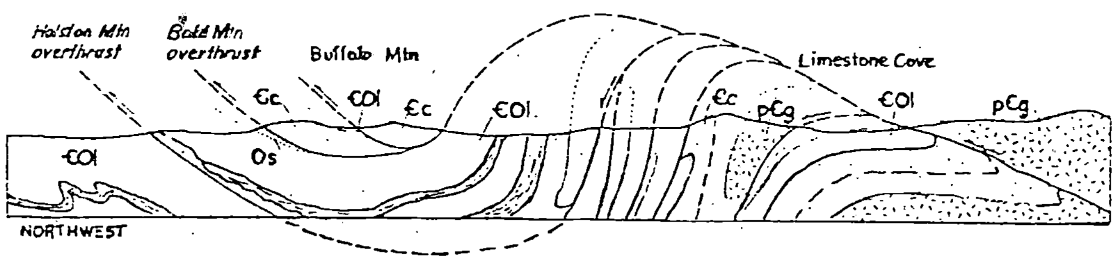


Figure X - 1. Cross-section near Erwin, Tennessee along the Valley and Ridge - Blue Ridge boundary illustrating typical Group 6 thrusts (from King, 1950). pЄg - basement rocks. Єc - Chilhowee Group. ЄOI - Cambrian and Ordovician sedimentary rocks. Os - Ordovician shale.

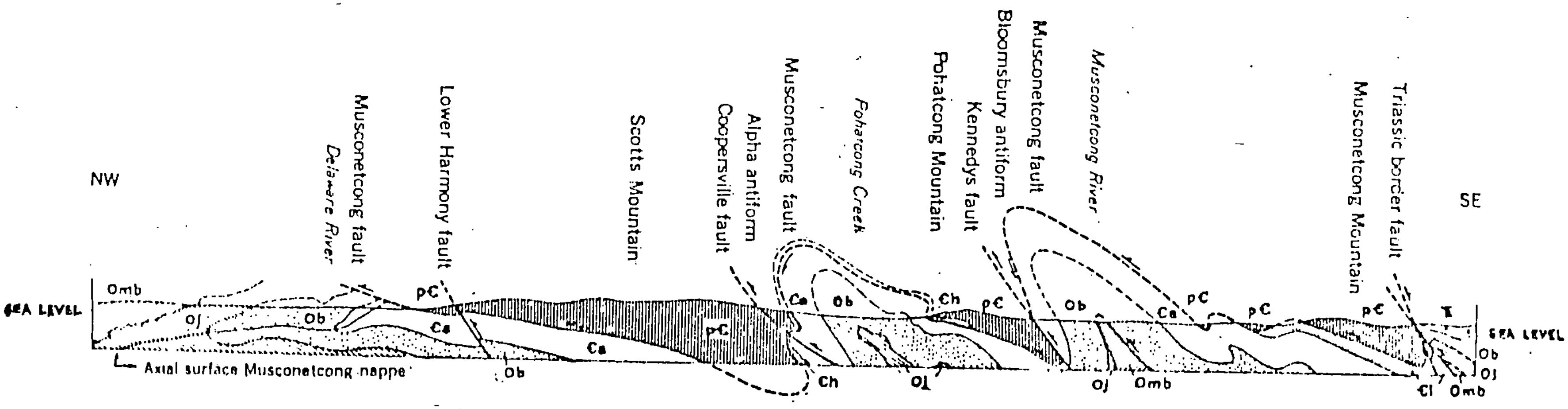


Figure X - 2
Geologic section across the Reading Prong in the Delaware Valley (from Drake, 1970). Symbols: Tr, Triassic rocks; Omb, Martinsburg Formation; OJ, Jacksonburg Limestone; Ob, Beekmantown Group; Єa, Allentown Dolomite; Єl, Leithsville Formation; Єh, Hardyston Quartzite; pЄ, Precambrian rocks.

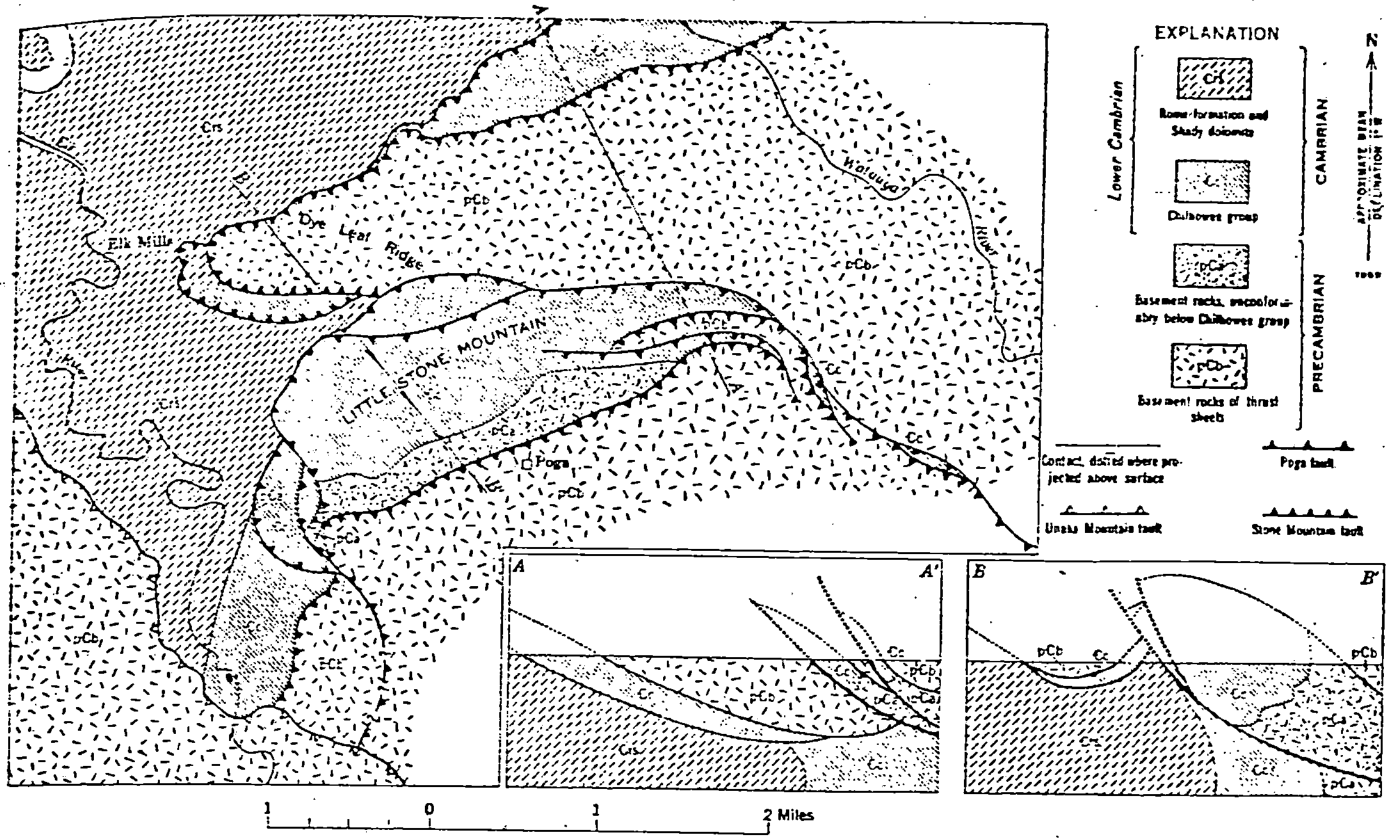


Figure X - 3.
Map and sections of Little Stone Mountain area, Tenessee, showing interpretation of complex structures there, on the assumption that the rocks have been broken successively by three faults of the Stone Mountain fault family--the Stone Mountain fault, the Poga fault, and the Unaka Mountain fault (from King and Ferguson, 1960).

3. Berkshire Highlands type - Thrusts of this subgroup are relatively high angle but may also be low angle ductile faults which deform the core and western flank of the Berkshire massif (Fig. X-4). These thrusts are commonly imbricated. Eastward, basement and cover were metamorphosed during the Taconic event. Basement along the western edge was also retrograded as well during the Taconic.

B. Description of Fault Group

1. Basic Geometry

a. Strike Length - Group 6 thrusts have strike lengths ranging from tens to hundreds of km.

b. Width Perpendicular to Strike - Thrusts sheets of Group 6 have widths of several km to several tens of km. Thicknesses of fault zones generally are in the range of 1-2 m and rarely exceed 10 m.

c. Spacial Orientation - Orientation of thrusts of this group is generally parallel to the regional grain.

d. Displacement - Displacements range from a few km to more than 100 km horizontally. Vertical displacements range up to at least 10 km.

e. Continuity - The nature and continuity of these thrust zones range from single continuous thrust to splayed and overlapping, interleaving sheets to complex imbricate zones.

f. Curvature - Generally, thrusts of this group follow the curvature of the deformed belt of which they are a part. However, all Group 6 thrusts are folded so another dimension of curvature is added.

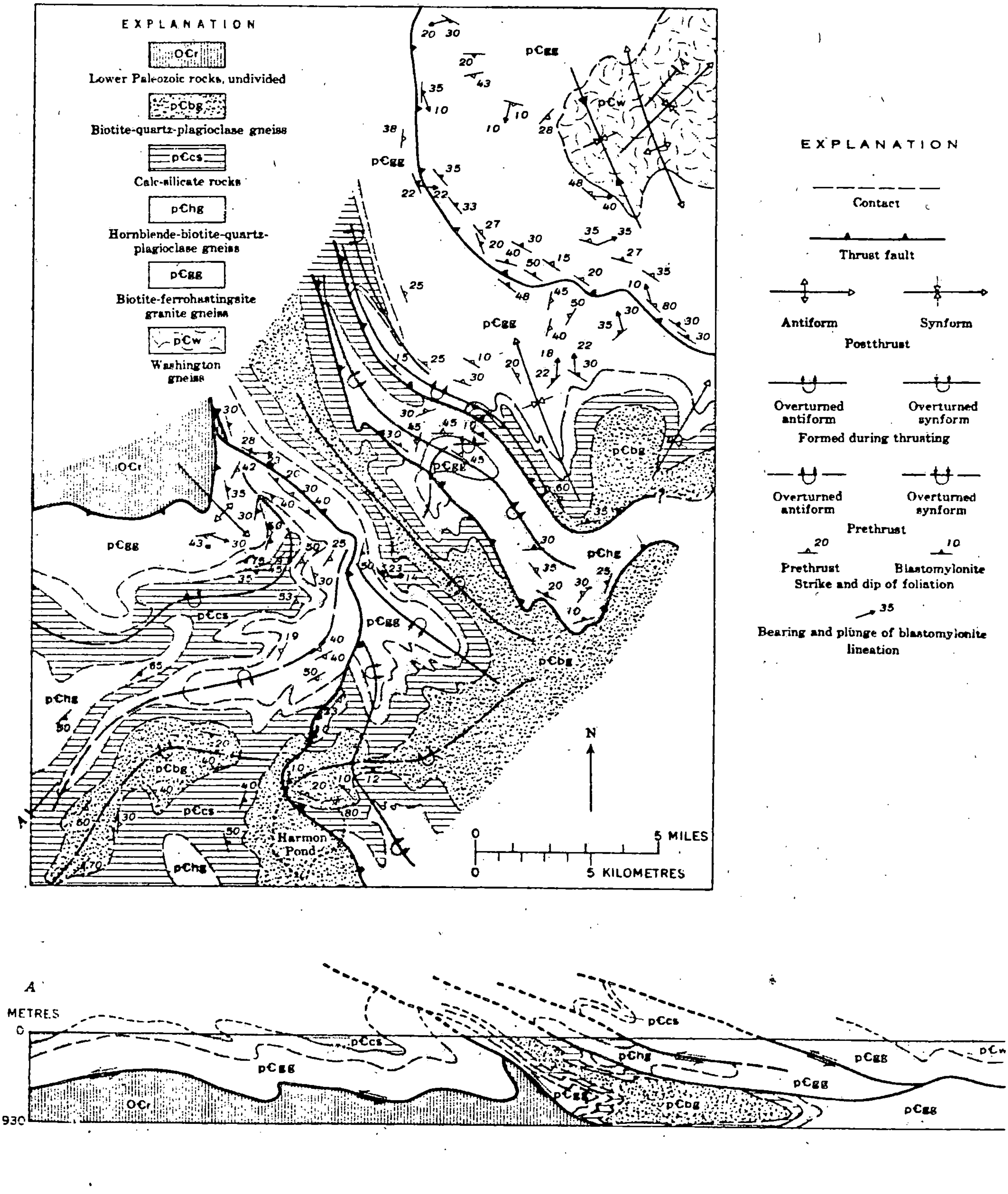


Figure X - 4 Detailed geologic map and cross section showing major recumbent folds and fold-thrust relationships in north-western part of the South Sandisfield Quandrangle, Massachusetts. (from Ratcliffe and Harwood, 1975).

g. Termination Along Strike - Thrusts of the Blue Ridge type (Subgroup 2) terminate northeastward into one or more folds of the Blue Ridge anticlinorium. Those of the Berkshire type (Subgroup 3) appear in places to terminate into folds (Ratcliffe and Harwood, 1975; Hatcher, 1975), while it is uncertain how those of the Reading Prong (Subclass 1) terminate (see Drake, 1970, 1978).

2. Tectonic Setting - Thrusts of Group 6 are localized at the boundary between the metamorphic core and fold/thrust belt as external massifs. Basement rocks involved in these external massifs may have been the thin feather edge of continental crust in the Precambrian (Grenville) continent, thus readily lending themselves toward breakage and westward transport during the Paleozoic orogenies. Some of these thrusts may result from reactivation of old normal faults produced during thinning of the crust after the Grenville orogeny.

3. Characteristics of the Fault Surface or Zone

   a. Type of Fault - Group 6 faults occur in the transition zone between brittle and ductile behavior. Both mylonites and cataclasites may be found in these fault zones. In some instances, e.g., in the Reading Prong type, faults may have almost no deformed zones along them. The transitional character of these fault zones may be solely a function of depth of burial, but it may also be a function of strain rate.

   b. Surface Texture - Discrete nonpenetrative surfaces are unobserved within fault zones of this group. The texture is to a large degree dependent upon lithologies adjacent to the fault. Slickensides and/or fibers may be developed in subsidary fractures.

c. Material Present - A mixture of cataclastic and mylonitic material may be present; gouge veins may be present locally but may represent later movement.

d. Metamorphism and/or Mineralization - There is usually minimal metamorphism and/or mineralization and this is characteristically in the greenschist facies and of a retrograde nature. Calcite, sericite, epidote, quartz, low grade K-spar, and chlorite (after garnet and biotite) are characteristic assemblages.

e. Datable Materials - Sercite and K-spar formed during faulting might yield mineral ages.

4. Relationships to Country Rocks

a. Group 6 faults are generally parallel to the structural grain on a regional basis. However, they exhibit cross-cutting relationships where examined in detail.

b. Promontories or Embayments - These faults generally occur at major promontories within the mountain chain and die into embayments, except those in the Reading Prong.

c. Thick-skinned or Thin-skinned - Faults of Group 6 are obviously thick-skinned but exhibit many of the behavioral characteristics of thin-skinned thrusts. (see Group 3 faults).

d. Relationships to Isopachs - These thrusts may relate to original basement highs where late Precambrian and Eocambrian sedimentation was absent. A similar relationship involving the same kinds of thrusts have been noted by Burchfield and Davis (1975) in the U.S. Cordillera.

e. Stratigraphic Interval Affected - Basement rocks and the immediate cover are involved in these thrusts.

f. Relationships to Folds - Most faults of this group appear to die into folds. This is the case with Blue Ridge type thrusts (Subgroup 2) where northeastward termination of thrusts into the Blue Ridge anticlinorium occurs (Fig. X-5). These thrusts are characteristically folded.

g. Relationships to S-surfaces - Mylonitic foliations generally parallel the fault zones. S-surfaces related to low grade regional metamorphism may be coeval with thrusting.

h. Changes in Fault Character with Changing Lithology - Where deformed zones are thick within or adjacent to basement rocks there is a notable thinning (sometimes to a knife edge) of the deformed zone into a wholly sedimentary section.

i. P-T Conditions - Group 6 faults form at metamorphic conditions of greenschist facies or below, implying temperatures below 300-400°C and maximum pressures of a few kb.

j. Relationships to Metamorphic Isograds - These faults may parallel Barrovian zones in the metamorphic core zone and may locally truncate Paleozoic isograds.

k. Relationships to Intrusions - Thrusts of Group 6 may transport earlier intrusions and they are in turn cut by Triassic-Jurassic diabase dikes where the latter extend this far to the west in the orogen.

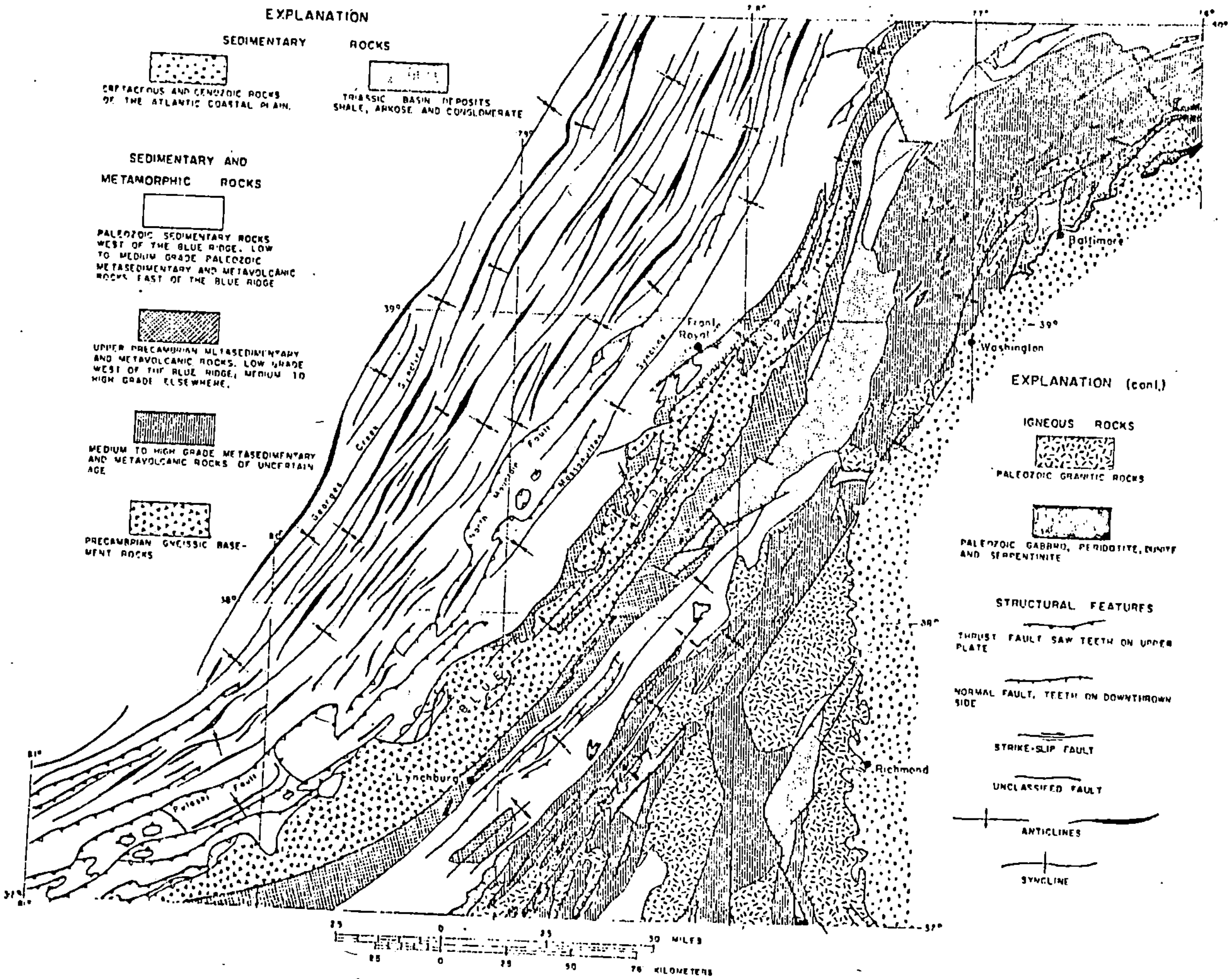


Figure X-5 Map showing the geology of the Blue Ridge and adjacent terranes in Virginia, Maryland and Pennsylvania (from Wickham, 1972). Note the termination of the thrust along the northwestern edge of the Blue Ridge from southwest to northeast as the Blue Ridge passes from a surface-faulted allochthon to an anticlinorium in northern Virginia, Maryland and Pennsylvania.

4. Tectonic Injections and Forced Injections - Veins of K-spar (±quartz) and gouge veins may be related to late-stage movement on these thrusts.

5. History

a. Age of Inception - The age of inception of Group 6 faults is different with location in the orogen. Generally the age decreases toward the south. Group 6 thrusts formed during the Taconic event in the Berkshires (Ratcliffe and Harwood, 1975) and Reading Prong (Drake, 1970), and are Acadian or younger in the Blue Ridge (Cloos, 1971; Wickham, 1972; Hatcher, 1978).

b. Recognition of Syndepositional Effects - For the most part, syndepositional effects have not been demonstrated. However, Cooper (1968a, 1968b) attempted to relate coarse clastics in the middle Ordovician succession of the Valley and Ridge to the Holston-Iron Mountain fault of the Blue Ridge.

c. Radiometric Ages - Dietrich, Fullagar and Bottino (1969) concluded that the movement of thrusts in the western Blue Ridge partially reset some mineral age determinations. Russell (1976) used the Rb/Sr whole rock technique to determine a Devonian (Acadian?) age for mylonitic rocks along a thrust in north Georgia.

d. Relationships to Unloading - Not applicable (see 5b above).

e. Indications of Last Motion - Cataclastic veins in the Berkshires are overprinted by Acadian metamorphism and faulting (Ratcliffe and Harwood, 1975). The Cross Mountain transcurrent fault (post-Alleghanian?) cuts the Blue Ridge subclass faults in northeast Tennessee (King and Ferguson, 1950; Hardeman, 1966). Triassic-Jurassic diabase dikes cut all subclasses.

6. Stress Field

a. Orientation of Principal Stresses at Inception - The orientation of σ_1 during the initial stages of movement was probably oriented toward the northwest to west.

b. Magnitude of Principal Stresses and Strains - Since the masses of material moved are of considerable size the principal stresses must have been of considerable magnitude, but this is strain rate-dependent. It is difficult to estimate strains or strain rates because of the nature and complexities of deformational processes affecting these rocks. Because of the large amounts of transport of slabs of considerable size, it can be concluded that stresses were immense. Total strain within a particular fault zone varied with position in the zone and the nature of the processes operating at a particular time.

c. Variation in Time of Stress and Strain - There is abundant evidence of reactivation of Group 6 thrusts in the Berkshires (Ratcliffe and Harwood, 1975) and the western Blue Ridge. Most thrust sheets of this size probably experienced an episodic movement history rather than a single emplacement event.

d. Present _in situ_ stress - Unknown.

e. Seismic First Motion Studies - Not applicable.

f. Rates of Motion - Faults of this group probably experienced variable rates of motion throughout their movement histories.

g. Fluid Pressure Changes and Effects - Unknown.

7. Geophysical and Subsurface Characteristics

   a. Seismic Activity - None presently associated with this fault class.

   b. Subsurface Displacements - By projecting seismic reflection data in the southern Appalachians (Cook and others, 1979), it has been suggested that the Group 6 (Subgroup 2) thrusts have horizontal displacements of several tens to hundreds of kilometers in the subsurface.

   c. Relation to Gravity and Magnitude Anomalies - The rocks transported by these thrusts determine the magnetic signature of the faulted masses. The fault zones are generally not expressed magnetically. Crystalline massifs along the western edge of the Blue Ridge have an obvious high frequency signature relative to the non-magnetic platform rocks at the surface in the Valley and Ridge. Drake (1970, 1978) has related gravity anomalies in Pennsylvania and New Jersey to the Reading Prong (Subgroup 1) nappes. The Berkshire massif is expressed in the magnetic signature in southern New England (Harwood and Zietz, 1977).

   d. Relation to Geophysically Expressed Lineaments - There is no clear relationship between faults of Group 6 and geophysical lineaments.

8. Geomorphic Relations - Group 6 faults have transported resistant units over relatively nonresistant units on the Appalachian platform. This forms an extensive escarpment at the western edge of the Blue Ridge. Successive thrust sheets may be observed as ridges in the Blue Ridge of northwestern North Carolina and southwestern Virginia (Rankin, 1971). The Mountain City window

occupies a valley between two segments of several basement thrusts (King and Ferguson, 1950). The Reading Prong has a less prominent topographic expression but some of the basement units do form resistant hills. The Berkshire massif occupies a topographically high area in western Massachusetts.

9. Methods of Identification - Principally these thrusts are identified by careful analysis of the stratigraphy, recognition of transported basement rocks and deformed zones along the thrust sheets. Care should be taken to recall that these thrusts are generally folded.

10. Pitfalls in Identification

    a. Confusion with high grade synmetamorphic to postmetamorphic thrusts.

    b. Where present in platform sequences, may be confused with thin-skinned thrusts.

    c. Dating of greenschist assemblages may be difficult initially and ages may be age of metamorphism or late movement not principal event.

11. Possibility of Reactivation - There may be a slight chance of reactivation if brittle and/or high angle segments. Actually there is little concern that these faults will be reactivated with this one exception.

12. Selected Reference List

Cloos (1971)

Drake (1970, 1978)

King and Ferguson (1950)

Professional Paper 888

Ratcliffe (1975 - NEIGC Guidebook)

Wickham (1972)

XI

Group 7: HIGH ANGLE REVERSE FAULTS

A. Generalized Description

Small scale reverse faults are unbiquitous in much of the Appalachians and reflect minor local adjustments to the several periods of compressional tectonics. Many other large scale, high angle reverse faults occur in obvious associations with changing initial dips of master thrust sheets or with subsequent deformation of master thrusts. These types of structures are discussed elsewhere in this study and are not included in this group.

The focus of this chapter is that class of high angle faults bounding major structural features, showing a reverse type displacement, and not obviously related to simple dip changes of some master thrust. This is not to guarantee that these faults have no relationship to some well concealed, deep thrusting in the region but rather to specify that such association should at most be cryptic. Many, such as the Bloody Bluff and Clinton-Newbury (Fig. XI-1) are also compound faults and are discussed elsewhere (Chapter XIV).

Recognized faults of this restricted group are comparatively rare in the Appalachians, the best examples being those associated with deformations of the sedimentary basins of the Boston to Rhode Island region. These faults seem to be comparatively young in the tectonic development of that region and to be associated at least in part with the bounding faults of the Boston, Norfolk, and Narragansett basins. They are rather poorly exposed at the surface although field descriptions supplemented by tunnel exposures have been done by Billings (1929), LaForge (1932), Cuppels (1961),

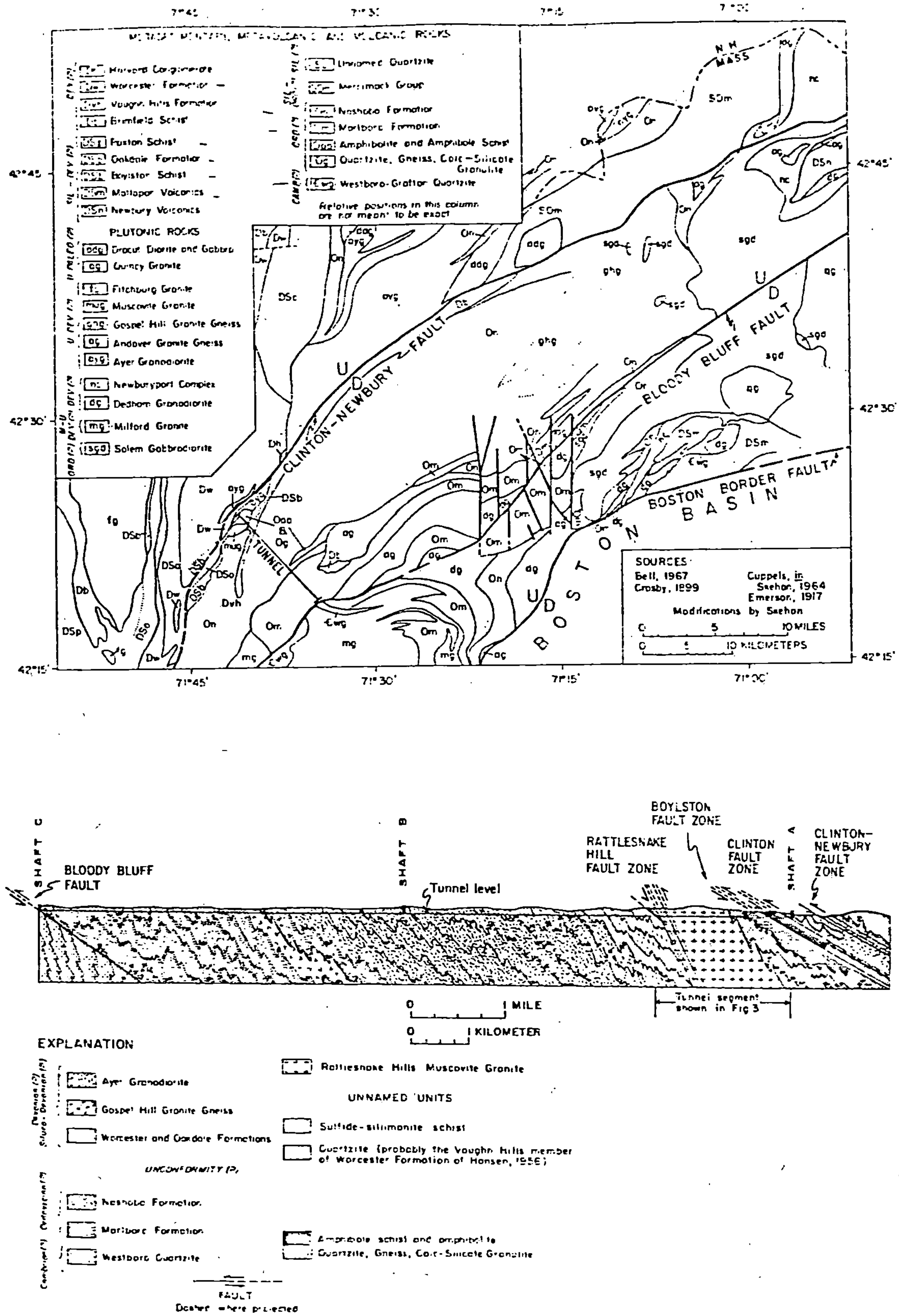


Figure XI-1.
Reverse and thrust fault complex in the area northwest of Boston. Cross section is along the Wachusetts-Marlboro Tunnel. Tunnel exposures show a variety of reverse fault motions, brecciation, mylonites, silicification, and pyritization. From Skehan, 1968.

and Skehan (1968). The age of this compressional faulting in the Norfolk and Narragansett Basins must be at least as young as the Carboniferous fill which was locally subjected to high grade metamorphism, cleavage development, and realignment of long axes of cobbles. These are most likely Alleghanian structures. The Boston Basin structures seem analogous and may well correlate with the structures to the south. However, the age of the Boston Basin sediments is so uncertain that they are being designated "Precambrian-Paleozoic undifferentiated" on the new state map of Massachusetts (Peter Robinson, personal communication, 1980). Consequently, a much greater range of ages is possible for the structures superimposed on them.

B. Description of Fault Group

1. Basic Geometry

a) Strike length up to 20-50 km, in SE New England.

b) Widths of zones perpendicular to strike as determined in tunnel exposures vary from knife sharp to a few hundred feet (Billings, 1976, Skehan, 1968).

c) Spatial orientation - crudely parallel to and in part helping define some of the northeasterly structural grain of the Boston platform.

d) Displacements through generally poorly documented may be upward of 10,000 feet (Billings, 1976).

e) Continuity - zones seem reasonably easy to trace along strike in a general way but details of individual splaying smaller faults of the zone would probably prove quite complex as judged by the tunnel data.

f) Curvature, broad arcuation in map pattern for major faults, and local offsets are common.

g) Terminations along strikes are difficult to trace beyond the basin fills. Some of the termination is by merger with or curvature into other fault zones, as well as truncation against cross faults.

2. Tectonic setting: These faults may be in part a southwestward continuation of Carboniferous basin development and associated strike-slip fault motions of Nova Scotia. Depending on the age of the fill of the Boston Basin, those structures might also record earlier events.

3. Characteristics of surface or zone.

The type of fault is largely brittle. The zones described for the Rattlesnake Hill fault zone (Fig. XI-1) by Skehan (1968) include highly sheared and crushed rock with 1-2 mm thick bands developed in it, the bands commonly showing drag folds and slickenlines. Other of the fault zones produce diamond to spindle shaped blocks by closely-spaced intersecting faults of several attitudes. Some include calcite and rhodochrosite as well as simple clay seams. Still others show knife sharp contacts.

4. Relation to country rock

a) On a regional scale these faults run sub-parallel with the overall grain of the Boston platform. Some of the oldest rocks of the platform, the Precambrian Blackstone Series, have a general northwest strike which is essentially perpendicular to these faults.

b) This faulted southeastern New England region might be considered as localized on a re-entrant of the Appalachians. However, the location on the cratonic eastern half of the orogen raises questions of the applicability of the terms salient and re-entrant.

c) The faults are thick-skinned involving crystalline basement.

d) Stratigraphic changes in the largely continental basin fills are marked and conform in a general way to some basin margins.

e) Stratigraphic interval affected is the Pennsylvanian in the Narragansett and Norfolk Basins. The Boston Basin has completely different stratigraphy in spite of its separation from these basins by about 5 km. Its age is so uncertain that it is listed as "Precambrian or Paleozoic" on the soon-to-be-released state map of Massachusetts.

f) Some of the folds in the Boston Basin are crudely parallel to the northern border fault. Folding in the Narragansett Basin is more irregular and of questionable relationship to any border faults (Fig. XI-2). Billings (1976) suggests that near-vertical faults of the southern Boston Basin must have formed prior to any important folding.

g) S-surfaces with associated folding are developed in some of the basin rocks. Some of the later movements on the basin bounding faults may post-date these S-surfaces but Billings

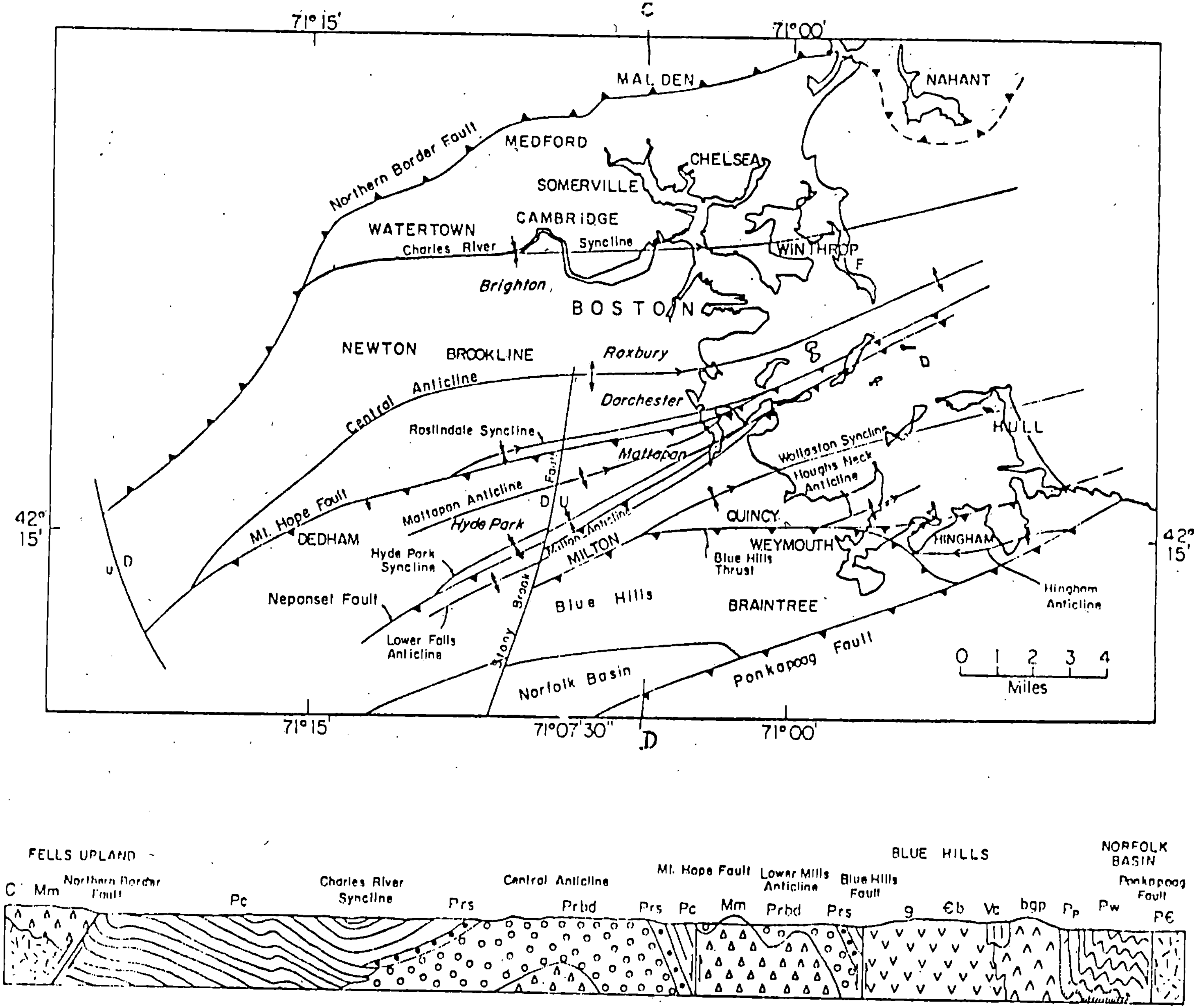


Figure XI-2.
High angle reverse and near-vertical faults of the Boston Basin. Billings interprets many of the faults of the southern part of the basin as early or pre-fold reverse faults subsequently rotated into their present position (from Billings, 1976).

(1976) argues that many of the faults predate folding in the southern Boston Basin.

h) Change in fault character with lithology: unavailable.

i) P-T conditions - apparently low temperature and relatively shallow burial.

j) Isograds as high as sillimanite exist in the fill of SW portion of the Naragansett Basin. The isograds trend NW at a high angle to the basin axis. The presence of a border fault of any type in this portion of the basin is not well documented.

k) The faults apparently post-date most intrusions in the Narragansett Pier Granite and the associated Westerly Granite.

l) Associated tectonic injections are unrecognized.

5. History

a) The age of inception of the faulting depends on the age assigned to the sediments of the Boston Basin. The other two basins were apparently initiated in the Pennsylvanian, most likely with some associated faulting.

b) Syndepositional effects are discussed above.

c) Radiometric ages - a number of nearly igneous bodies yield ages of middle to later Paleozoic as summarized by Lyons and Faul (1968) but there appear to be no unequivocable dates of the reverse faults themselves.

d) Relation to erosional unloading - NA.

e) Indications of last motion: no certain indications of motions subsequent to Paleozoic.

6. Stress field

The stress field causing the southeastern New England basins and their associated faults is uncertain. The reverse nature of many of the faults, their EW to NE trends, associated folds and S-surfaces in the basin sediments are suggestive of a NW or NNW oriented σ_1. The possible connection of these basins with the Nova Scotia strike-slip related structures further clouds the already muddied stress relationships.

7. Geophysical and subsurface characteristics

a) There appears to be no present seismic activity located on the land portions of these basin-related faults. However, the fault complex of the area just north of the Boston Basin trends north-easterly toward the Cape Ann epicentral region. Whether a genetic relationship exists with is complex is uncertain.

b) Subsurface displacements are documented largely in relation to tunnel exposures and drillings.

c) Relation to geophysical anomalies are those which might be expected from contrasting lithologies on either side of any fault zone.

8. Geomorphic relations are typical differential erosion fault line scarps of a few hundred feet relief caused by removal of less resistant basin fills.

9. Methods of identifcation have been largely through association with contacts at the edges of the sedimentary basins and through tunnel exposures.

10. Pitfalls of identifcation. There has been a tendency to consider most of the boundaries of these basins to be fault related. This caution may be commendable for seismic risk analyses but may also grossly overexaggerate the role of faulting. Extensive drilling, mapping, and excavation in the current studies of coal potential of the Narragansett Basin have failed so far to give unequivocable proof of the existence of any border fault for that basin (Dan Murray, personal communication, 1980).

    Many of the faults within the Boston Basin are essentially vertical. These may have originated with other dips indicating an original reverse of thrust nature as discussed by Billings (1976).

11. Possibilities of reactivation should be taken seriously for high angle relatively brittle faults bounding major basement blocks in the vicinity of a known major earthquake epicenter. On the other hand, no certain youthful movements have been detected on these faults.

12. Discussions of these faults and their settings are given by Skehan (1968) Quinn and Moore (1968) and by Billings (1976).

XII

GROUP 8: STRIKE-SLIP FAULTS

A. Generalized Descriptions

1) Introduction

Strike-slip faults include faults on all scales whose major component of slip is parallel to the fault strike. At least seven subgroups of strike-slip faults can be distinguished based either on scale, tectonic history or geologic setting: 1) Major strike-slip faults; 2) Cross-structure faults with a horizontal component of slip; 3) Faults reactivated with strike-slip motion (all reactivated faults are class 9- Complex faults); 4) Tear faults associated with décollement tectonics; 5) Small displacement strike-slip faults on the limbs of folds; 6) Small displacement strike-slip faults in flat-lying sediments; and 7) Strike-slip faults in Mesozoic basins.

The Appalachian Mountains south of the Canadian border have a few examples of well exposed major strike-slip faults. In contrast, several major strike-slip faults are known in the Maritime Appalachians of Canada. Strike-slip faults with narrow fault zones, less than 1 km of slip and mappable less than a few kilometers parallel to strike are commonly encountered in the U.S. Appalachians.

The seismicity of the Appalachian Mountains includes a few examples of strike-slip faulting as determined by focal mechanisms. One example is the Quebec-Maine border earthquake (Sbar and Sykes, 1977).

2) General Morphology

There are many examples of strike-slip fault zones where shear displacement is accomplished not on one surface but rather on a complex of several subparallel slip surfaces. On the outcrop scale the number of slip surfaces increases with displacementuntil zones of deformation approach a meter thick (Engelder, 1974a). These zones of deformation have the same morphology as shear zones formed by fracturing of cylinders in the laboratory (Fig. XII-1). There are several ways to interpret these structures: 1) each slip surface (actually a fracture with gouge) strain-hardens as it deforms, making it stronger than the parent rock. This shifts the deformation to the weaker host rock. Here the fault zone may be generated during repeated fracturing. 2) The deformation may be activated, forming a slip surface that then becomes indurated before the deformation band is reactivated. Here again the indurated slip surface becomes strong and the deformation shifts upon initiation of slip. 3) If deformation is continuously creating irregular slip surfaces, the irregularities may lock and shear off. In these three interpretations of the deformation bands documented by Engelder (1974a) and Aydin and Johnson (1978) friction changes in either time or space to effect a locking of the fault surface. Reactivation must be accomplished by shearing the undeformed rock, rather than reshearing the fault gouge of an existing fault surface.

Surface traces of major strike-slip faults show the same complicated geometry. For example, Rogers (1973) shows that the San Andreas and Calaveras fault zones form Hollister to San Jose are a complex pattern of subparallel to braided curvilinear fault traces, transected by a single, generally continuous, rectilinear fault trace (Fig. XII-2). His model for the evolution of the fault system includes locking at bends, or asperities, and subsequent shearing through the locked sections to restore a rectilinear path of least resistance. Rogers (1973) suggests that the system of locking at

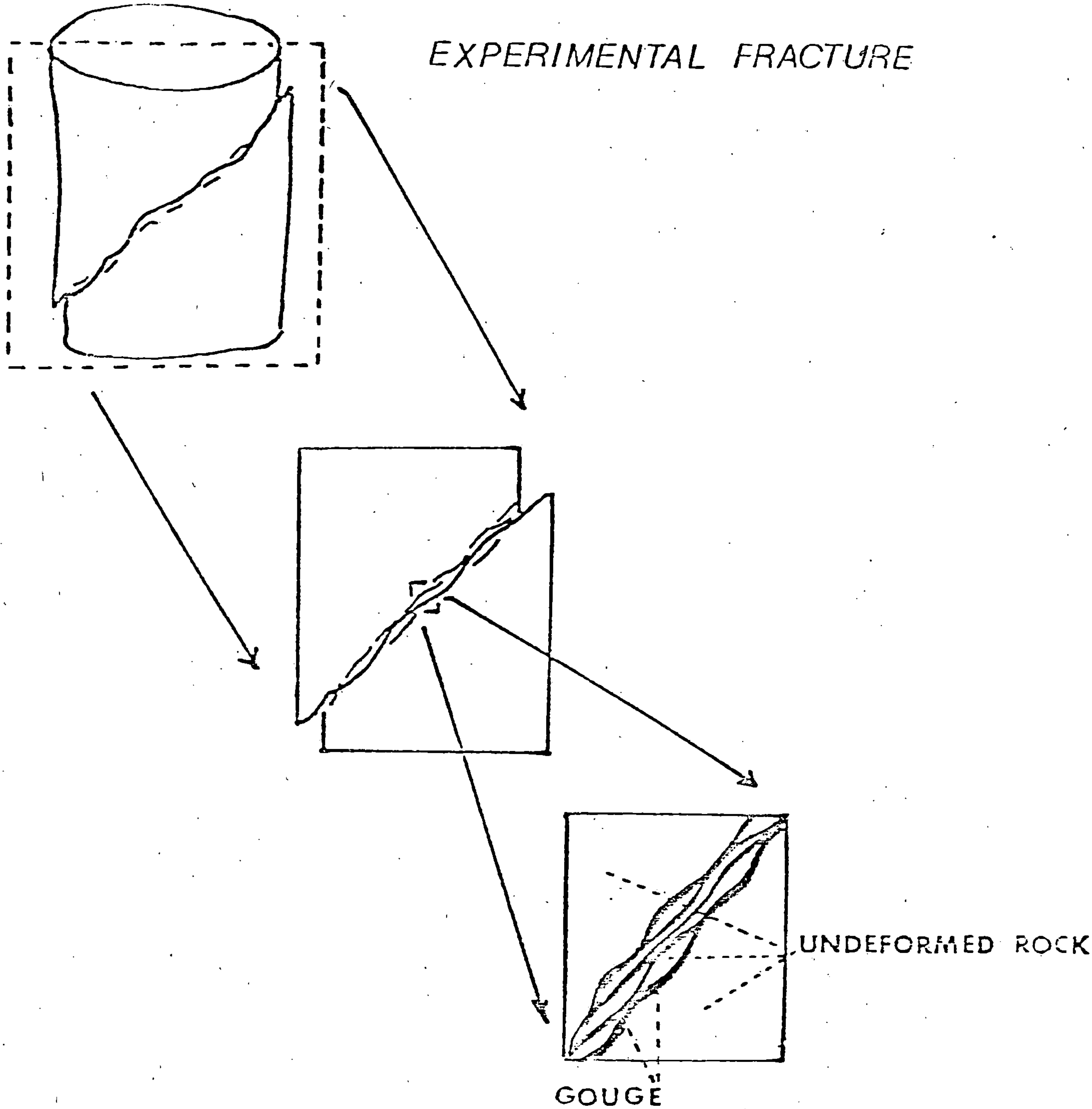


Figure XII - 1. Laboratory example of the development of a shear zone in a rock cylinder 5 cm in diameter. Slip within the laboratory sample is accomplished on several subparallel slip surfaces containing gouge (Engelder and others, 1975).

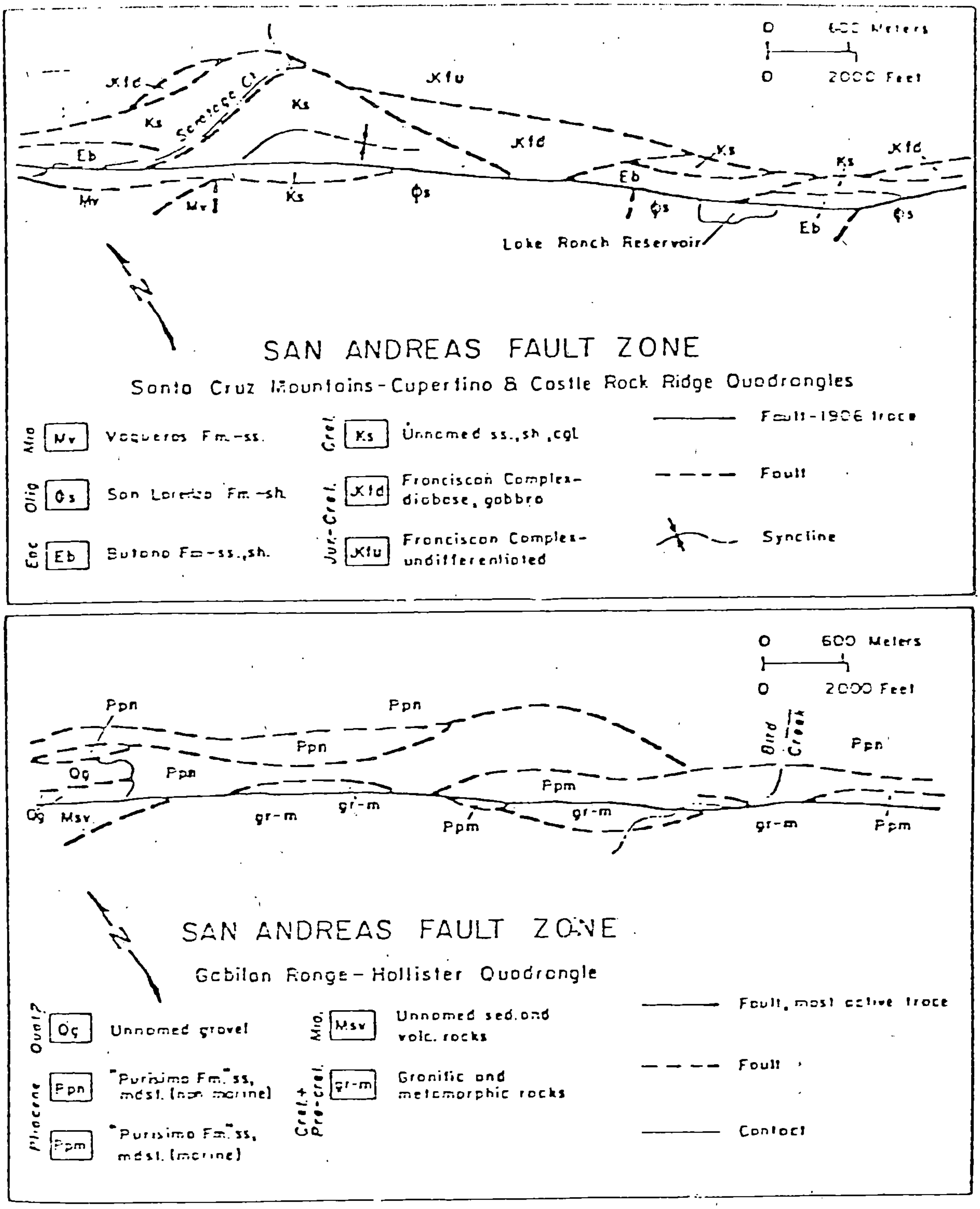


Figure XII - 2. Example of strike-slip fault zone with a comples pattern of subparallel to braided curvilinear fault traces (Rogers, 1973).

bends is more common where there is a contrast in bedrock strength on either side of the fault.

B) Description of Subgroups

1) Major Strike-Slip Faults of the Maritime Appalachians

In general, the major strike-slip faults of the Appalachians outcrop in Canada where massive Carboniferous sections have been disrupted by strike-slip faults (Fig. XII-3). Major strike-slip fault zones are more common in the New England and the Canadian Maritimes where the Acadian and Carboniferous deformational events were partially characterized by strike-slip faulting. These strike-slip faults are relevant to a compilation of faults in the U.S. Appalachians because some of the Maritime strike-slip faults may be traced southwestward into Maine. The most notable example is the Frederiction fault of New Brunswick which is on strike with the Norumbega fault of Maine (Stewart and Wones, 1974). The major strike-slip faults are important in light of recent paleomagnetic measurements indicating 15° of northward movement of Devonian sediments on the continental edge relative to the craton of North America (Kent and Opdyke, 1978). For this 15° of latitudinal movement there may be unrecognized strike-slip faults buried under the Coastal Plain of the U.S. (Fig. XII-4).

Although the Norumbega fault zone is on strike with the Canadian strike slip faults, its size and extent is unknown. The Norumbega fault is mapped as a set of parallel shears near Calais, Maine. However, many of the slickensides along the fault indicate post-Pennsylvanian reactivation on a series of minor normal faults (Ludman, 1978). The specific significance of the Norumbega fault is

Paleozoic Wrench Faults in Canadian Appalachians

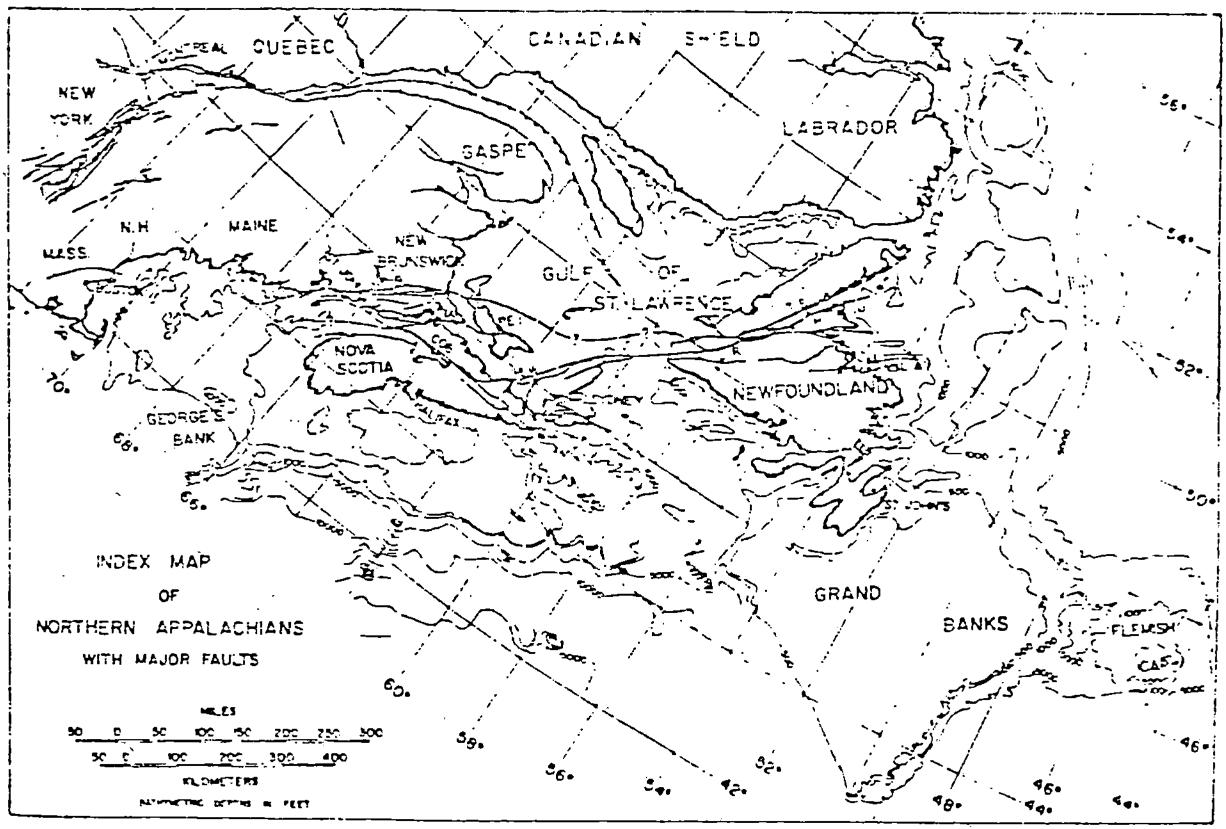


Figure XII-3. Index map of Canadian Appalachians showing major post-Devonian faults. Lu, Lubec fault; BL, Belleisle fault; HH, Harvey-Hopewell fault; COB, Cobequid fault; HLW, Hollow fault; TB, Taylors Brook fault; H. Hampden fault; LR, Long Range fault; LA, Lukes Arm fault; PEI, Prince Edward Island. (Webb, 1969).

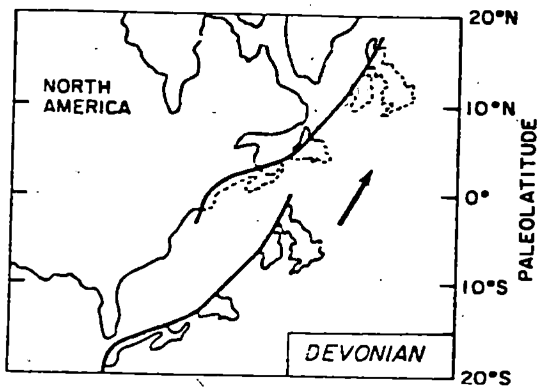


Figure XII- 4. Paleogeographic sketch of North America in the Devonian showing the position of the New England - Maritime region along with parts of the British Isles, with respect to the North American craton. The arrow shows the inferred sense of motion suring the Carboniferous which brought the Maritime -New England-British Isles area to the position shown by the dashed outline, (Kent and Opdyke, 1978).

unclear and its relationship with mylonite zones as described by Hatheway (1971) farther southwest in Maine is uncertain. The Clinton-Newberry fault zone of Massachusetts is a candidate for strike-slip faulting but documentation of strike-slip motion is limited to some horizontal slickensides (Cameron, 1976; Skehan, 1968, 1969) (Fig. II-9).

New England has several Carboniferous basins including the Narragansett basin of Rhode Island. Although no major fault with lateral displacement has been thoroughly documented, strike-slip slickensides are known within these basins (Cameron, 1976). The possibility therefore exists that the tectonic events of the New England Carboniferous basins are similar to that of the Maritime provinces. In this case there may be unrecognized major strike-slip faults associated with the Carboniferous of New England.

Strike-slip faults in the Canadian Maritime Appalachians are typified by the Cobequid (Eisbacher, 1969) and Cabot (Wilson, 1962) faults (Fig. XII-3). The east-trending right-lateral Cobequid fault separates pre-Carboniferous rocks to the north from Carboniferous rocks to the south. Transcurrent movement occurred in Pennsylvanian time with total displacement unknown. Two unusual characteristics of the fault zone are flexural flow folds in argillite-limestone and systematically fractured clasts in Carboniferous conglomerates close to the fault. The Orpheus gravity anomaly associated with salt movements may represent the eastern extension of the Cobequid fault zone (Webb, 1963).

List of Type Examples

a) Cabot, Newfoundland (Wilson, 1962)

b) Harvey-Hopewell, New Brunswick (Webb, 1969)

c) Cobequid, Nova Scotia (Eisbacher, 1969)

d) Frederiction, New Brunswick (Ludman, 1978)

e) Norumbega, Maine (Ludman, 1979, personal communication)

f) Wiscasset-Casco Bay , Maine (Hatheway, 1971)

g) Narragansett Basin , Rhode Island (Cameron, 1976)

2) Major Cross-Structure Faults with a Horizontal Component of Slip

Few examples exist within the Appalachian fold belt including the most notable, the Cross Mountain fault of eastern Tennessee. These faults are recognized primarily by the horizontal offset of stratigraphic units and are in general traceable by correlation of outcrops in adjacent anticlines in the Valley and Ridge. Little is known about the origin and history of this fault subgroup.

Root and Hoskins (1977) describe the Carbaugh-Marsh fault, part of the latitude 40°N fault zone, that consists of many individual faults (Fig. XII-5). The 40°N lineament is the name some give this zone. The entire latitude 40°N zone of many subvertical faults is 15 km wide. Root and Hoskins (1977) visualize these faults as a zone across which, during Paleozoic and Mesozoic time, blocks of the continental plate have been "jostled", rather than sliding by one another (see enigmatic structures in this volume). In this interpretation the faults extend down into the basement. Although the basement faults may have been present prior to folding of the cover rocks, the present surface exposures dictate that the faults were active during and after folding. One hypothesis might be that the cross-structure basement faults may be related to fractures associated with the breakup of continents or that they were older continental fractures that were reactivated during the latest opening of the North Atlantic at about 180 m.y. (Root and Hoskins, 1977). Regardless, the

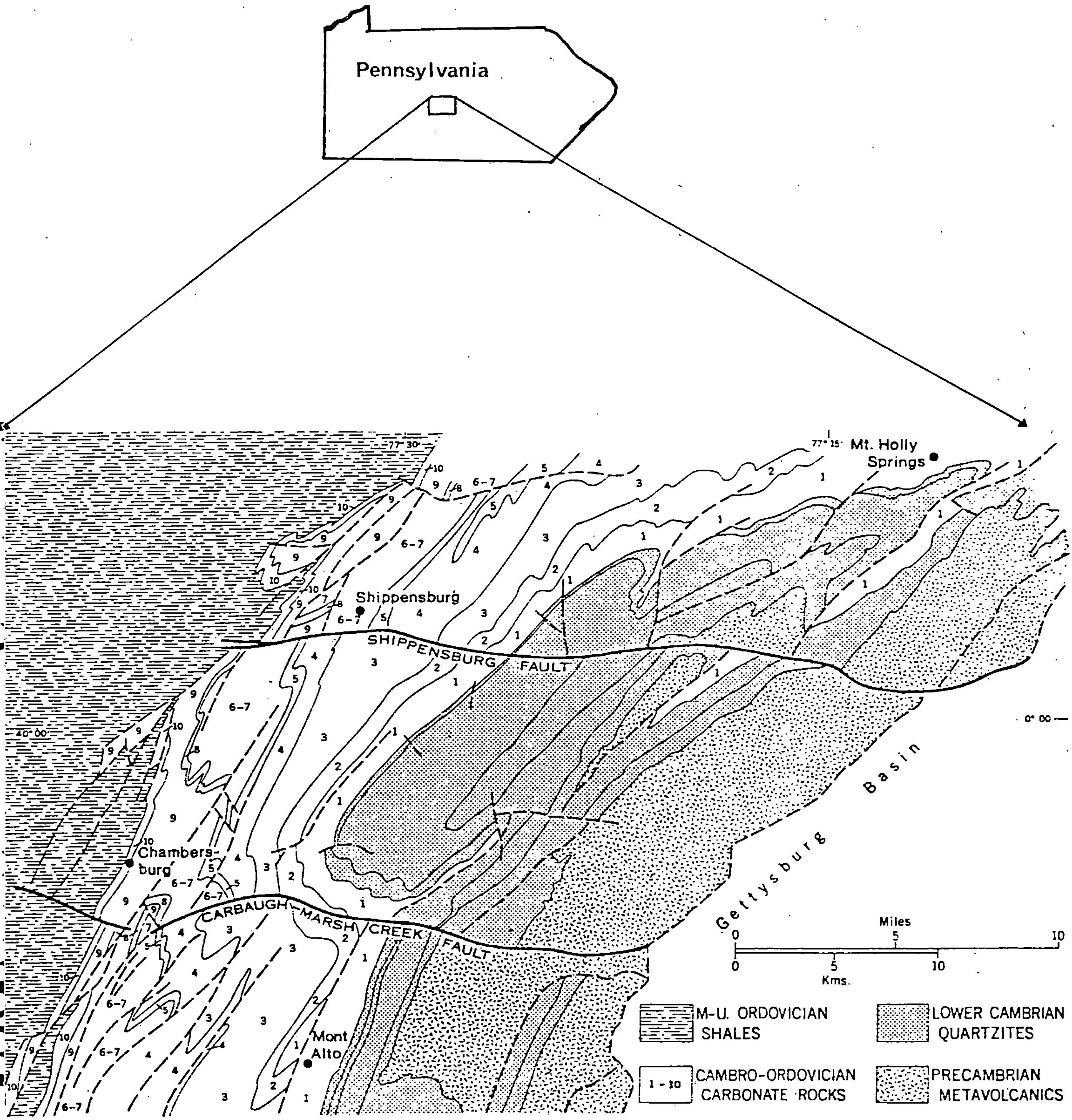


Figure XII-5. Geologic -ap of the Carbaugh-Marsh Fault area, Pennsylvania (Root and Hoskins, 1977).

tectonic significance of these faults is poorly understood.

The strike length of these major cross-structure faults is tens of km, crossing more than one fold in the Valley and Ridge Province. The fault zones are not exposed but assumed to be relatively narrow. These E-W striking faults have slipped up to 4 km as indicated by apparent offset (Root and Hoskins, 1977). The faults appear discontinuous because of poor outcrop exposure and are traced from anticline to anticline. Specific faults such as the Sideling Hill and Breezewood faults appear to terminate by rotating into thrust faults (Fig. XII-6). The Shippenburg and Carbaugh-Marsh Creek faults disappear under the Triassic sediments of the Gettysburg basin but the nature of the termination is unclear. The Sideling, Breezewood and Bedford faults all cut obliquely across the folded Appalachians.

Sykes (1978) describes zones of seismicity that pass on-shore through New England and South Carolina. It is unclear whether these trends in seismicity follow a single fault zone or are just fortuitous clusters of seismicity associated with unrelated faults. Sykes (1978) postulates these are projections of transform faults that developed during the opening of the Atlantic 180 m.y. ago and are now readjusting in the same manner as Root and Hoskins (1977) imagine the latitude 40°N fault zone developed during the jostling of crustal blocks (Fig. XII-7). However, in the case of cross-structure transform faults through the Appalachian Mountains, the faulting is believed to be predominantly normal or reverse, rather than strike-slip.

Lineaments are commonly used to identify or extrapolate cross-structural strike-slip faults. Maps commonly show apparent strike-slip offset of stratigraphy and on the ground these zones may be indicated by zones of fractures or crushed rocks. Enhanced fracturing across the anticlines may indicate the presence of this subclass.

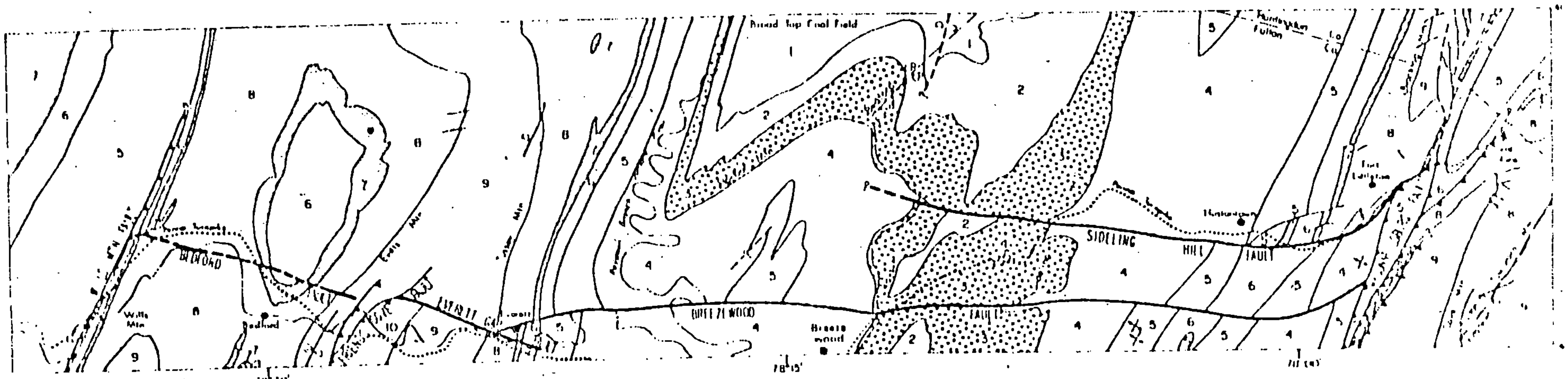


Figure XII-6 **Geologic Map of Sideling Hill, Breezewood and Bedford Faults, South-Central Pennsylvania**

Root and Hoskins (1977)

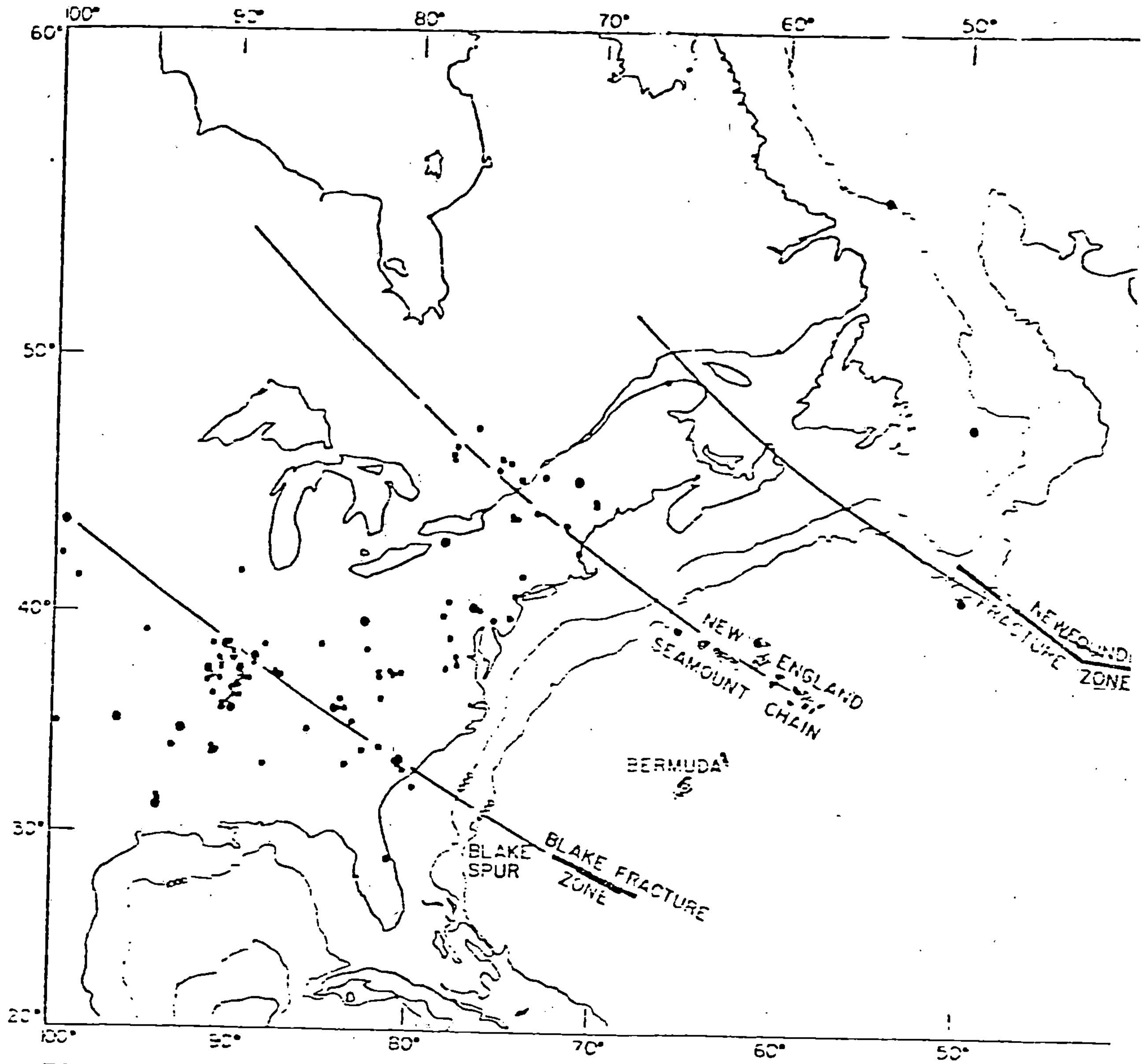


Figure XII-7. Seismicity of eastern and central North America, 1961-1974, from data of National OCeanic and Atmospheric Administration (NOAA). The seismic patterns align across the grain of the Appalachian Mountains. Sykes (1978) postulates that the seismic trends are projections of transform faults. Fletcher and others(1977).

Lineaments should not automatically be regarded as faults. See pitfalls of lineament analysis in section on enigmatic structures in this report.

List of Type Examples

a) Cross Mountain, Tennessee (King and Ferguson, 1950)

b) Sideling Hill, Pennsylvania (Root and Hoskins, 1977)

c) Breezewood, Pennsylvania (Root and Hoskins, 1977)

d) Carbaugh-Marsh, Pennsylvania (Root and Hoskins, 1977)

e) Shippensburg, Pennsylvania (Root and Hoskins, 1977)

3) Faults Reactivated with Strike-Slip Motion

Faults of this subgroup are also described in this report as compound faults. Some compound faults have demonstrable strike-slip displacements based on offset of local rock units. One example is the Ramapo fault system of New York that experienced as much as 4 km of right-lateral slip in the Paleozoic (Ratcliffe, 1971). The Canopus fault of the Ramapo fault system is characterized by extensive mylonitization along a complex fault system (Fig. XII-8).

Ratcliffe (1971) describes the Canopus fault:

"It is significant that cataclastic deformation similar to that ascribed to the older faulting ... marks the extension of the fault zone to the northeast rather than the open work breccia of the youngest fault episode. Cataclastic deformation took place at various times in the Canopus area, judging from the cross-cutting relationships of mylonite zones. However, the details are imperfectly understood are presented in Figure [XII-8]. The area was mapped by the writer at a scale of 1 in : 1000 ft during investigation which spanned a three-week period. ...

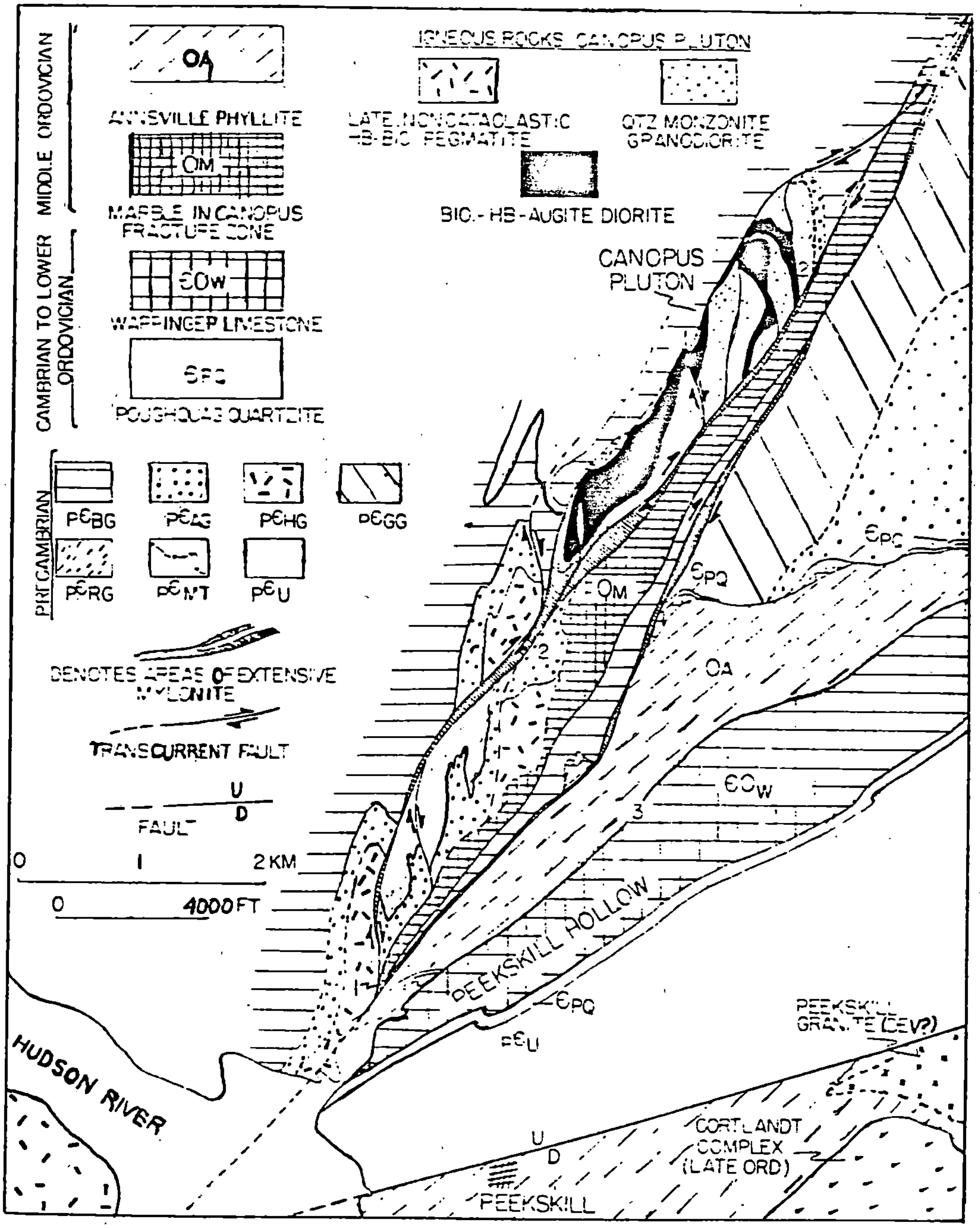


Figure XII-8. Geologic map showing the projection of the Ramapo fault system northeast of the Hudson River along the Canopus Valley (Peekskill Quadrangle, New York), and the position of the Canopus pluton. Note extensive mylonite along west margin of Canopus pluton. (Ratcliffe 1971).

The mylonite zones shown on Figure [XII-8] are all marked by strong development of minor folds showing right-lateral shear sense and near vertical fold axes. Evidence for right-lateral transcurrent faulting is best displayed along the western side of the Canopus Valley marble belt in the vicinity of the Canopus pluton. Here, offset of a distinctive 1.5- to 3-ft-thick magnetite deposit, shown by a special symbol on the map (Fig. [XII-8], Loc. 2), suggests a right-lateral displacement of 4 km (2.48 mi). The age relationships of this fracturing will be discussed in the section dealing with the intrusive rocks."

4) Tear Faults Associated with Décollement Tectonics

Commonly the décollement sheets of the Central Appalachians moved as units separated by tear faults. Figure XII-9 shows the location of geologic lineaments that are inferred to be tear faults. This inferrence is based on different amounts of displacement between sheets (Gwinn, 1964). Of the few examples of tear faults visible, the best may be seen in some of the salt mines in south-central New York (Prucha, 1968). In the context of this report, these faults are also discussed under bedding-plane faults. In some cases it is difficult to distinguish between this subgroup and faults of subgroup 2, major cross-structural faults.

The largest of the tear faults are those separating semi-independent décollement sheets (Gwinn, 1964; Rodgers, 1963). Kowalik and Gold (1975) postulate that these tear faults form over major basement faults. The basement faults are topographic steps in the basement (Fig. XII-10).

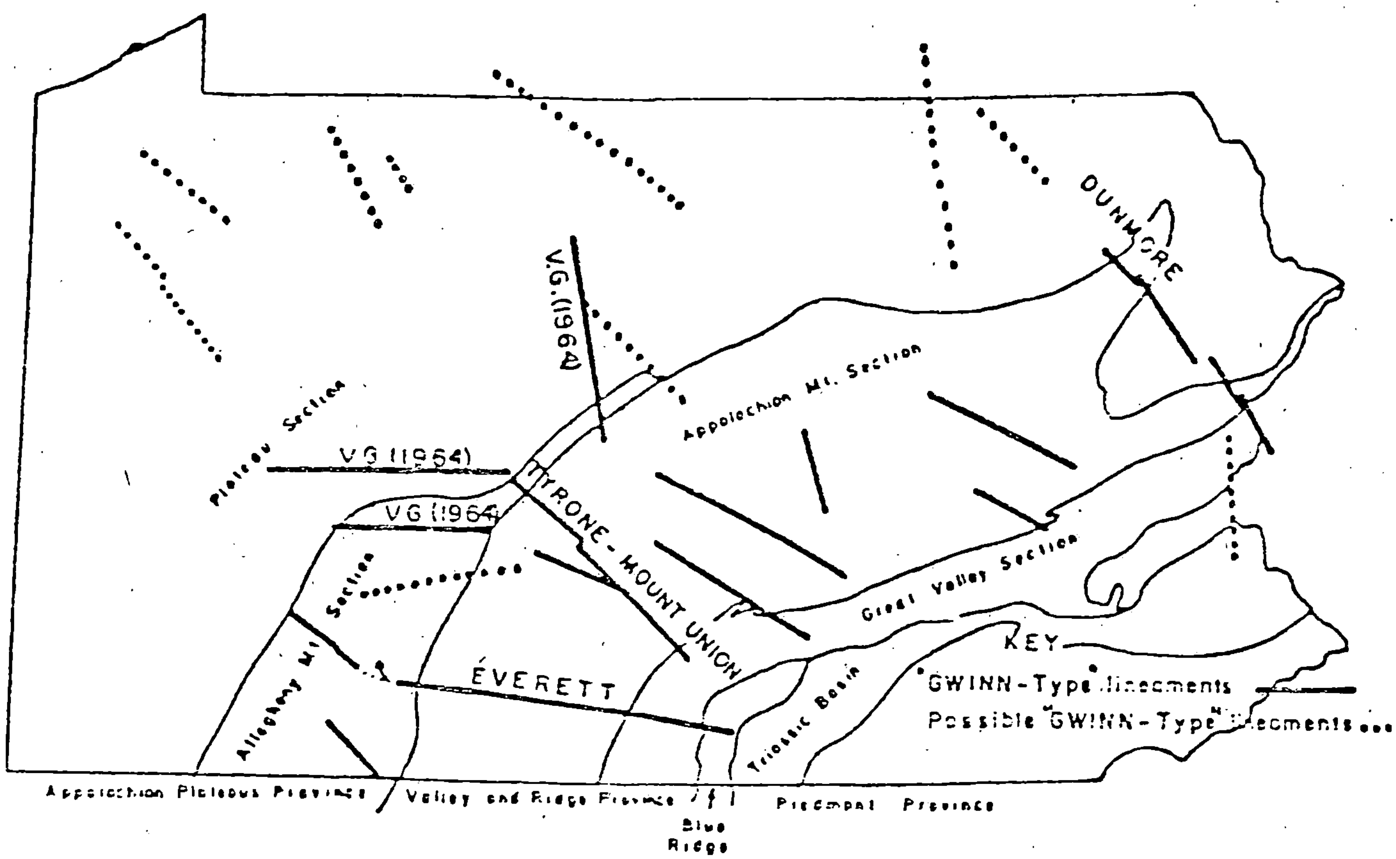


Figure XII-9. Distribution of the best expressed lineaments (solid lines) in Pennsylvania. The dotted lines represent possible lineaments on the Appalachian Plateau. The lineaments marked "V.G. (1964)" were not detected in the imagery work of Kowalik and Gold (1975) but were mapped by Gwinn (1964). Some of these lineaments were thought to represent tear faults between decollement sheets(Gwinn, 1964). (Kowalik and Gold, 1975).

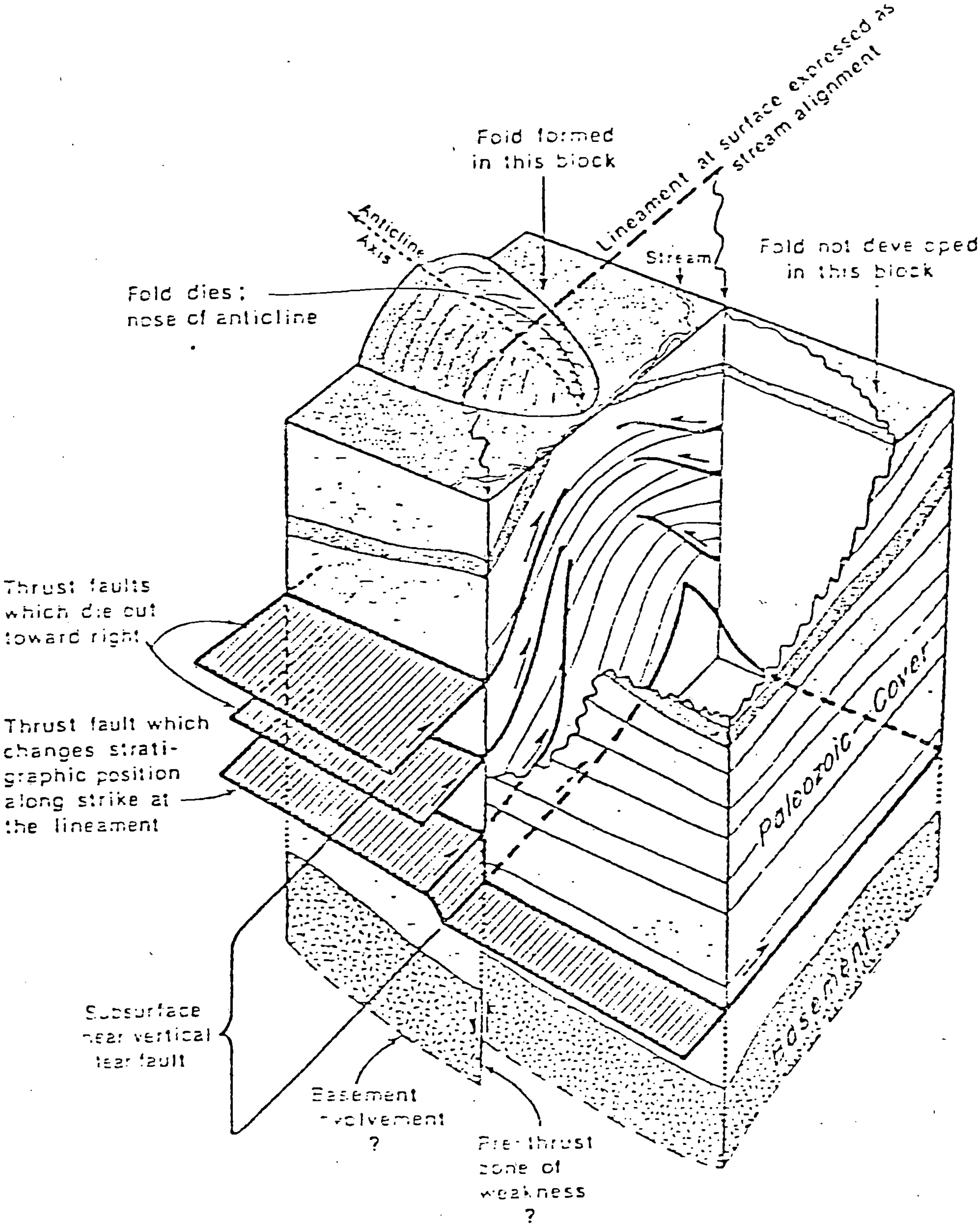


Figure X11-10. Idealized block diagram showing the postulated three-dimensional structure of a lineament. These lineaments are thought to represent the boundary between semi-independent thrust blocks. (Gwinn, 1964), from Kowalik and Gold, (1975).

Kowalik and Gold conclude that:

"Eleven major tear faults, as described by Gwinn (1964), have been identified. These trend northwest parallel to the transport direction of thin-skinned tectonics. One of these, the Everett lineament, traverses the Blue Ridge Province and the Valley and Ridge Province suggesting that the basal décollement of the Appalachians underlies the Blue Ridge and that the Blue Ridge has probably been transported westward to its present position [Fig. XII-9]. ... Many probable 'stepped' tear faults pass through gaps in ridges, indicating that the gaps are points of structural weakness and are not randomly located, as theories of drainage superposition contend."

List of Type Examples

a) Lineaments of Central Pennsylvania (Gwinn, 1964)

b) Jacksboro fault, Tennessee (Rich, 1934)

c) Russell Fork fault, Virginia (Rich, 1934)

d) Silurian Salt tear faults, New York (Prucha, 1968)

5) Small Displacement Strike-Slip Faults on the Limbs of Folds

This subgroup is characterized by local faults or shear fractures within individual thrust sheets rather than tear faults separating sheets. In some instances the faults or shear fractures make a conjugate set oriented to allow extension parallel to the fold axes. The fault surfaces are characterized by slickensides of fibrous calcite. These faults or shear fractures are characterized by either a single fracture discontinuity or a narrow zone of gouge (< 5 cm) with slickenside surfaces. In many instances these features have been described as one of several types of fracture sets found on folds

(Stearns, 1968; Fig. XII-11). These small displacement faults are a ubiquitous minor structure within the Appalachian fold belt.

Typical examples of this subgroup are found in the Bear Valley strip mine (Nickelsen, 1979; Fig. XII-12). These faults apparently develop early in the history of the Appalachian folds and in general are oriented so that the acute angle between the conjugate pair bisects the direction of maximum compression for folding. These faults extend up to 100 s of meters across folds in the Appalachians.

The surfaces are typical slickensides with wear grooves oriented indicating horizontal slip. Fibers of calcite are also commonly found on these surfaces. Zeolite mineralization is also found along the surfaces. Often the small displacement strike-slip surface is a single fracture in the rock. If gouge is present, it resembles the cataclastic material described in Engelder (1974a). Brecciation is rare.

In general these faults present little danger of causing a destructive earthquake if reactivated. Reactivation next to the foundation of a nuclear power plant may cause concern to the foundation engineers.

List of Typical Examples

a) Bear Valley, Pennsylvania (Nickelsen, 1979)

b) Teton anticline, Montana (Friedman and Stearns, 1971)

6) Small-Displacement Strike-Slip Faults in Flat-Lying Sediments

Strike-slip faults with strike lengths of several km and uncertain offset have been mapped on the Appalachian plateau (Nickelsen and Hough, 1967, Fig. XII-13). Faults of this subgroup may be genetically related to those of the small displacement strike-slip faults on the limbs of folds in the Valley and Ridge but these

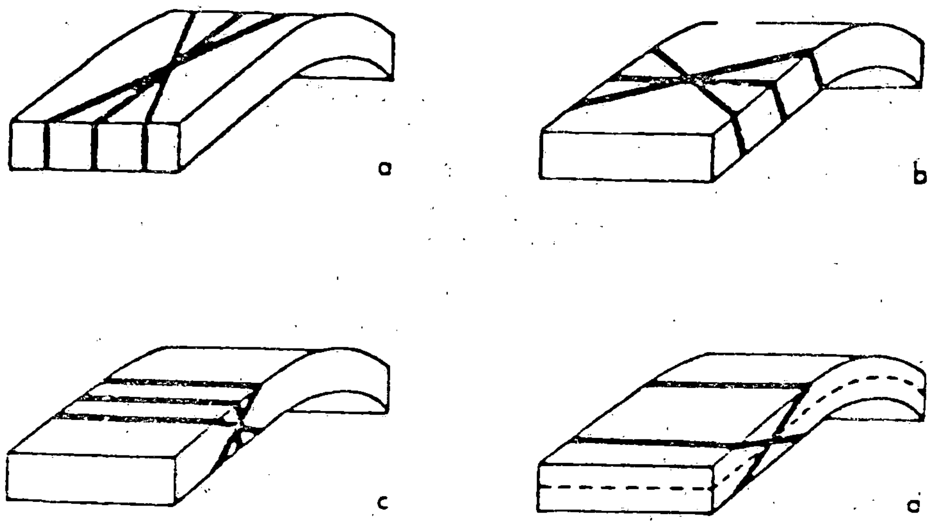


Figure XII-11. The four main fracture sets found in folded rocks and their relationships to bedding. (Sterns, 1968).

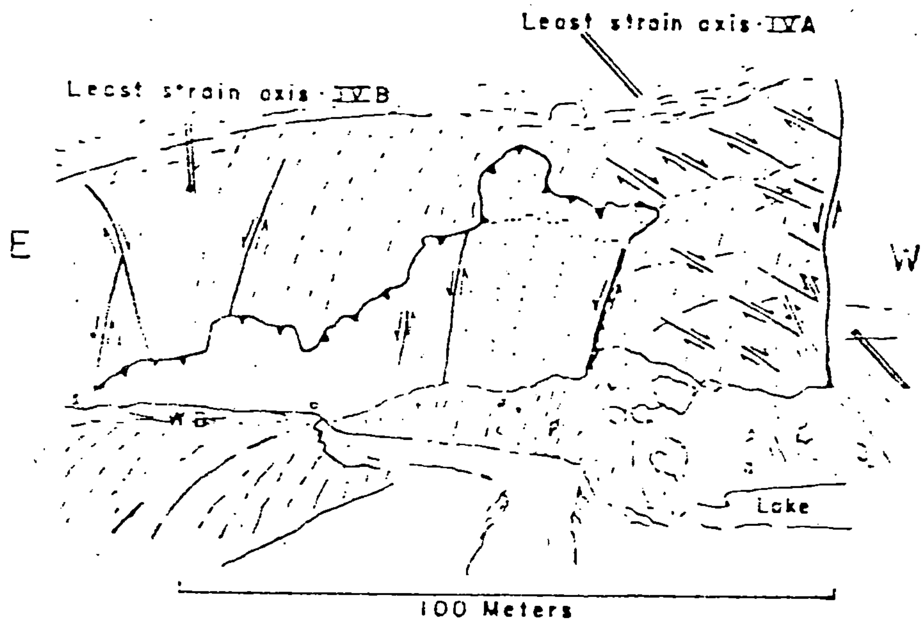


Figure XII-12. Small displacement strike-slip faults on the limb of the fold. From Nickelsen (1979).

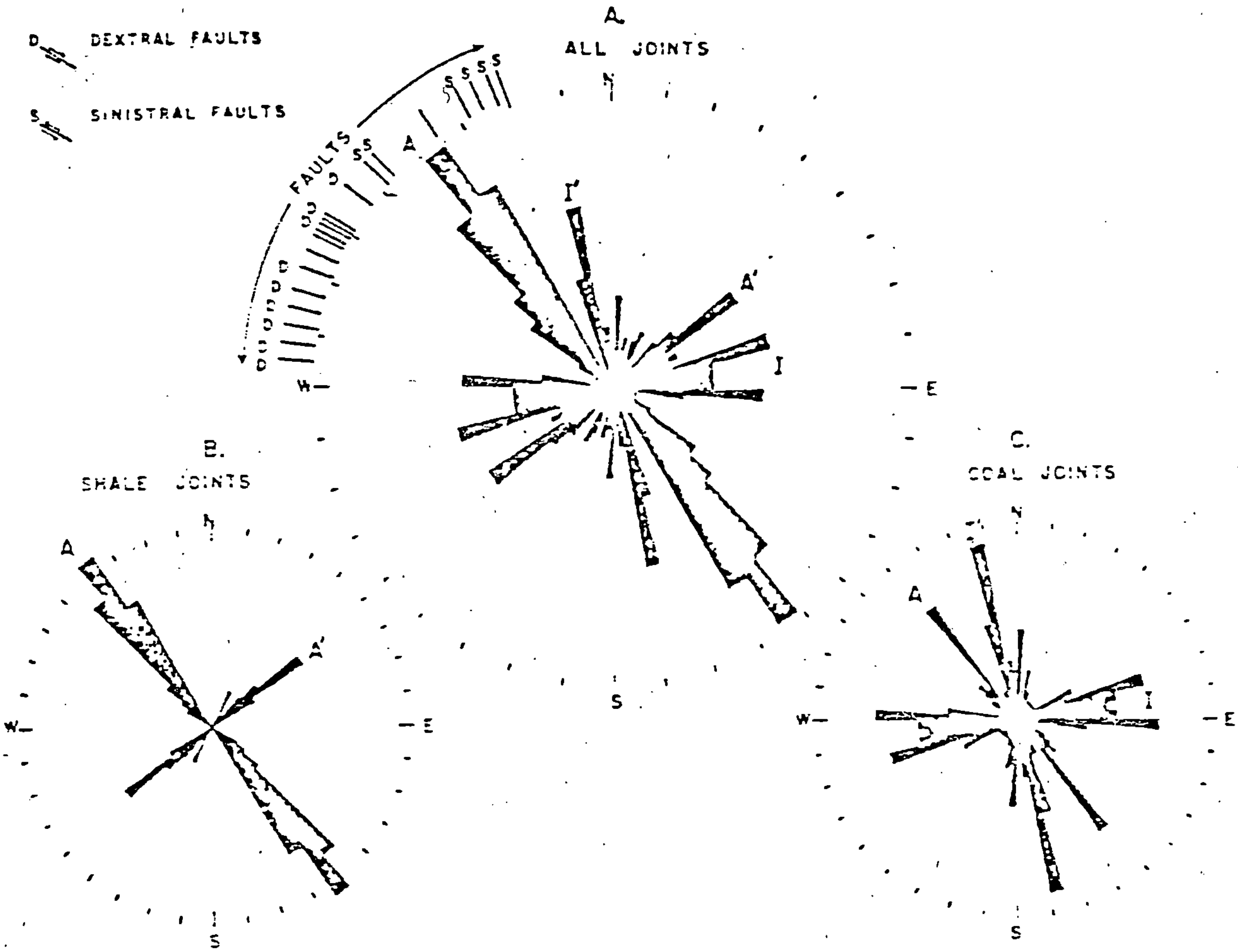


Figure XII-13. Histograms of Houtzdale quadrangle faults and joints in coal and shale. Redrawn from Nickelsen and Williams (1955). These faults are the small-displacement strike-slip faults in flat lying sediments of the Appalachian Plateau, Pennsylvania. From Nickelsen and Hough (1967).

structures have greater strike length and are not so obviously related to the folds.

Faults of this subgroup are distinguished largely on the basis of horizontal slickensides and minor offset of formations (Edmunds, 1968; Glass, 1972; Glover, 1970). The faults apparently develop early in the history of the Appalachian folds and in general are oriented in conjugate sets so that the acute angle between the conjugates is bisected by the direction of maximum compression for folding. On the Appalachian plateau Engelder (1979a) suggests that these conjugate sets of small displacement faults serve to permit extension parallel to fold axes. Locally horizontal slickensides may be seen, although these faults are not well exposed.

Faill (1979) further focuses attention on this point in his discussion of the Tipton block between Clearfield and State College, Pennsylvania:

> "Two adjacent rock masses moving in divergent directions create a zone of extension between them, within which structures may develop which differ from those in the adjoining blocks. The Tipton block, straddling the Appalachian structural front in the folded Appalachians, occurs in such a zone of extension 20 km north of Altoona in central Pennsylvania. To the southwest, the major structural trend is 027° azimuth; to the northeast, the trend is 151°. Slickenlines, perpendicular to these trends, indicate that these two masses moved in divergent northwestward directions as the Alleghanian folds were formed.
>
> The Tipton block, a triangular-shaped mass with the wedge point towards the northwest, was apparently thrust under the Appalachian Plateau rocks from the southeast in response

to décollement splays and other faults within the Nittany arch in the Valley and Ridge province. This underthrusting has produced a northwestward bulge in the regional structure contours in the Plateau.

Associated with the Tipton block are two sets of transverse faults trending (on the average) 100° and 138° azimuth. Subhorizontal slickenlines indicate that movement was predominantly strike-slip, and that this (probably) conjugate fault system produced a northeast-southwest extension in the zone between the rock masses to the northeast and southwest. The Tipton block and the associated transverse faults are local expressions of the divergent movements in the Pennsylvania salient of the Folded Appalachians."

List of Typical Examples

a) Clearfield County faults, Pennsylvania (Nickelsen and Hough, 1967)

b) Tipton block, Central Pennsylvania (Faill, 1979)

7) Strike-Slip Faults Associated with Mesozoic Basins

Slickensides with horizontal striae are common within the Mesozoic basins of the Appalachians. Some are associated with faults that can be traced several km within the Mesozoic basins (Dames and Moore Report, 1977)[1], whereas others are found within the border fault zones (Ratcliffe, 1979, personal communication). Similar strike-slip movement domains can be traced westward from the Connecticut basins (Wise and students; Fig. XII-14) into the crystalline terranes of the Berkshires. In general, the sense of slip along the border faults is mixed (i.e., both right- and left-lateral).

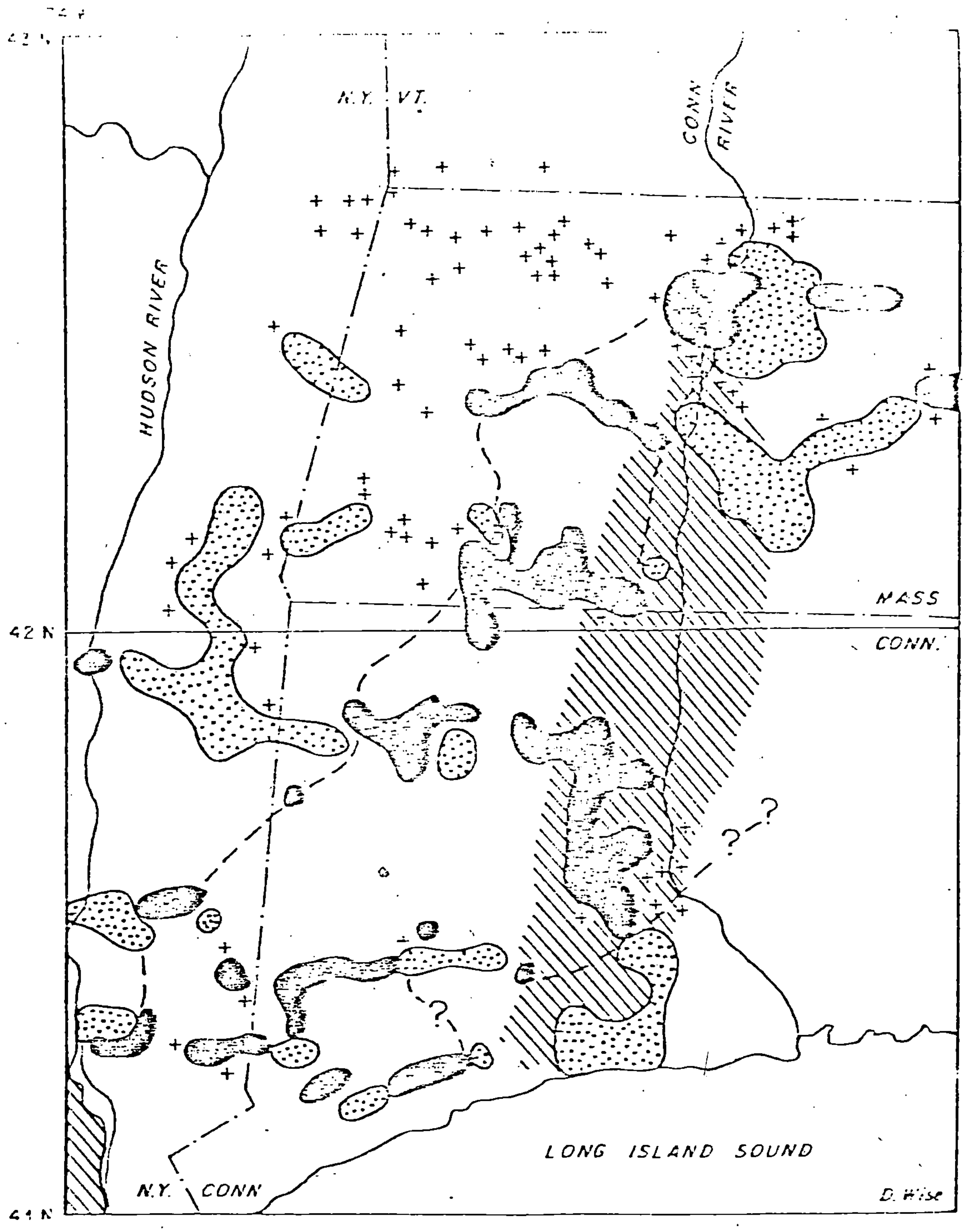


Figure XII-14. Patterns of Minor Slickenside Motions in Southwestern New England. Wise and Students (1979).

STATION CLUSTERS IN WHICH MINOR SLICKENSIDES SHOW STRIKE SLIP AND OBLIQUE SLIP > 50% OF TOTAL NUMBER OF FAULTS

STATIONS WITH MINOR SLICKENSIDES SHOWING DIP SLIP > 50% OF TOTAL NUMBER OF FAULTS

STATION AREAS WITH VERY FEW OR NO MINOR FAULTS RECORDED

MESOZOIC ROCKS

Within the basins slip along individual faults is consistent. For example, the northern end of the Newark Basin shows left-lateral slip along several faults subparallel to Ramapo (Lomando and Engelder, unpublished manuscript). Strike-slip faults within the Newark Basin have been traced into adjacent crystalline rocks (Fig. XII-15).

Displacement on most slickenside surfaces is on the order of mm to cm. Some of the intrabasin faults have a few meters of slip. The abundance of these faults is illustrated by the Limerick P.S.A.R.[2] Zeolite minerals are found in some of these Mesozoic strike-slip faults.

List of Type Examples

a) Rockland Lake fault, New York (Dames and Moore Report, 1977)[1]

b) Ramapo fault, New York (Ratcliffe, 1979, personal communication)

1 Preliminary Safety Analysis Report for the Indian Point, N.Y. Nuclear Power Plant, by Dames and Moore for Consolidated Edison. Document available in the Public Document Room of the U.S.N.R.C. at 1717 H Street NW Washington, D.C.

2 Preliminary Safety Analysis Report for the Limerick Nuclear Power Plant. Available at U.S.N.R.C. Public Document Room.

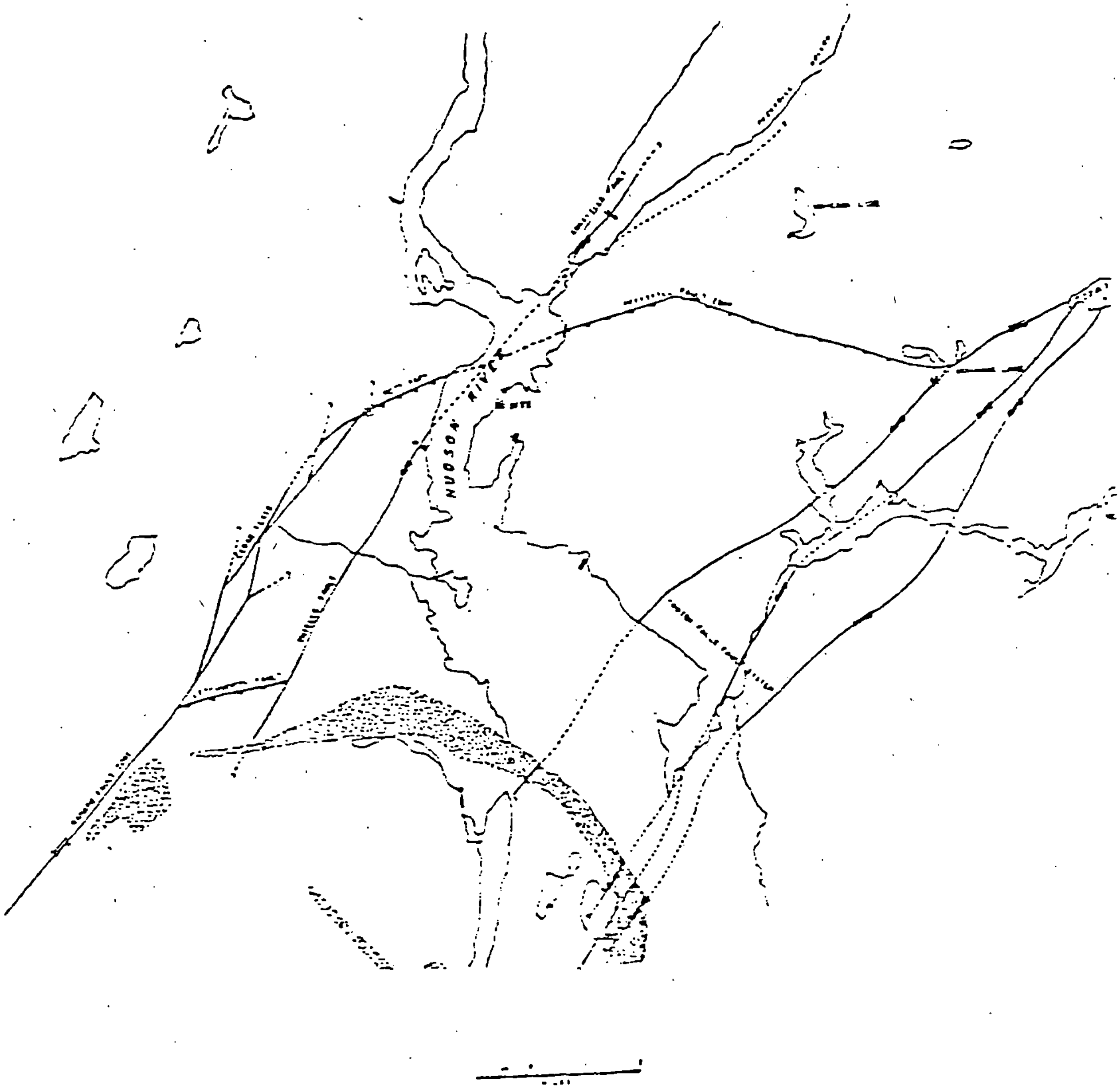


Figure XII-15. Northern end of the Ramapo fault system where the fault splays into the Hudson Highlands northeast of the Newark Basin. (Dames and Moore Report, 1977).

XIII

GROUP 9: BLOCK (NORMAL) FAULTS

A. General description

Faults of this group are steeply-dipping faults (Ave. ~60°) that extend to and disrupt basement (antithetic faults in hanging wall are truncated by master fault). Though they might have experienced strike-slip or even reverse motion, these faults are primarily normal faults. Faults of this group have probably developed at several times in the history of the Appalachians: in the Precambrian associated with crustal extension and rifting (Bird and Dewey, 1970) within the Grenville crust, during latest Precambrian-Cambrian time associated with the Avalonian activity in the northern Appalachians (Long, 1979), during Pennsylvanian-Permian activity in the Narragansett-Norfolk Basin area [though faults here are primarily thrusts (Skehan and others, 1979)], and during the Mesozoic Era associated with the continental separation.

Faults of this group which might have formed - and probably did - prior to Pennsylvanian time have not been documented, and because of later deformational activity probably no longer can be identified as belonging to this group. The one known exception is the boarder fault of the late Precambrian Rome Trough

The Mesozoic subgroup contains the overwhelming majority of faults in Group 9. Also the Mesozoic faults are the only members which can be said to regionally characterize an area of the Appalachians. Thus the example and detailed description given in this chapter, refers to the Mesozoic subgroup.

Group 9 faults are common throughout the Piedmont Province and in the Coastal Plain subsurface (Fig. II-9). All high angle brittle faults within the Piedmont Province, and certainly those which can be shown to be normal, post-metamorphic faults, are prime candidates for this group. Regionally and temporally associated with these faults are sedimentary basin fills and dolerite dikes which fill NW-to NE-trending fracture systems.

The example of a Group 9 fault described is the Jonesboro fault. In addition to the description given, the reader is referred to "Fault Investigations, Shearon Harris Nuclear Power Plant Units 1, 2, 3, 4" (Carolina Power and Light Company) report prepared by Ebasco Services, Incorporated. This document is available in the Public Document Room of the U.S.N.R.C. at 1717 H Street NW, Washington, D.C.

Example:

Jonesboro fault - The Jonesboro forms the eastern border fault of the Durham and Sanford Triassic basins (collectively known as the Deep River Triassic basin). The fault was named by Campbell and Kimball (1923) for exposures of the fault near the village of Jonesboro; which is now part of the city of Sanford.

The fault extends nearly 160 kilometers along strike (figure XIII-1). It is bordered on the east by a narrow belt of low-grade metamorphic rocks, further east is a large antiformal region (Raleigh belt) containing high grade schist, gneiss, and plutonic bodies.

The trace of the Jonesboro fault is not linear over long distances (figure XIII-2). Lindholm (1978) suggested the local orientation of foliation may have affected the trend of the fault trace, producing a curvilinear trace. From a detailed study of the fault trace,

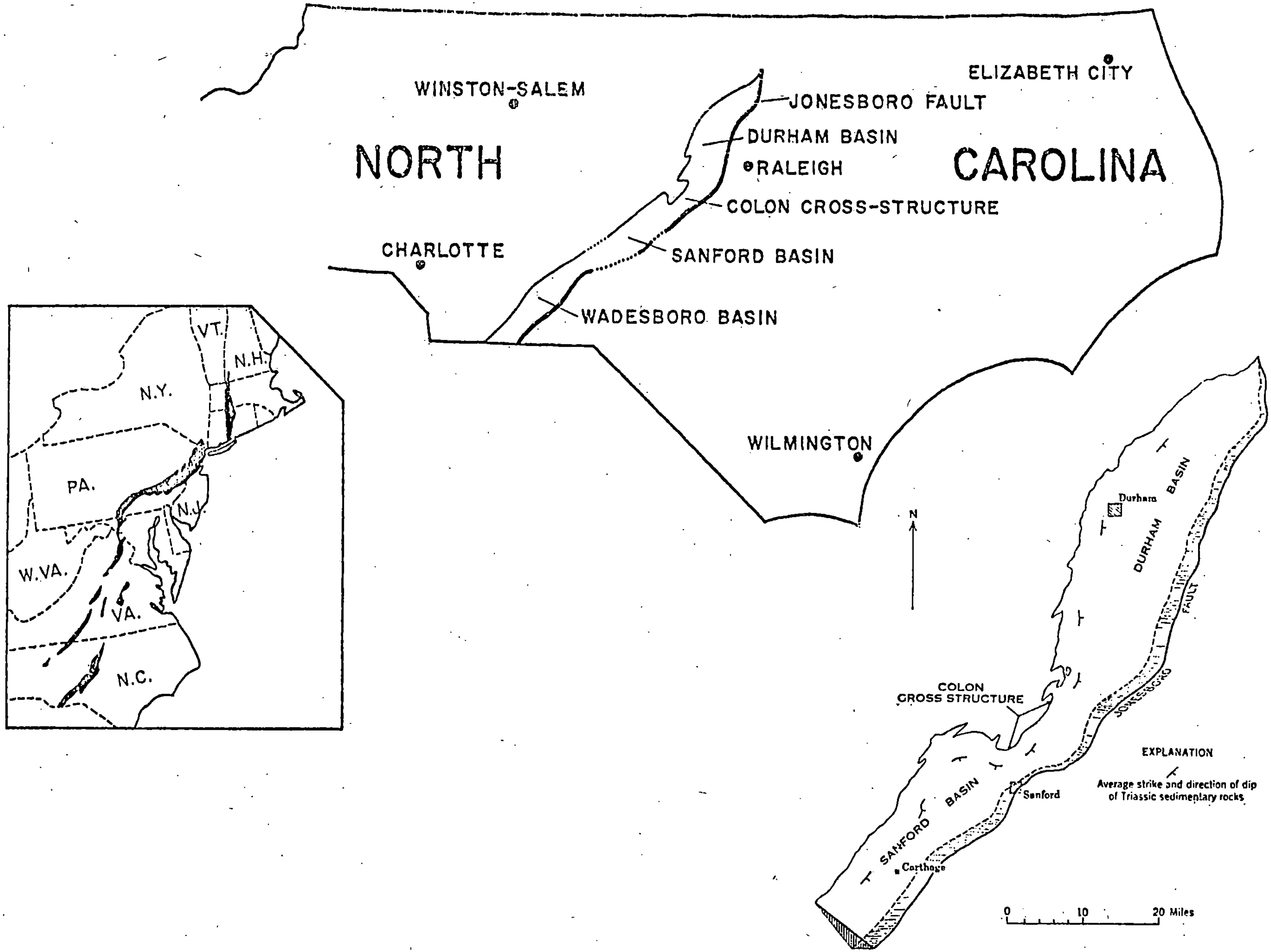


Figure XIII-1. LOCATION MAP OF DURHAM-WADESBORO TRIASSIC BASIN
Modified from Bain and Harvey (1977)

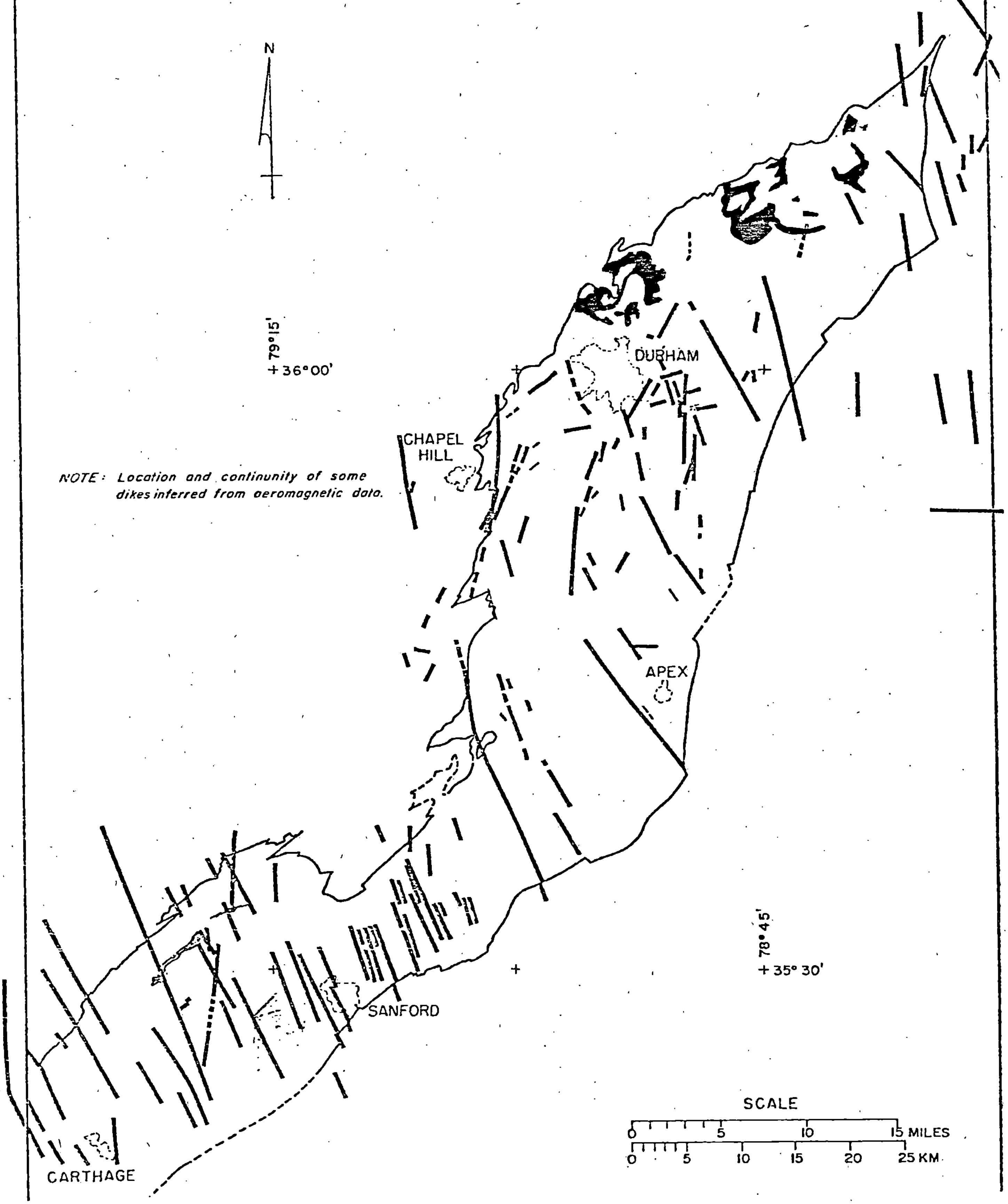


Figure XIII-2. Durham-Sanford, from Bain and Harvey (1977).

Reinemund (1955) suggested that the Jonesboro fault is cut and offset by cross faults which had significant strike-slip component and that these faults were subsequently intruded by diabase dikes (figure XIII-3). More recent studies (Bain and Harvey, 1977) reinterpret the structures and suggest the Jonesboro is not cut by younger faults but does in fact cut diabase dikes (figure XIII-4). In this case latest movement on the fault post-dates the approximately 180 ma-old dikes, however it has not disturbed early (?) Cretaceous sediments which cover the fault south of Sanford, N.C.

Reinemund (1955) has described several exposures of the fault contact. At one location the contact is between a light-gray late Paleozoic granite and brown and gray banded Triassic claystone interbedded with granite boulders. The fault surface is described as being sharp and fairly straight. Shearing is also present in both the granite and claystone adjacent to the fault. In most exposures the fault zone is only a few meters wide and movement appears to have been localized along a single surface (Reinemund, 1955). Carpenter (1970) has described siliceous breccia zones extending north of the Jonesboro fault into low grade metamorphic rocks.

The Jonesboro fault has been considered to have been the major fault of the Durham-Sanford basins (figure XIII-5). Recent studies, utilizing geophysical methods (figure XIII-6), suggest the border fault actually has relatively minor displacement, with the major faulting occurring within the basin (Bain and Harvey, 1977).

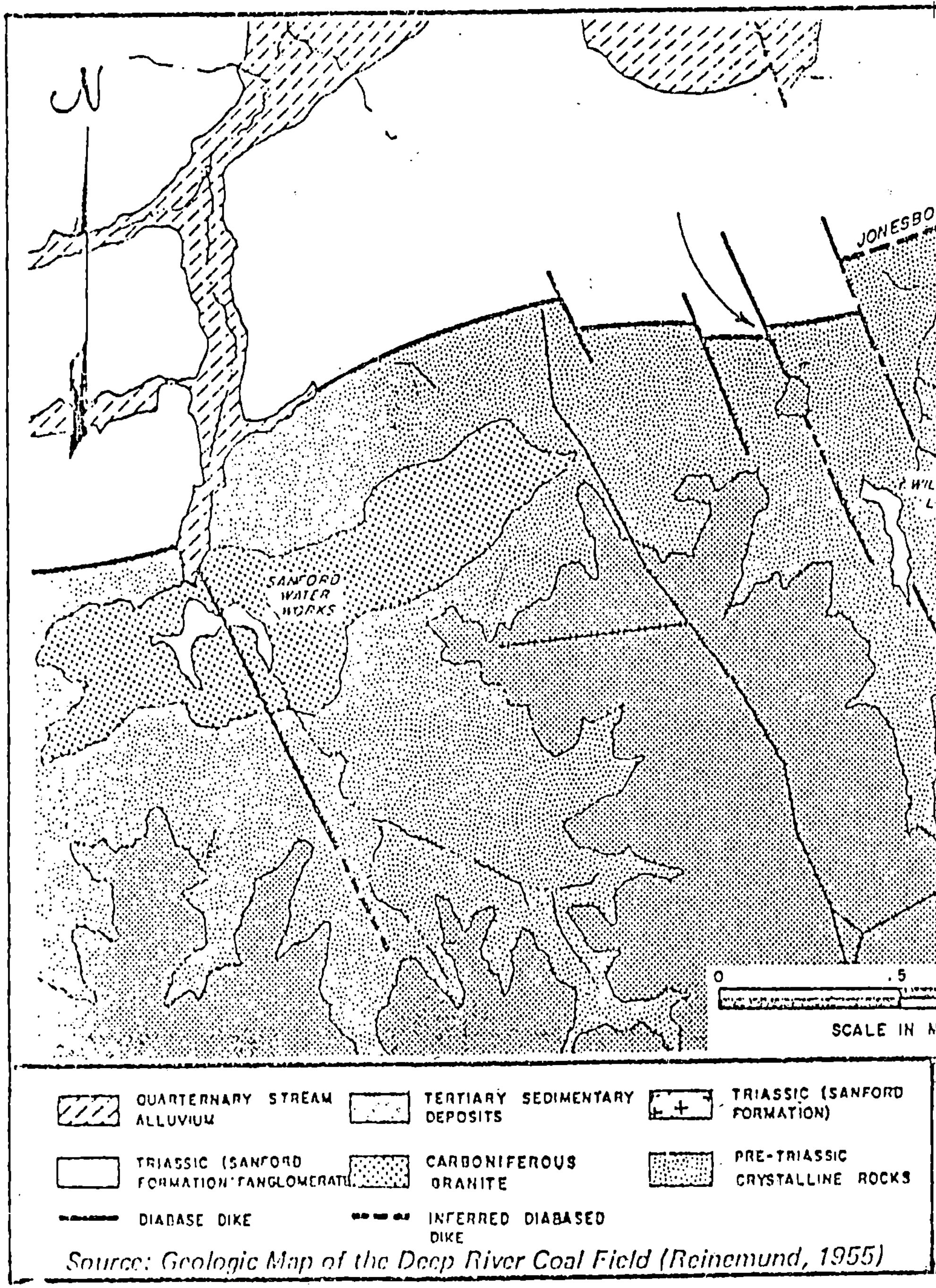


Figure XIII-3. Original interpretation of the Jonesboro Fault, Chatham and Lee Counties. From Bain and Harvey (1977).

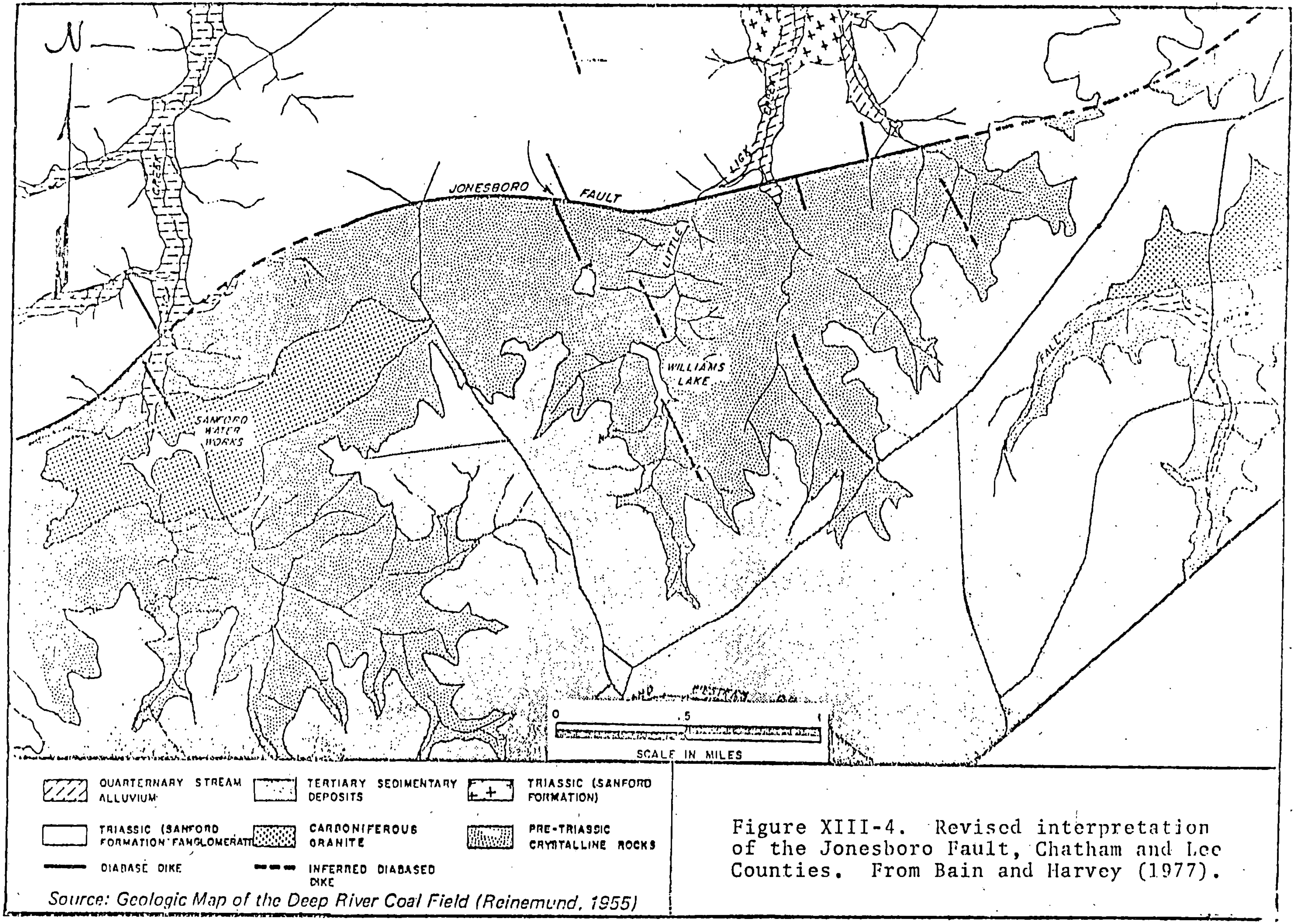
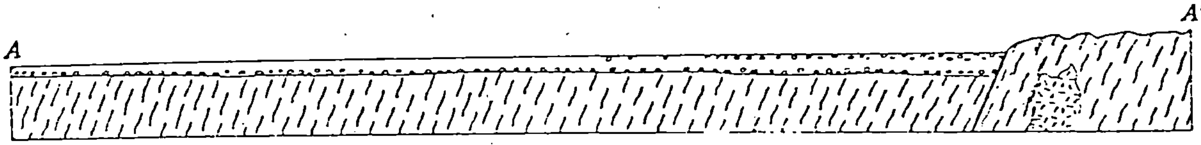
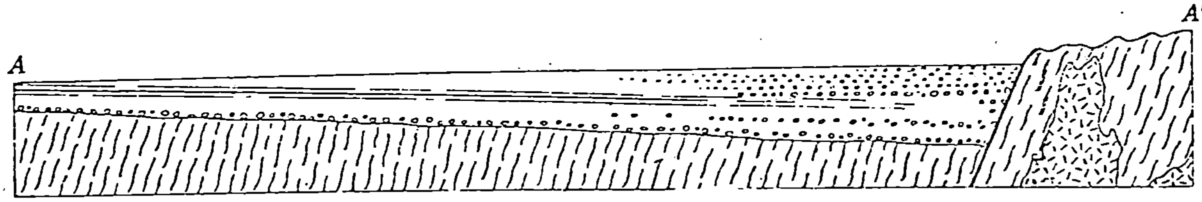


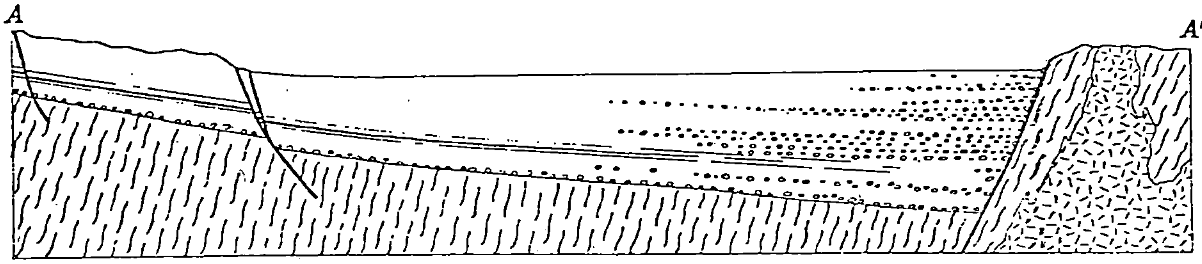
Figure XIII-4. Revised interpretation of the Jonesboro Fault, Chatham and Lee Counties. From Bain and Harvey (1977).



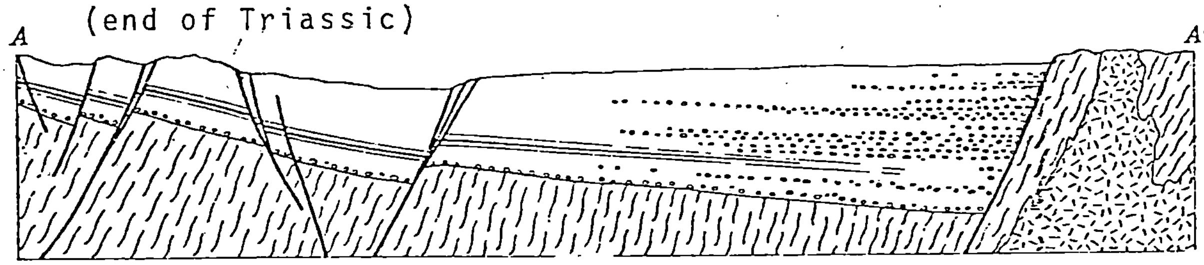
(1) Shape of slope during deposition of Pekin formation



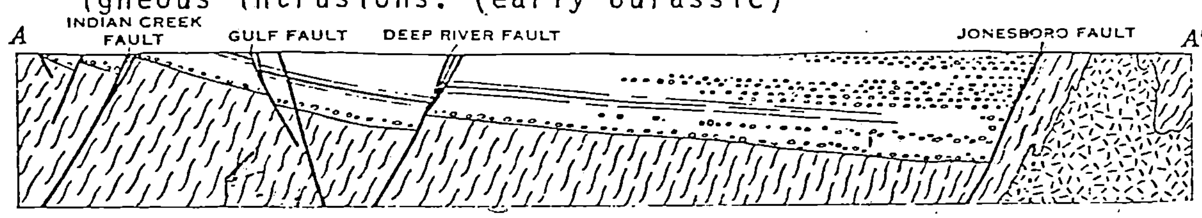
(2) Shape of trough during deposition of Sanford formation



(3) Trough after final movement on early longitudinal faults. (end of Triassic)



(4) Trough after development of late longitudinal faults and igneous intrusions. (early Jurassic)



(5) Trough after erosion of Jurassic mountains. (early Cretaceous)

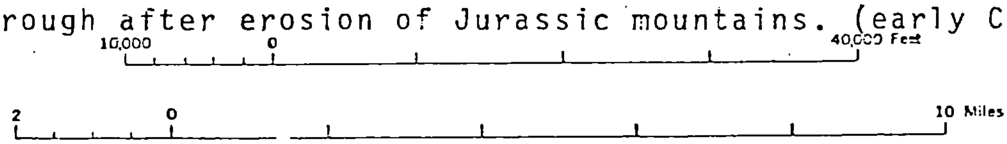


Figure XIII-5. From Reinemund (1955).

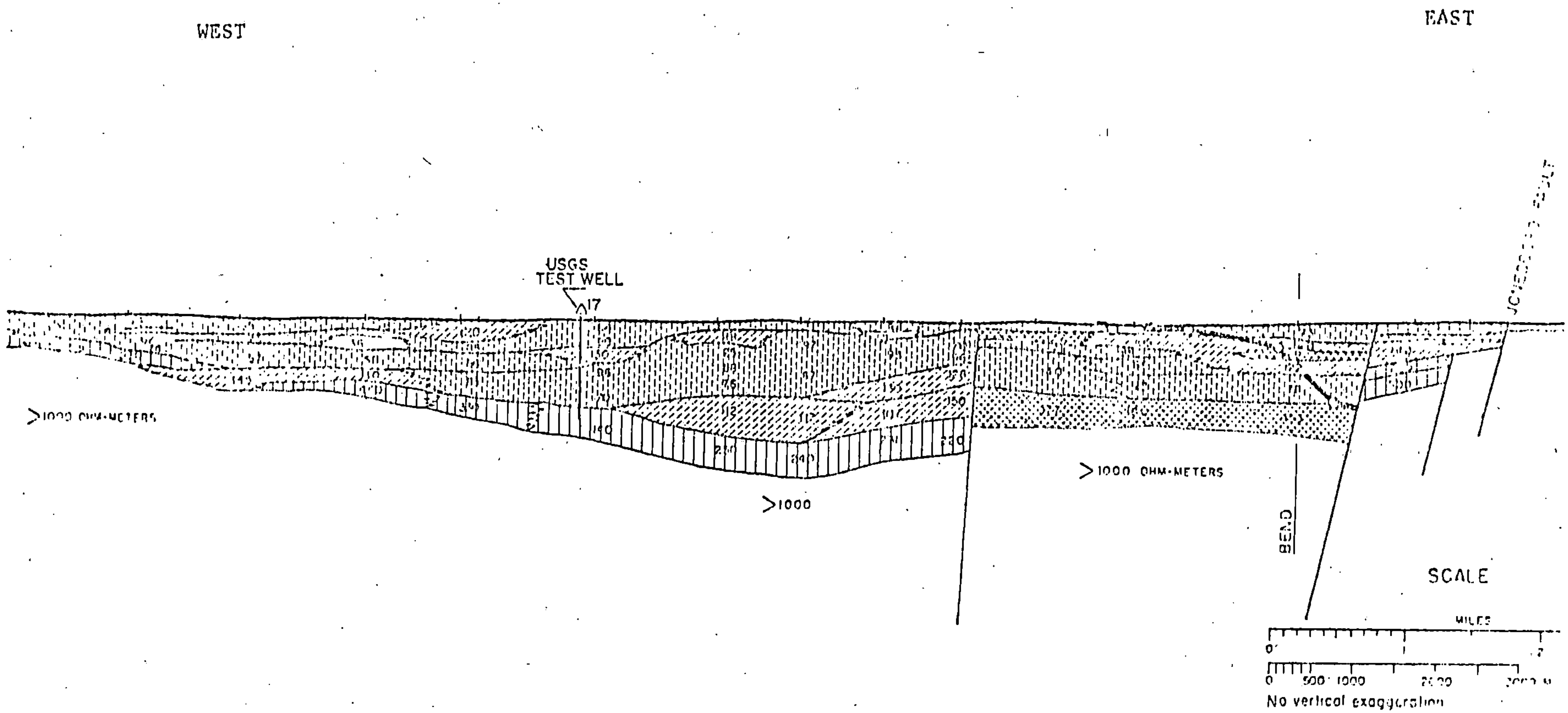


Figure XIII-6.
Revised interpretation for the configuration of the Durham Basin and Jonesboro Fault based on geophysical investigations utilizing gravity and electrical resistivity. Modified from Bain and Harvey (1977).

B. Description of Fault Group

1. Basic geometry

a) Strike Length - Meters to hundreds of kilometers.

b) Width - (Dimension perpendicular to strike) - Downdip extensions uncertain, but probably disappear into ductile zone at great depth. Antithetic faults may truncate against synthetic faults.

c) Orientation - Strike generally parallel to regional grain of the Appalachians, locally departing due to basement anisotropy.

d) Displacement - Dominantly dip-slip motion and most commonly normal movement. The total apparent thickness of stratigraphic section in basin might greatly exceed the total relief on the basement and displacement along any one fault. Displacement is from meters (or even centimeters to a few kilometers, maximum). Cross-faults tend to have smaller displacements. Present border faults might not be the major fault, but only an "accident" of erosion. The major fault may be outside the basement.

e) Continuity - Individual faults tend to link through a series of roughly contemporaneous normal faults and cross faults, especially along the down dip margin of the basins.

f) Curvature - (i) along dip - The faults may be listric. Many faults may flatten into subhorizontal basement faults with depth. At shallow depths the dips are 60° to vertical.
(ii) along strike - Tends to parallel regional strike of basement. Most lack significant curvature, but may locally

show curvature due to local anisotropy. Composites or coupling of contemporaneous straight segments can give a regional indication of curvature.

g) Termination along Strike - May terminate in rotational faults, splays, monoclines or other folds which decrease in magnitude, or may extend into crystalline basement where fault is difficult to trace.

2. Tectonic Setting

Mesozoic block faults are located east of the billion year old Pre-cambrian massifs of the Long-Blue-Green axis in the Piedmont and Coastal Plain provinces. These faults were formed in response to the rifting and separation of continental crust which produced the Atlantic ocean.

3. Characteristic of Fault Surface or Zone

a) Type of Fault - Typically in brittle domain and non healed, partially filled to completely filled - occassionally silicified; breccia and gouge common, with zones from tens of centimeters to several tens of meters.

b) Surface texture - Slickensides - wear groves are common on surfaces; fiber veins much less common. Slickensides can have diverse orientations, including horizontal, but the predominant direction is parallel to dip slip direction.

c) Metamorphism and Mineralization - Post-barrovian metamorphism. There is a range of hydrothermal mineralization up to greenschist facies. Zeolites are common; carbonates are calicte, ankerite, and siderite; sulfide mineralization; wide zones of silicification including box-work and multiple development of veins. Open space crystal growth indicating pressures lower than hydrostatic are common. Oxide minerals may be present.

4. Relation to Country Rock

a) Parallel or Cross Regional Grain - Short fault segments commonly cross regional grain, but long fault segments usually parallel regional grain.

b) Promontory or re-entrant - No obvious association.

c) Thick or thin-skinned - Faults cut and displace basement.

d) Relation to Isopachs - Border faults truncate sedimentary basin fills. Faults within basins commonly are surfaces across which thicknesses change abruptly. For faults outside of basins, this does not apply. See Figure XIII-5.

e) Stratigraphic Interval Transected - Maximum P E thru Mesozoic. Most include rocks as young as Jurassic and as old as lower Paleozoic. In Coastal Plain, faults have been found to cut Cretaceous strata.

f) Relation to Folds - Broad warping of strata in basins and local folding marginal to faults; dragfolds, reverse drags and flexures associated with terminations of faults.

g) Relation to S-surfaces - No genetically associated S-surfaces on a regional scale, but locally kink bands might develop adjacent to fault. Also numerous, closed spaced, parallel fractures adjacent to faults are observed in some areas.

h) Relation of Fault Character to Rock Type - Faults are not affected by rock type except change in strike which might result from rock anistrophy.

i) P-T Conditions - Crystalline basement involved in faulting is below the brittle-ductile transition and not above the chlorite zone of greenschist facies; generally low temperature and confining pressure. Locally precise P-T conditions can be determined by fluid inclusion studies or from stabilitites of vein or other associated minerals (zeolite assemblages have been used in this regard).

j) Relation to Isograds - Regional isograds are displaced by the faults. Displacement of isograds can be used to establish limits to magnitude of displacement. However, caution must be exercised in areas of inverted isograds.

k) Relation to Intrusions - Usually dolerite dikes predate faulting or are penecontemporaneous. Faults may wrap around older, unfoliated granites (such as the Jonesboro fault) giving a false impression of the granite intruding the fault.

5. History

a) Age of Inception - For the Mesozoic subgroup, major motion is not known with certainty, some may represent reactivation of older (Paleozoic faults). Major motions are Triassic and Jurassic. Motion frequently occurred during sedimentation. Geological investigations made indicate that these faults are not active at present.

b) Recognition of Syndepositional Effects - Basin fills and fanglomerates, thickness variations of volcanic flows in northern basins, rotation of initial dips with associated gravity slides. There is some question as to the extent to which basin configuration was controlled by the faults. Local ponding affects can be found.

c) Radiometric ages - K-Ar and fission track ages have been measured on fault filling material. Depending on mineralogy, condition and history of samples, the analytical ages either approach or are greatly less than the true ages.

d) Relationship to Unloading - Not applicable.

e) Indications of Last Motion - Cross cutting dikes (though rare), growth of minerals in the fault zones and the age of those minerals which can be shown to post date movement; Coastal Plain overlap; relation to fluvial deposits; estimates from P-T conditions of movement or fault fill and possible range of uplift and erosional rates; seismic information where applicable.

6. Stress Field

a) Orientation of Principal Stresses - σ_1 is vertical and σ_3 is normal to strike at the time of faulting. Slickensides and seismic first motion studies indicate that stress orientation can and in some cases has changed (e.g., seismic activity associated with Ramapo fault zone). σ_2 generally parallel to basin border fault, but locally considerable re-orientation of stress axes occurred during Mesozoic.

b) Magnitude of Stress and Strain - Unknown.

c) Variation of Stress and Strain - Unknown.

d) In situ Stress - Unknown.

e) Seismic First Motion Studies - Unknown.

f) Rates of Motion - Unknown.

g) Fluid Pressure Changes and Effects - Unknown.

7. Geophysical and Subsurface Characteristics

a) Seismic Activity Levels - Microseismicity might be associated with, or at least near a few of these faults, but this is not well established.

b) Subsurface Offset - Displacements have been revealed by geophysical methods indicating subsidiary faults of this class beneath basin fill - and also beneath Coastal Plain sediments (even displacing Coastal Plain sediments; e.g. Charleston, South Carolina area).

c) Relations to Anomalies - Cut magnetic anomalies and generally parallel or nearly parallel gravity anomalies.

d) Geophysical Lineaments - Not applicable.

8. Geomorphic Relationships

Fault line scarps are frequently developed where basin fill adjoins the fault. Springs are frequently aligned; colluvium and colluvial sliding may be present. Strong topographic changes often occur across border faults of this group. Faults of this group might also exhibit topographic expression due to the nature of fill.

9. Methods of Identification and Detection

a) Best detected by evidence of basin fill and offset of basin fill.

b) Fault scarp-lines and buried scarps detected by geophysics and drill holes.

c) Zones of silicification, zeolite mineralization, microbressia can be a clue - but must be considered with other features; open box-work silica is often characteristic.

d) Commonly associated with increase fracture density.

e) Abrupt changes in metamorphic isograds not associated with Coastal Plain or thrust faults.

f) Faults offsetting dolerite dikes are good candidates.

g) Localized zones of metamorphic retrogression in high grade terranes might be a candidate for this class.

h) Monoclinal flexures and drapes in basin fill may indicate buried faults at depth or exposed along their projection.

i) Brittle reactivation of earlier steeply dipping faults might be a clue of this group of faults.

10. Pitfalls in Recognition

a) Mere brittle behavior of fault with strike parallel to regional grain is not adequate evidence.

b) The present border fault may be a younger feature than the basin and might have counterparts buried beneath basin fill or beyond basin.

c) Where sufficient stratigraphic control exists, some of these faults can be shown to have movements extending into Upper Mesozoic rocks; the possibility of late Mesozoic and perhaps earliest Cenozoic cannot be ignored.

d) Along feather edge of basin fill, flexuring and faulting may be confused with the sub-Triassic unconformity; sudden changes in dip of sediments along "unconformity" should be examined with suspicion and care.

e) Horizontal slickensides and other indications of horizontal motion do not preclude faults from being in this class.

f) Faults may splay along strike.

II. Possibilities of Reactivation

These faults are among the major, deep-seated, unhealed basement strain anisotropies. They are also conduits for movement of groundwater. Members located near Coastal Plain hinge line should be carefully considered. The possibility of reactivation might be significant. It is important to know the orientation of the stress field.

XIV

GROUP 10: COMPOUND FAULTS WITH LONG, REPEATED MOVEMENT HISTORY

Compound faults are defined herein as those with a repeated movement history. While most faults in the Appalachians, particularly the larger faults in the crystallines, have experienced multiple movement histories, they have had a single major episode of movement, usually associated with a particular orogenic event. However, those faults grouped as compound faults have experienced several major episodes of movement. Discussion of the group will be through two well-known, but still incompletely understood, examples: the Brevard zone and the Ramapo fault. Other faults have also had multiple histories of movement, but the two examples cited herein represent both multiple reactivation over very long periods and a great many studies. Recent investigations in Virginia have revealed the complex history of the Hylas zone (Bobyarchic and Glover, 1979).

BREVARD ZONE

A. Generalized Description

The Brevard zone consists of a linear belt of mylonitic and cataclastic rocks extending from central Alabama to northern North Carolina (Fig. XIV-1). Mylonites are both prograde and retrograde with major segments having undergone a later brittle movement history. The dominant mylonitic foliation in the Brevard zone is parallel or subparallel to the dominant regional (S_2) foliation in the southern Appalachians. But the dominant foliation in the Brevard zone transposes the regional S_2. It is in large part stratigraphically controlled: distinctive lithologies (graphitic phyllonite, marble and quartzite) are associated with the structurally defined zone. Slices of platform carbonates have been brought into the fault zone from the footwall of the Blue Ridge thrust sheet (Fig. XIV-2).

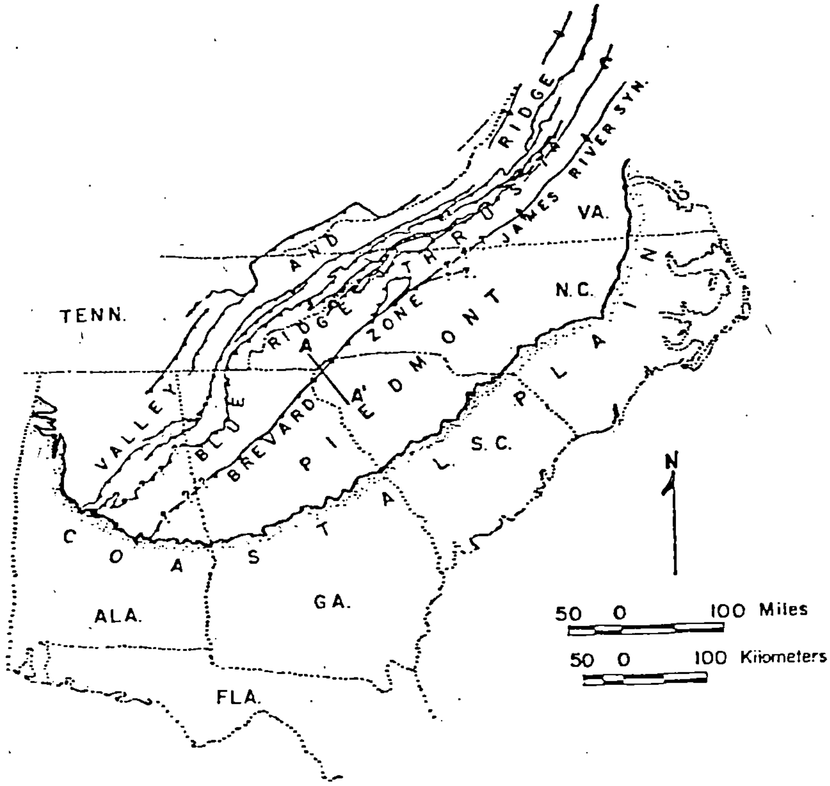


Figure XIV-1. Location and known extent of the Brevard Zone and other major Late Paleozoic thrusts of the Southern Appalachians (from Hatcher, 1971).

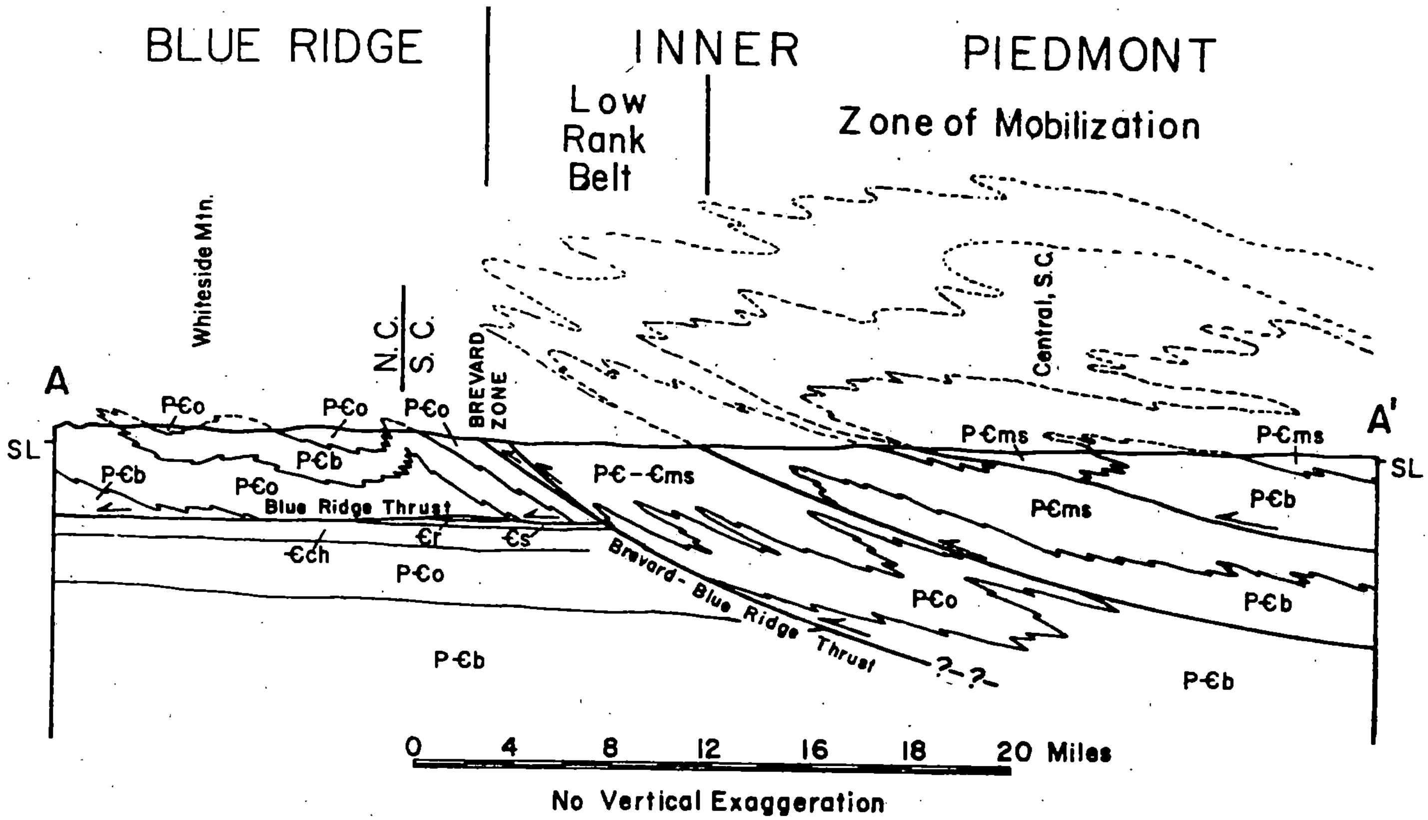


Figure XIV-2. Geologic cross section along A-A' (fig. XIV-1) showing the present structural configuration of the Blue Ridge thrust sheet, Brevard Zone, Low Rank Belt, and mobilized Inner Piedmont as interpreted by the writer (the interpretation within the Blue Ridge thrust sheet is modified from that of McKniff, ms). The structural configuration of the Blue Ridge-Brevard thrust system is unknown but is presented here relativeley undeformed with the rock units concluded from surface data to be present in the footwall. P €b-basement rocks, P €o-Late Precambrian Ocoee equivalent metasedimentary rocks, P €ms- Late Precambrian metasedimentary rocks (probable Ocoee equivalents in the mobilized Inner Piedmont), P €-€ms-Chauga River-Poor Mountain Group and Henderson Gneiss (probably Late Precambrian or Early age),€ch-Chilhowee Group, €s-Shady Dolomite, €r-Rome Formation (from Hatcher, 1971).

B. Description of Fault Group

1. Basic Geometry

a. Strike Length - 400 km.

b. Width Perpendicular to Strike - 1 -4 km.

c. Spacial Orientation - Parallel to the regional structural grain.

d. Displacement - May be the sole of the Blue Ridge thrust that was cataclastically brought to the surface as a back-limb thrust by a late brittle event. This latter event probably involves 10 km or less displacement. Mylonitic phase may record a minimum of 225 km of movement (Hatcher and Zietz, 1978).

e. Continuity - Probably is the most continuous single structure in the Appalachians over that length.

f. Curvature - Very straight along strike with only minor curvature. Individual faults within the Brevard zone may exhibit considerable curvature (Fig. XIV-3). Faults flatten at depth and become concave up.

g. Termination along Strike - Cataclasis and retrogressive mylonitization event not recognizable southwest of Horseshoe Bend, Alabama; earlier phase may carry the zone beneath the Coastal Plain to connect with the Towaliga fault. The zone bifurcates at the northern end and is truncated by Triassic faults (Danville basin).

2. Tectonic Setting

Resides in the metamorphic core of the southern Appalachians between two high grade terranes, separating the Piedmont and Blue Ridge geologic provinces (Fig. XIV-1). The Brevard zone is <u>not</u> a suture; the deformational sequence from the Blue Ridge or Piedmont is continuous across the zone (Figs. XIV-4, XIV-5). There is a

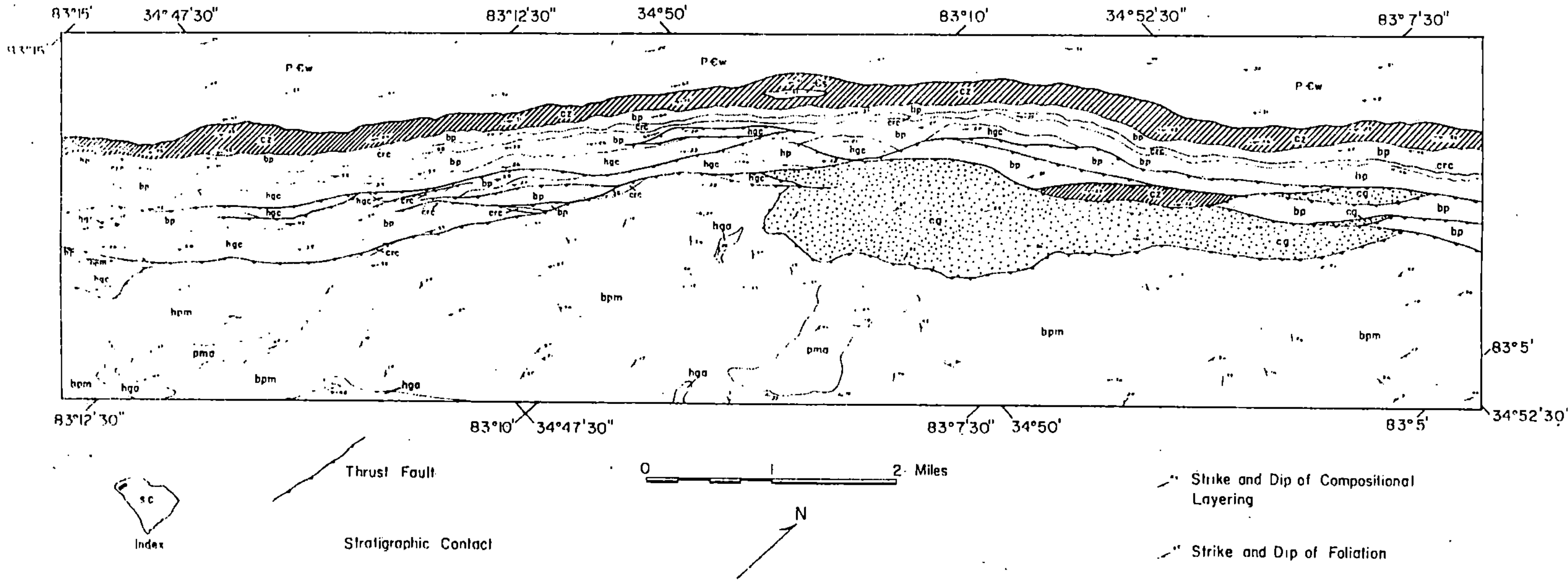


Figure XIV-3. Detailed geologic map of a portion of the Brevard Zone in South Carolina showing the thick cataclastic zone to the northwest, the unbroken belt of Chauga River Formation, the belt of complex faulting on the southeast, and the masses of cataclastic mortar gneiss (cg). P Єw-Whetstone Group metasedimentary rocks, cz-cataclastic zone, Єs-Shady (?) Dolomite slice, bp-Brevard Phyllite Member of the Chauga River Formation, crc-Chauga River Carbonate Member, hgc-cataclastic Henderson Gneiss, bpm-Brevard-Poor Mountain Transitional Member of the Poor Mountain Formation, pma-Poor Mountain Amphibolite Member, hga-Henderson augen gneiss. (East of 87°7'30" the mapping is modified from data supplied the writer by V. S. Griffin, Jr. and P. J. Roper (from Hatcher, 1971).

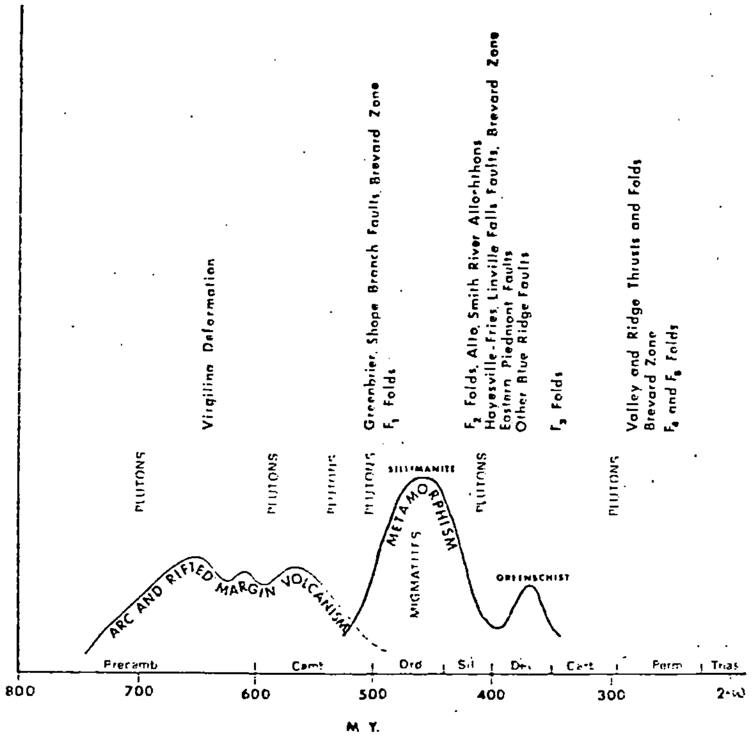


Figure XIV-4. Summary of events affecting the southern Appalachian orogen, compiled from numerous published and unpublished sources. Folding sequence (F_1-F_2) is recognizable in all subdivisions of moderate to high metamorphic grade. Parts of this deformational sequence may be recognized in low grade zones. Carolina slate belt contains a very early deformation (Virginia) that does not survive elsewhere. Metamorphism curve is best applied to high grade zones of Blue Ridge and Inner Piedmont. However, timing of the major peak is reasonably close for most of the orogen (from Hatcher, 1978).

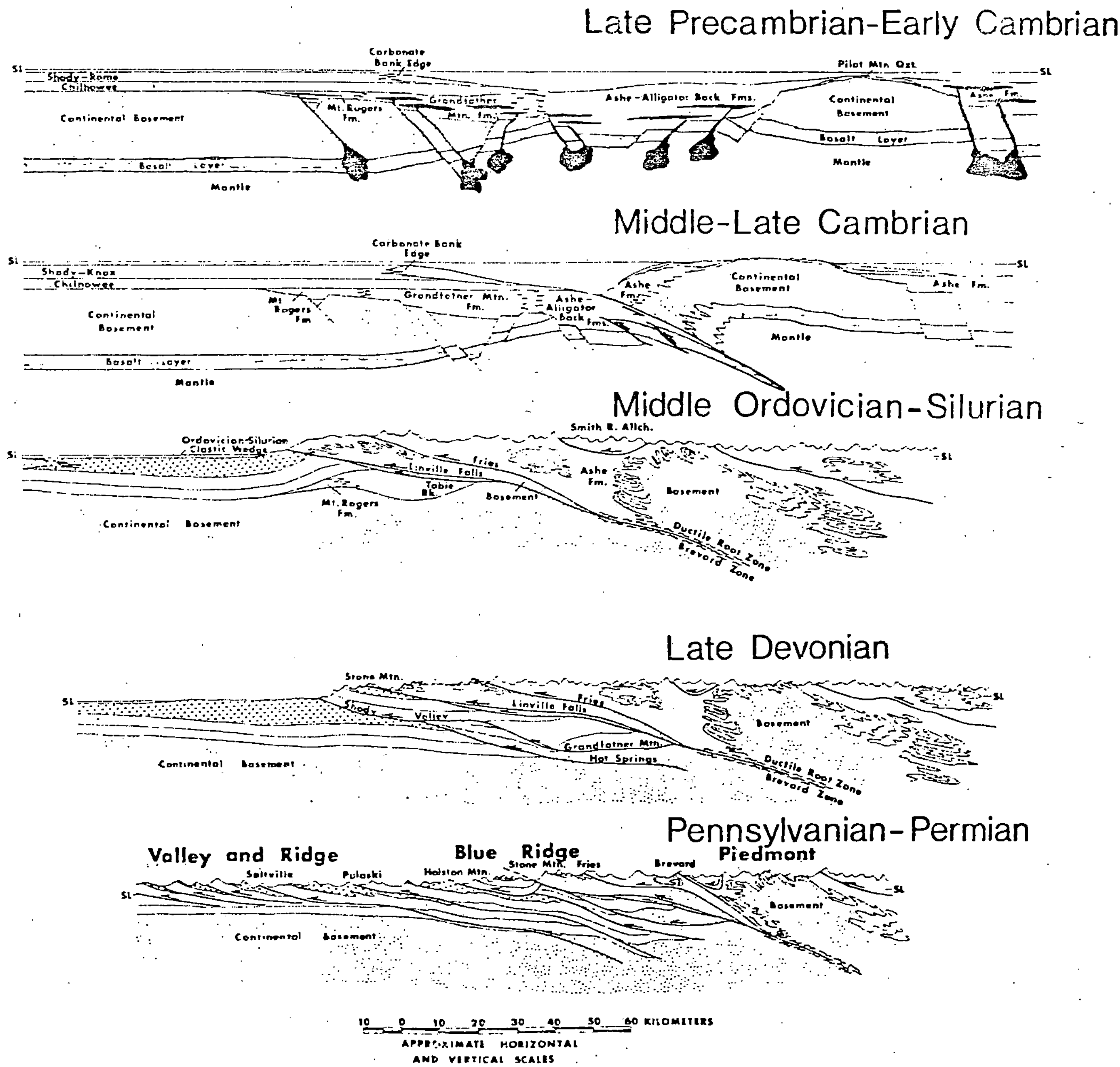


Figure XIV-V. Composite sequential cross sections from the Valley and Ridge into the Inner Piedmont constructed near the present Grandfather Mountain window and including nearby features. Early volcanic rocks are black; granitic plutons are cross-hatched (from Hatcher, 1978).

possibility that similar stratigraphy may be present in both the Blue Ridge and Piedmont across the Brevard zone.

3. Characteristics of the Fault Surface

   a. Type of Fault - Ductile during early history (Taconic and Acadian), brittle later (Alleghanian).

   b. Surface Texture - Not applicable.

   c. Characteristics of the Zone - Early mylonitic rocks have a fabric which is related to protoliths (mylonite, blastomylonites derived from quartzfeldspathic rocks; phyllonites from micaeous rocks). Cataclastic zones represent no more than 10 percent of the thickness of the Brevard zone and are mostly concentrated along the northwest margin; a few narrower cataclastic zones also may occur within any part of the zone.

   d. Metamorphism and/or Mineralization - Early ductile phases were probably coeval with the Taconic (Sinha and Glover, 1978) and Acadian (Odom and Fullagar, 1973) events. Prograde metamorphism to staurolite/kyanite grade occurred in some portions of the fault zone during Taconic. The Acadian was primarily a greenschist event.

   e. Datable Materials - Whole rock studies have been made of mylonites (Odom and Fullagar, 1973) from the Brevard zone, and zircons have also been separated from the mylonites to attempt to resolve some of the early movement history (Sinha and Glover, 1978). Cross-cutting Mesozoic diabase dikes provide a minimum age.

4. Relationships to Country Rock

a. Parallel or Across Regional Grain - The Brevard zone is parallel on any scale, except on the microscopic scale, to the regional grain. Overprinting of S-surfaces may be better observed microscopically (Roper and Dunn, 1973).

b. Promontories or Embayments - The Brevard zone is best developed in the Tennessee embayment.

c. Thick-skinned or Thin-skinned - The Brevard zone involves a thick slab of crystalline rocks of subcrustal dimensions, yet its faults may be related to stratigraphy. Roper and Dunn (1970) presented a thin-skinned interpretation for the Brevard zone which is in many ways favored by the results of a seismic reflection study (Clark and others, 1978).

d. Relationships to Isopachs - None known.

e. Stratigraphic Interval Affected - Rocks involved in the Brevard zone range from late Precambrian to early Paleozoic with slices of Cambro-Ordovician and possibly Grenville basement rocks. Associated igneous units indirectly involved may be as young as Silurian (Lemmon, 1973).

f. Relationship to Folds - Mylonitic foliation is axial planar to Taconic and Acadian folds but is deformed by younger more open folds. Fault terminations in some cases are in the vicinity of broad folds but may not be related in time.

g. Relationship to S-surfaces - Early ductile faulting along the Brevard zone developed subparallel to regional S_2 (and transposes it) but transposed all earlier S-surfaces. Later movement served to transpose initial mylonitic S-surfaces (Roper and Dunn, 1973).

h. Change in Fault Character with Changing Lithology - Protoliths control the character of mylonites and mylonitic foliation but not the orientation (Fig. XIV-2).

i. P-T Conditions - Earliest movement is probably pre-Taconic thermal peak; major movement occurred at staurolite-kyanite conditions, then later during Acadian greenschist conditions, then again under lower to subgreenschist conditions when the brittle event occurred. Isograds indicate a decrease in grade approaching the Brevard zone both from the northwest and southeast, reflecting the synclinal folding of the isograds in the Chauga belt.

j. Relationships to Isograds - movement on Brevard faults occurred both before and after progressive regional Barrovian metamorphism.

k. Relation to Intrusions - Cambrian Henderson Gneiss (535 m.y. Rb/Sr and zircon Odom and Fullagar, 1973; 600 m.y. zircon Pb-Pb Sinha and Glover, 1978) transformed into mylonites. Stirewalt and Dunn (1973) presented evidence that Brevard zone is cut by the Mount Airy Granite in North Carolina. The latter has a mineral-whole rock isochron age of 320 m.y. (Odom, unpublished data).

l. Tectonic Injections - other than documented slices (Hatcher, 1971, 1978), no other tectonic injections have been directly related to Brevard faults. Pseudotachylite veins and masses (Reed and Bryant, 1964) may or may not be related to early history.

5. History

a. Age of Inception - probably Taconic.

b. Recognition of Syndepostional Effects - Not applicable.

c. Radiometric Ages - Rb/Sr whole rock on mylonite 360-350 m.y. (Odom and Fullagar, 1973); K-Ar mineral age ~300 m.y. (Stonebreaker, 1973).

d. Relationships to Unloading - Not applicable.

e. Indicators of Last Motion - Mesozoic diabase dikes cross the Brevard zone at the Grandfather Mountain window and in northeast Georgia. These dikes are not displaced.

6. Stress Field

a. Orientation of Principal Stresses at Inception - The orientation of σ_1 at inception was probably northwest.

b. Magnitudes of Principal Stresses and Strains - Magnitude of both stresses and strains are immense. Total ductile strain on the Brevard zone is probably in the order of hundreds of km. Total brittle strain is probably in the order of 10 km or less.

c. Variation in Time of Stress and Strain - There must have been considerable variation in stress and strain, since the Brevard zone exhibited ductile behavior early in its history (through several movement events) and brittle behavior later (again with several movement events). Orientation may have changed so that at times a strike-slip component of movement may have existed (Reed and Bryant, 1964; Reed, Bryant and Myers, 1970; Higgins and Atkins, in press).

d. Present <u>in situ</u> stress - Measurement of <u>in situ</u> stresses have been made by hydrofracturing in the Toxaway Gneiss immediately northwest of the Brevard zone in South Carolina by Haimson (1975). The orientation determined for σ_1 is N60E. Values for σ_1 = 22.75 MPa, σ_2 = 15.86 MPa, and σ_3 = 6.21 MPa. Schaeffer, <u>et al</u>, (1979), report similar values using the technique of overcoring in the same rock body.

e. Seismic First Motion Studies - Not applicable.

f. Rates of Motion - Both stick-slip and uniform rates of motion probably occurred on the Brevard zone throughout its history.

g. Fluid Pressure Changes and Effects - Retrogressive minerals reflect high fluid pressures during part of the movement history (Acadian younger) of the fault zone.

7. Geophysical and Subsurface Characteristics

a. Seismic Activity - None that can be directly associated with the faults. Some seismic events are located near the fault zone in North Carolina (MacCarthy, 1957).

b. Subsurface Displacements - Seismic reflection studies (Clark et al. 1978; Cook et al. 1979) strongly suggest the Brevard zone is a splay or ramp of the Blue Ridge sole.

c. Relationships to Anomalies - The Brevard zone is easily discerned as a narrow linear feature on regional magnetic maps. It also parallels the regional gravity gradient over part of its extent, as pointed out by Odom and Fullagar (1973) and Rankin (1975).

d. Relation to Geophysically Expressed Lineaments - see c. above.

8. Geomorphic Relationships - The Brevard zone exhibits strong geomorphic expression. Mylonites and cataclasites are strong ridge formers, mica-rich phyllonites form valleys or benches on spurs. However, the topographic lineament that is associated with the Brevard zone in some areas of North and South Carolina actually resides to the northwest of it in parts of northeast and western Georgia. This has prompted some geologists to conclude that there is no displacement

on the faults of the Brevard zone (see for example, Medlin and Crawford, 1973).

9. Methods of Identification

   a. Physiographic Expression

   b. Broad zone of mylonitic and cataclastic rocks

   c. Distinctive but not completely unique stratigraphy

   d. Continuity along strike

10. Pitfalls in Identification

   a. Assuming that the topographic lineament and the fault zones are always coincident.

   b. Multiple age of motion and change in character along strike.

   c. Button schists do not always indicate mylonite zones. They may be formed by in other environments, e.g., an environment of pure shear in which there is superposition of two S-surface at a low angle.

   d. Considering the Brevard zone outside of its regional context as a unique entity.

   e. Assuming that motion has to end before Mesozoic dikes were emplaced.

   f. Assuming the Brevard zone must extend down to the mantle or is a crustal feature (that great length means great depth).

   g. Misinterpretation of small-scale structures.

11. Possibilities of Reactivation - Generally slight, except for where cataclastic rocks exist.

12. Selected Reference List

Bentley and Neathery (1970)

Hatcher (1971, 1977, 1978)

Odom and Fullagar (1973)

Rankin (1975)

Reed and Bryant (1964)

Roper and Dunn (1973)

Roper and Justus (1973)

Stirewalt and Dunn (1973)

RAMAPO FAULT SYSTEM

1) Basic Geometry

a) Strike length - The Ramapo fault proper extends approximately 80 km from Stoney Point on the Hudson River to Peapack, New Jersey (Fig. XIV-6). The fault system may extend 18 km northeast into the Hudson Highlands where it may be traced into Canopus Hollow Fault system, Dennytown fault and Peekskill Hollow fault (Fig. XIV-7). Individual faults in the Ramapo fault system include the Thiells fault, Cedar Flats fault, Ambreys Pond fault, Timp Pass fault, Blanchard Road fault, Willow Grove fault, Bald Mountain fault, Buckberg Mountain fault, Letchworth fault, and Mott Farm Road fault.

b) Width perpendicular to strike - The Ramapo fault occupies a zone less than 100 m wide; but parallel faults near the northeastern end of the system spread over a zone up to 4 km wide.

c) Spatial orientation - The northeast trending Ramapo system is subparallel to the regional grain of the central and northern Appalachian Mountain system. Locally the Paleozoic folding of the Manhattan Prong is truncated by the Ramapo fault.

d) Displacement - As many as seven (7) stages of displacement have been distinguished by either Ratcliffe (1971) or the Dames and Moore report for Consolidated Edison of New York (1977).[1] Starting with the oldest stages of faulting are represented by:

Stage 1) Cataclasis of rocks during the Grenville orogeny broadly synchronous with the intrusion of local diorite and monzonite rocks of the Canopus pluton.

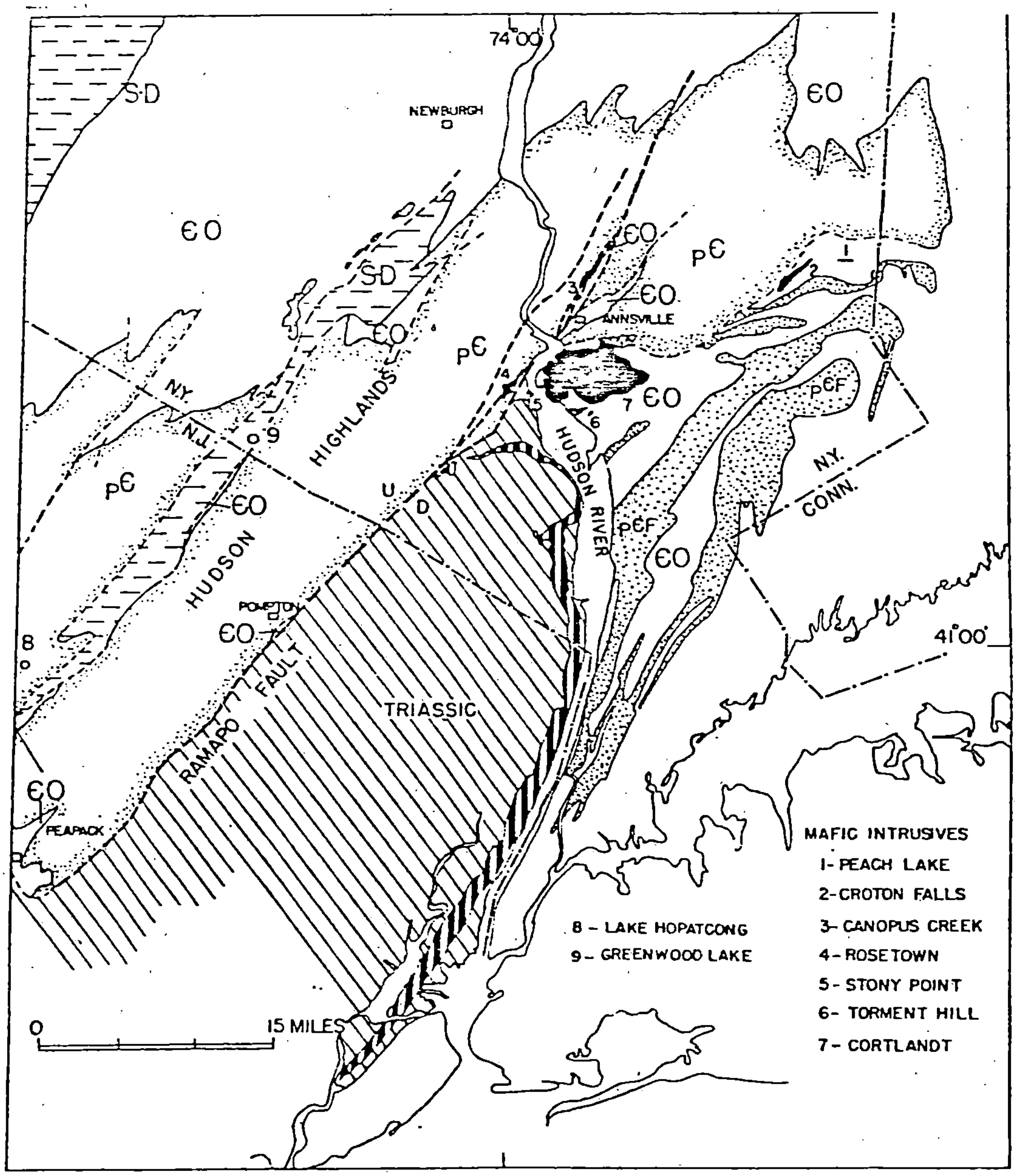
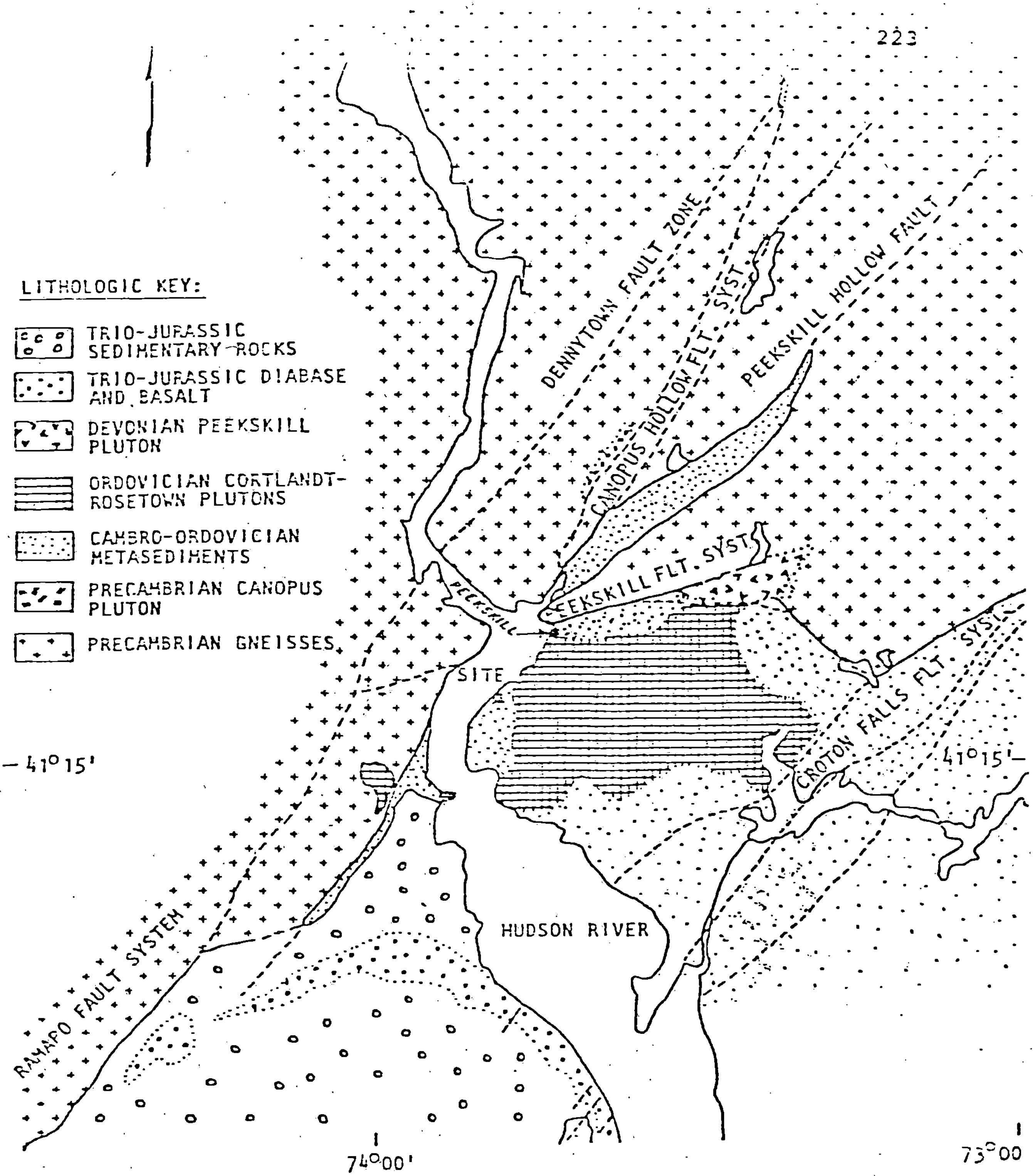


Figure XIV-6. Regional geologic map showing the northern end of the Newark basin, the Ramapo fault and its possible extensions into the Hudson Highlands (Ratcliffe, 1971).



GEOLOGIC MAP OF PEEKSKILL AREA

Figure XIV-7. Northern end of Ramapo fault system where it splays into several faults in the Hudson Highlands.

Stage 2) Late Precambrian phase of cataclasis marked by reutilization of the older Grenville fault zones. Amount of displacement for stages 1 and 2 unknown (Fig. XIV-8).

Stage 3) Block faulting of early Ordovician age with normal displacement 1000 - 1300 m (Ratcliffe, 1971) Dames and Moore (1977)[1] interpret this stage as one of high-angle reverse faulting in which imbricate slices of Paleozoic metasediments are preserved as inliers between upfaulted blocks of Precambrian gneiss.

Stage 4) Ordovician right-lateral strike-slip faulting utilized and cross-cut the earlier Ordovician faults. Evidence from the Canopus Hollow fault system shows 3 km of slip (Ratcliffe, 1971).

Stage 5) Ratcliffe (1971) recognizes a stage of early Mesozoic block faulting with up to 200 meters of throw.

Stage 6) Northeast left-lateral strike-slip faulting occurred during and after the sedimentation and lithification of the Newark strata and the emplacement and cooling of the Tria-Jurassic diabase and basalt.

Stage 7) Seismicity has been used to derive fault-plane solutions indicating high-angle reverse faulting on faults related to the Ramapo fault system (Aggarwal and Sykes, 1978). A differing interpretation is given by the Dames and Moore report (see section 6 e).

e) Continuity - The system is easily traceable through its entire length. Individual displacement events cannot be documented throughout its length, but are found only locally.

f) Curvature - In general, the system is straight as traced on the scale of 1:2,500,000. However, the northern end of the fault system splays. Individual faults such as the Timp Pass fault exhibit curved

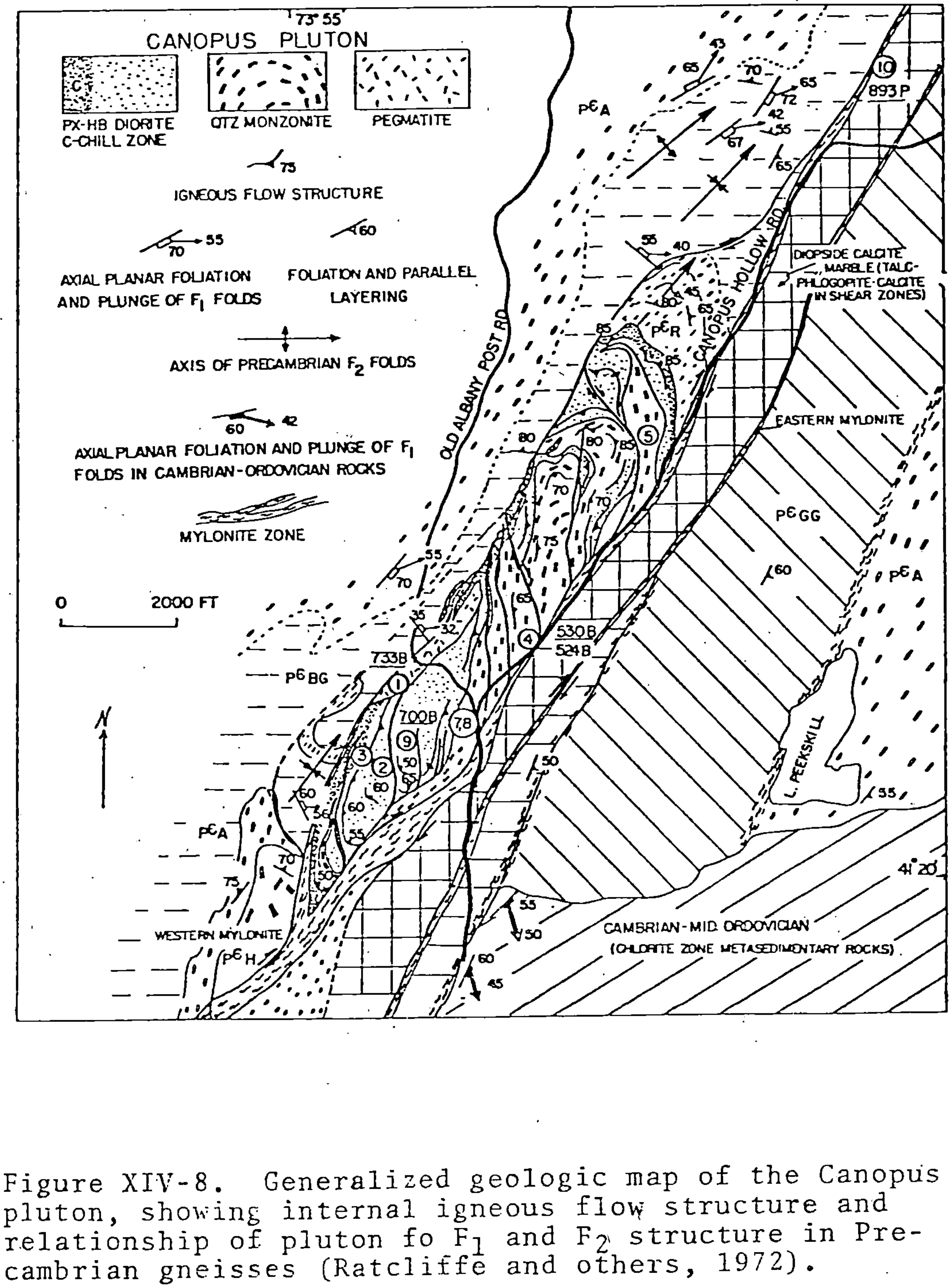


Figure XIV-8. Generalized geologic map of the Canopus pluton, showing internal igneous flow structure and relationship of pluton fo F_1 and F_2 structure in Precambrian gneisses (Ratcliffe and others, 1972).

surfaces. Little is known about down-dip curvature.

g) Termination along strike - On the northern end the Ramapo system divides into several Paleozoic strike-slip faults (i.e., the Canopus Hollow, Annville, and Timp Pass faults) (Figs. XIV-7 and XIV-9). On the southwestern end the outcrop dips beneath the Mesozoic sediments of the Newark basin. Present patterns of seismicity also suggest that the Ramapo system may be complicated or associated with other faults in the Hudson Highlands.

2) Tectonic Setting

The fault system is presently located at the southeastern boundary of the Hudson Highlands and northwestern side of the Triassic Newark Basin. The tectonic significance of early Ordovician block-faulting and mid-Ordovician strike-slip faulting is unclear. The Mesozoic block faulting is related to the early stages of the opening of the present Atlantic Ocean. The left-lateral episode of faulting probably also represents the effects of on-going rifting in the central portion of the Appalachian orogen during the Mesozoic.

3) Characteristics of Fault Surface or Zone

Grenvillian Faults (Stage 1) - These are characterized by cataclasis broadly synchronous with the intrusion of local pegmatites and diorite-monzonite rocks of the Canopus pluton. Ductile deformation during the Grenville orogeny recrystallized and healed these cataclastic fault zones (Dames and Moore, 1977)[1].

Post-Grenville Precambrian Faults (Stage 2) - Recurrent fault movements in the Canopus fault zone granulated and altered both plutonic and country rocks during late Precambrian time. The altered rocks have mineral assemblages indicative of temperature-pressure regimes below hornblende granulite facies. Sinistral folds in altered mylonite

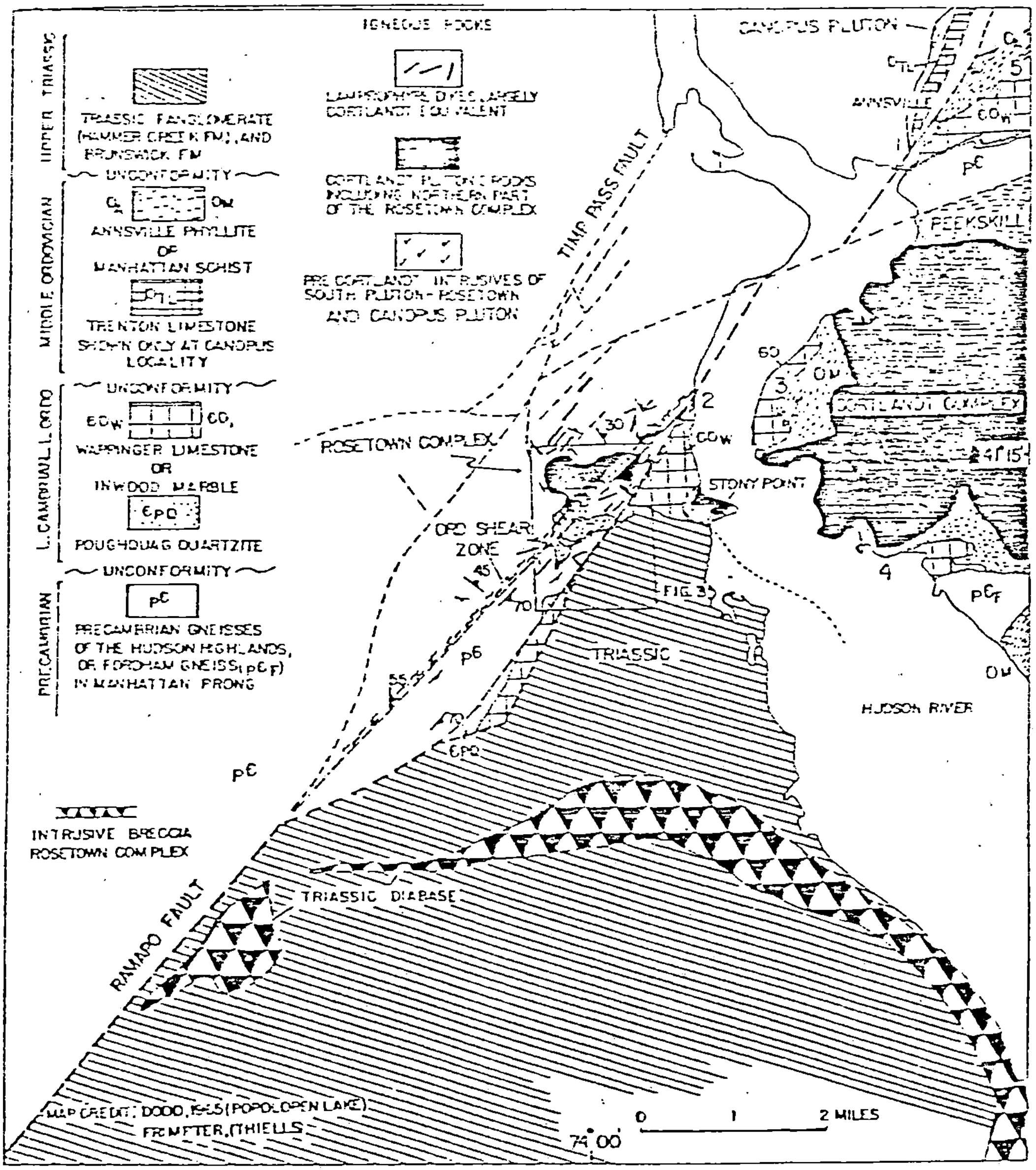


Figure XIV-9. Generalized geologic map showing northern termination of Ramapo Fault system. Heavy lines signify faults of the Ramapo fault system; fine dashed lines other high-angle faults in the Hudson Highlands (Ratcliffe, 1971).

along the Canopus pluton, suggest an episode of post-Grenvillian sinistral strike-slip faulting.

Lower Ordovician Faulting (Stage 3) - Because this stage is inferred from stratigraphic evidence little can be said about the characteristics of the fault surface. Part of this stage is preserved as inliers of Paleozoic metasediments between uplifted blocks of Precambrian gneiss. Well developed quartz-filled gash veins indicate reverse motion along the Canopus Hollow fault. Occasional slickensides are seen along the Annsville fault, indicating predominantly dip-slip motion.

Ordovician Strike-Slip Faulting (Stage 4) - The Canopus fault exhibits strike-slip shearing of mylonite with some gouge present. Likewise, the Peekskill Hollow fault shows sheared mylonite with strike-slip motion. Some of the strike-slip motion may be dated because the faulting was active during the intrusion of the Cortlandt complex (Fig. XIV-9).

Early Mesozoic Block Faulting (Stage 5) - Both slickensides and fibrous growths cover fault surfaces, indicating normal faulting. (See Appendix for pitfalls in identification of fibrous slickensides.)

Mesozoic Strike-Slip Faulting (Stage 6) - Many faults in the Ramapo system contain such materials as open-work breccia, slickenside surfaces, shear fractures. Well-formed sprays of zeolite crystals are present along several faults of this age. Some zones of zeolite mineralization are smeared. Other mineralization includes quartz, calcite, stilbite and chlorite.

Recent Seismic Events (Stage 7) - Not applicable.

4) Relationship to Country Rocks

a) Parallel or Across Grain - The Ramapo fault system is parallel to regional grain except at northern termination.

b) Promentory or Embayments - Located in the New York promonitory.

c) Thick-skinned or Thin-skinned - The Ramapo Faults cuts basement and is , therefore, thick-skinned.

d) Relation to isopachs - The Ramapo fault system controls mid-Ordovician and early Mesozoic depositional centers.

e) Stratigraphic Interval Affected - Stratigraphic interval affected by the Ramapo fault system is Precambrian to Mesozoic.

f) Relationship to Folds - Not applicable.

g) Relationship to S-surfaces - In the fault zone mylonite foliation parallels the fault zones.

h) Change in Fault Character with Changing Lithology - Fault character varies in a complicated manner depending on both lithology and age of faulting.

i) P-T Conditions - Precambrian faulting occurred in rocks at the granulite facies. Later stages of faulting occurred at lower metamorphic grade.

j) Relation to Isograds - Acadian isograds superimposed on the northern end of the fault zone. Mesozoic faulting cuts the isograds (Fig. XIV-10).

k) Relation to Intrusions - Precambrian intrusions along the Canopus fault zone are dated at 1061 ± 12 m.y. The Cortlandt complex was intruded during the Ordovician and subsequently cut by the Ramapo fault zone. The Rosetown plutons, lamprophyre dike swarms, the Peekskill granite, the Peach Lake intrusive and Croton Falls complex were emplaced along various fault zones and ages ranging from 435 m.y.

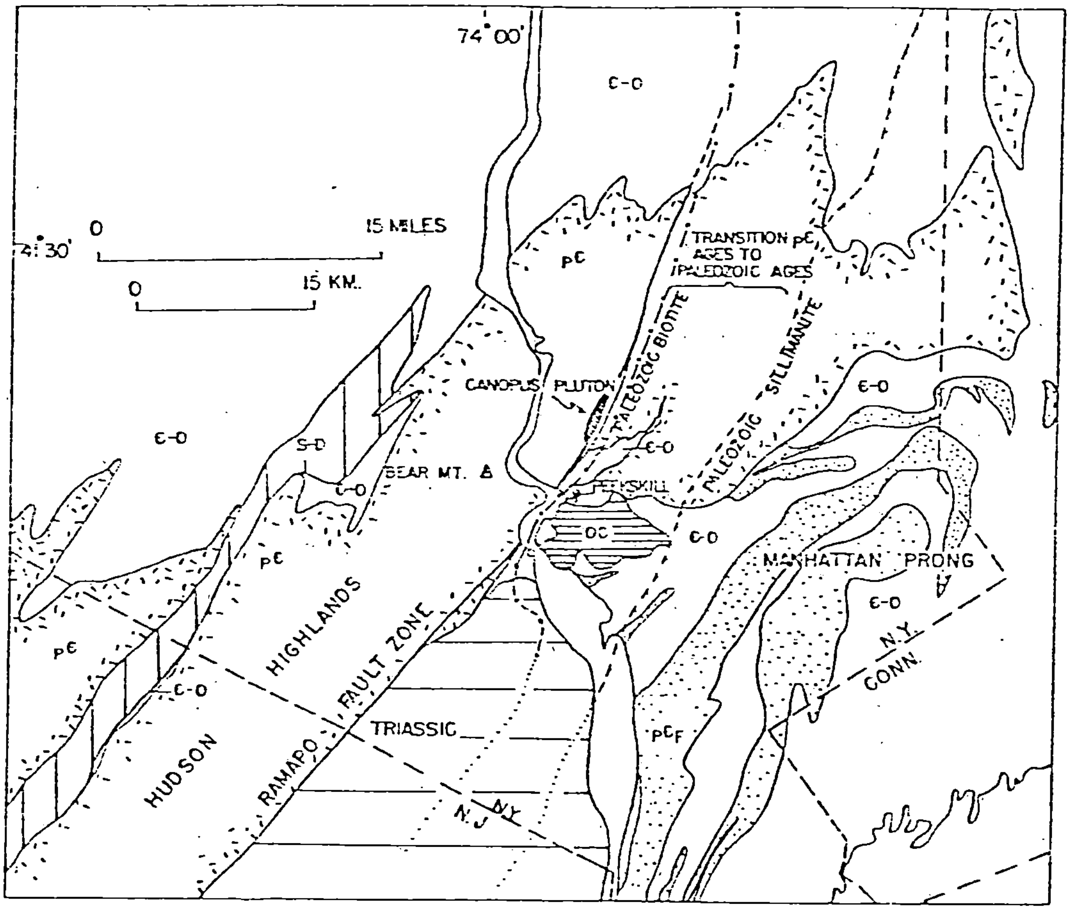


Figure XIV-10. Generalized geologic map showing location of Canopus pluton and Ramapo fault. Paleozoic isograds of biotite and sillimanite are shown extrapolated across Hudson Highlands (Ratcliffe and others, 1972).

to 371 m.y.

l) Relation to Tectonic Injections - Not applicable.

5) History

a) Age of inception - Precambrian

b) Syndepositional effects - mid-Ordovician and Mesozoic localized depositional centers.

c) Radiometric ages - Various intrusions were emplaced along the fault zones. The ages of these rocks range from 435 m.y. to 371 m.y. Mesozoic minerals give a minimum date of last movement in the Mesozoic of 73 m.y.

d) Relation to erosional unloading - Unknown.

e) Last motion - Seismicity along the fault zones has been interpreted to indicate that the Ramapo system is still active (Fig. XIV-11) (see section 6 e).

6) Stress Field

a) Orientation of stress at inception - Unknown

b) Magnitude of stresses - Based on U.S. Bureau of Mines gauge measurements the maximum horizontal compressive stress ranges from 20 to 100 bars oriented in a northeastern direction (Dames and Moore, 1977)

c) Variation through time - Complicated in order to accomodate several faulting modes.

d) Present in situ stress - See b.

e) Seismic first-motion studies - Aggarwal and Sykes (1978) show that modern seismicity is in response to a northwestern maximum compressive stress (Fig. XIV-11). Dames and Moore[1] offers an alternative interpretation for the same earthquakes

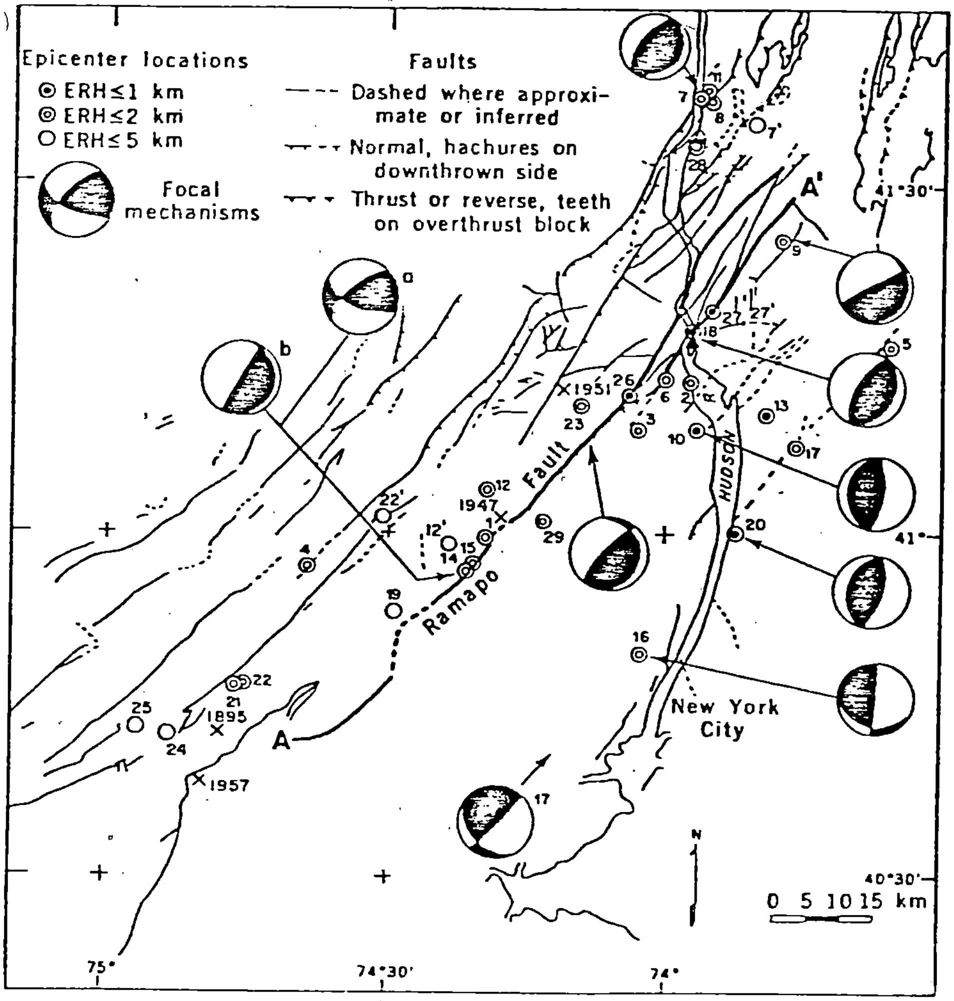


Figure XIV-11. Fault map of southeastern New York and northern New Jersey showing epicenters (circles) of instrumentally located earthquakes from 1962 through 1977. Indicated uncertainties (ERH) in epicentral locations represent approximately two standard deviations. Focal mechanism solutions are upper-hemisphere plots; the dark area represents the compressional quadrant. For event 14 there are two possible focal mechanism solutions: the data, however, are more consistent with solution b than a. The Ramapo fault and two of its major branches (A-A') are shown by the heavy lines. The solid triangle shows the location of the Indian Point nuclear power reactors (Aggarwal and Sykes, 1978).

f) Rates of motion - Unknown.

g) Fluid pressure changes - Unknown.

7) Geophysical and Subsurface Characteristics

a) Seismic activity level - Aggarwal and Sykes (1978) report several earthquakes near the Ramapo system within the past 5 years.

b) Subsurface displacement - Unknown.

c) Relation to anomalies and lineaments - Four sets of aeromagnetic lineaments were defined. Angular intersections and cross-cutting relationships between these sets support the geologic conclusion that a period of right-lateral movement preceded a period of left-lateral movement (Dames and Moore, 1977).

8) Geomorphic Relations

The Ramapo fault system forms the boundary between the Newark-Gettysburg Basin and the Hudson Highlands. There is a distinct scarp at the fault between these two geological provinces with the Hudson Highlands standing high. In the Newark Basin some of the Mesozoic faults parallel to the Ramapo cut a regular drainage pattern.

9) Methods of Identification - See individual classes of faults including strike-slip faulting and block faulting.

10) Pitfalls in Identification - See individual classes of faults including strike-slip faulting and block faulting.

11) Possibility of Re-Activation - Modern seismicity in the vicinity of the Ramapo fault system indicates that the eventual reactivation of the fault zone is possible.

1 Geotechnical Investigation of the Ramapo Fault System in the Region of the Indian Point Generating Station, prepared by Dames and Moore for Consolidated Edison, Vol. I March 28, 1977. Document available in Public Doc. Rm, U.S.N.R.C., 1717 H Street NW, Washington, D.C.

XV

GROUP II: STRUCTURAL LINEAMENTS

A. Generalized Description

Structural lineaments represent perhaps the most controversial class of large structural discontinuities and consist of a complex of structures arranged in linear belts of varying widths and lengths. The structures within the lineaments run the gamut from igneous intrusions, faulting, fracturing, fold plunge outs to photo lineaments; they may have geophysical and stratigraphic expression as well.

These features have been variously described as lineaments, fracture zones, and linears. The term structural lineament (SL) has been chosen as the general term for these features following suggestions by R. L. Wheeler (personal communication, 1980), who has done the most comprehensive documentation of these features (Wheeler, 1978a, 1978b, 1979; Wheeler et al., 1979). It is on the basis of this work that the various subgroups proposed herein were recognized.

Where studied, the features are frequently found to have very long histories, in some cases extending from the Eocambrian to the present. Some contain regions of present-day seismicity and thus should be treated with caution. Motions on these features are generally complex and are usually described as a region of "flexing" or "jostling". Some of the structures show evidence of basement involvement in either an active or passive mode (i.e., simply reflecting basement "roughness" vs. basement motion). Other structural lineaments are thin-skinned, and appear to be associated with regions where detachments cut up section at a large angle to strike.

1. Possible Subgroups

   a) Basement controlled

      i. Active SL s (Fig. XV-1) formed by any type of motion which is seated in the crust.

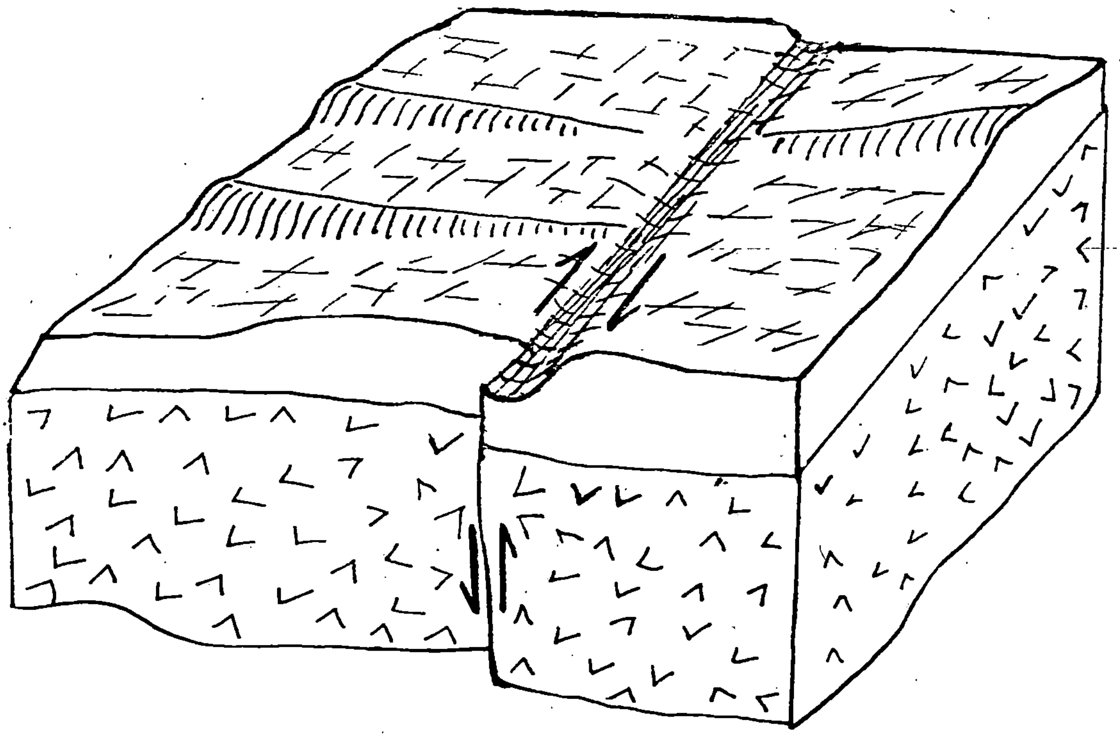


Figure XV-1 Active structural lineament formed by motion seated in the crust.

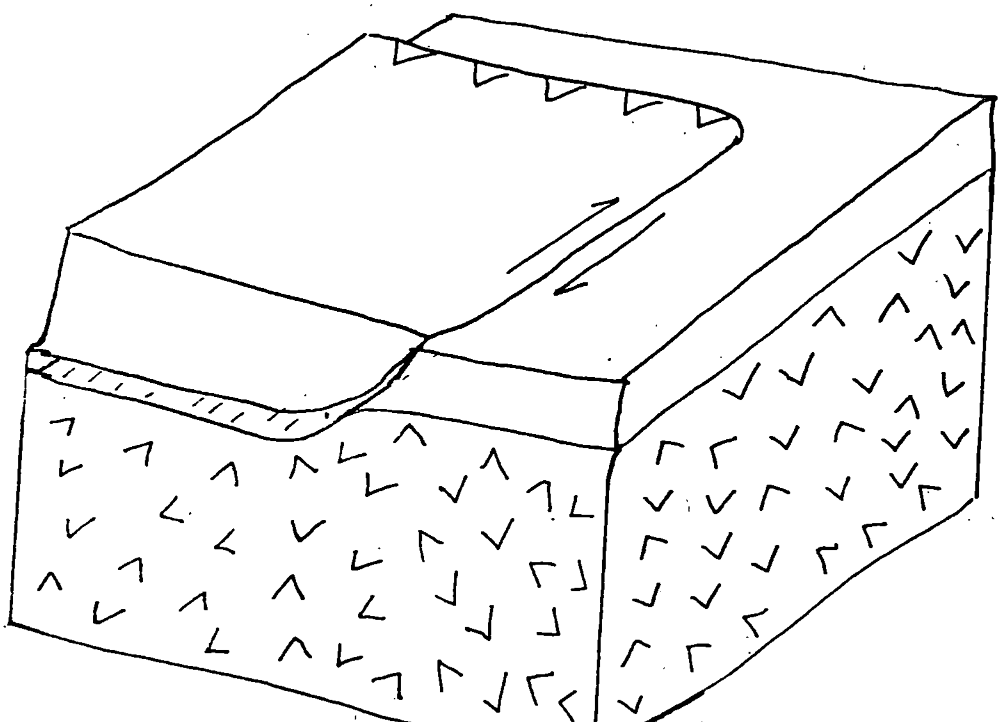


Figure XV-2 Passive structural lineament showing basement control of thrust boundary.

ii. Passive: (Fig. XV-2) SL s formed by interference or control by inactive irregularities in the basement, e.g., a fault controlling facies distribution which in turn controls thrust boundaries.

b. Supra-crustal (Fig. XV-3) This subgroup of structural lineaments has been termed cross-strike structural discontinuities (CSD) by Wheeler, et al. (1979). CSD s are restricted by Wheeler to foreland thrust-fold terranes where they are controlled by discontinuities in thin-skinned structures, e.g., tear fault at depth, boundary of "keystone" structure (Engelder, 1979, Fig. 5).

2. Typical examples

a. 38th parallel lineament; active, basement controlled.

b. Petersburg and Parsons CSD (Sites, 1978; Dixon and Wilson, 1979).

c. Transylvania fault (Root and Hoskins, 1977); active, basement controlled.

B. Description of Fault Group

1. Basic Geometry

a. Strike length - Map scale, varying from a few kilometers to over 1000.

b. Length perpendicular to strike - The discontinuities are thin relative to length. Widths are generally proportional to length and vary from a few 100 meters to up to 80 km.

c. Orientation - The structures occur at a large acute angle to the regional strike. Present knowledge indicates that the active SL s have strikes close to 090 (except see Clarendon-Linden fault, Hutchinson et al., 1979), while the supracrustal CSD's seem to occur within 20° - 30° of the normal to

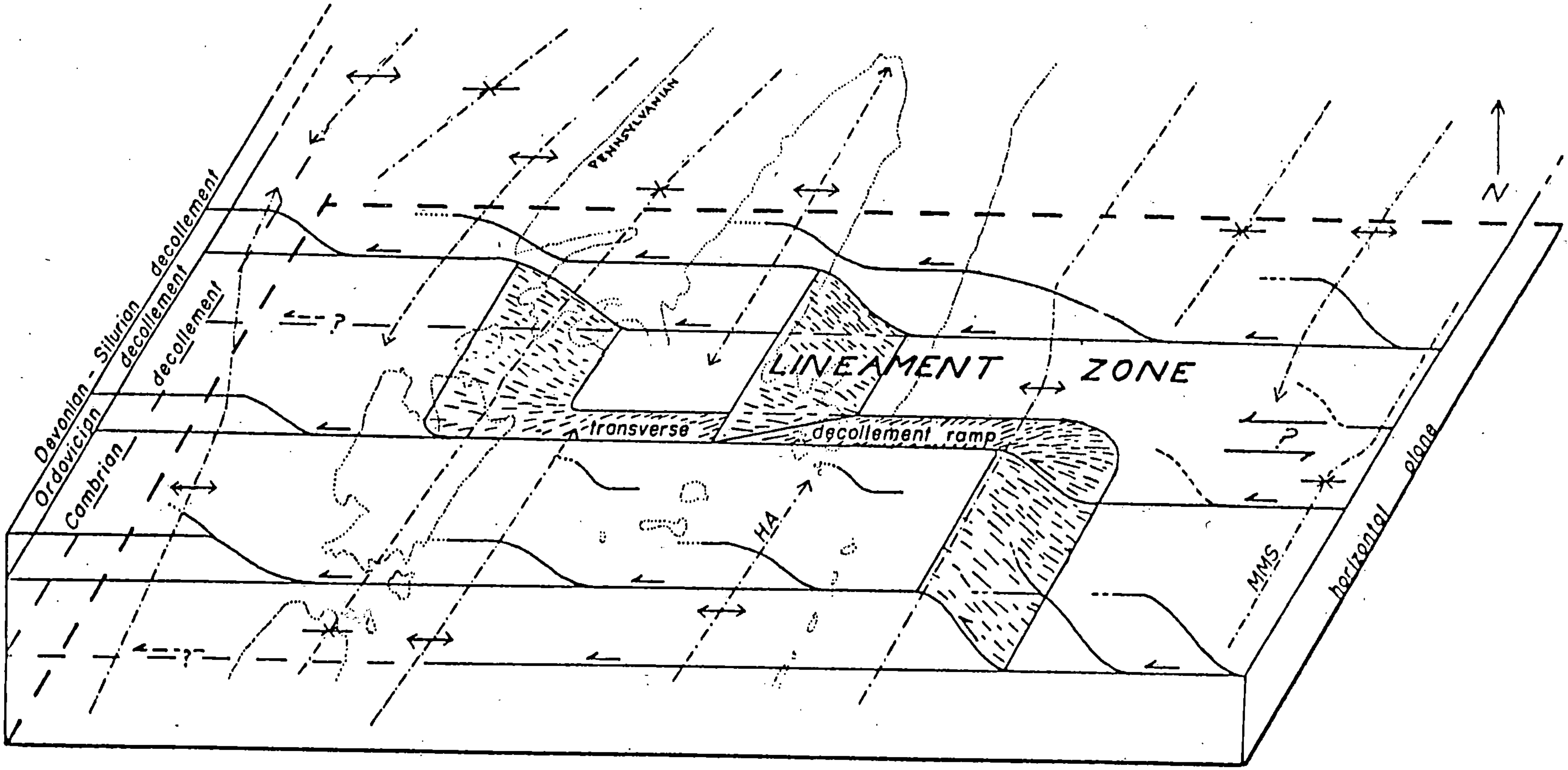


Figure XV-3 Supra-crustal structural lineaments controlled by discontinuities in thin-skinned structure. (Kulander and Dean, 1978).

the regional strike (e.g., Wheeler *et al.*, 1979).

d. Displacement - Supracrustal displacements occur only on individual faults within the SL. Displácements are small, varying from a few meters to several hundred (rare). Displacements are characteristically mixed, i.e., both normal as well as strike-slip motions, and lack any consistent pattern.

e. Continuity - The SL s do not have a well developed continuity, as they consist of an assemblage of structures of which any one or more may define the zone at any given locality. Since there is variation in both the intensity of development as well as the particular set of structures which forms the lineament, the surface continuity is generally poor.

f. Termination along strike - Almost nothing is known about the mode of termination, other than the zones of disturbance simply can no longer be found.

2. Tectonic Setting - Basement controlled SL s may extend across the entire fold belt and deep into the craton (e.g., 38th parallel lineament). The supra-crustal SL s are recognized most readily in the Plateau and rarely cross into the Valley and Ridge.

3. Characteristics of Zone (see Appendix B) - The SL s are characterized by one or more of the following: a) An increase in the intensity of development of a structure or set of structures, generally jointing or faulting, in a zone at a high angle to the tectonic grain. Examples: Transylvania fault zone (Root and Hoskins, 1977); Parsons lineament (Dixon and Wilson, 1979); b) Termination or change in trend of some structure or structural elements, e.g., fold plunge outs, strike disruptions. Example: Petersburg lineament (Sites, 1978); c) Belts of igneous activity, facies and thickness changes across the zone. Example: 38th Parallel lineament (Heyl, 1972).

4. Relation to Country Rock

a) SL s are most easily recognized when they occur at a large angle to the regional grain. However, this relationship may be an artifact of the difficulty in recognizing a SL which is parallel to the regional grain, since much of the basis for recognition is founded on the transverse disruption of the regional trends. The possibility that there are SL s approximately parallel to the regional trend is suggested by a magnetic and gravity lineament described by King and Zietz (1977) which parallels the Appalachian orogen along its western border. To date, no structural expression of this feature has been recognized.

b) There is no direct relation to embayments or promontories. However, the two most prominent SL s, the 38th and 40th Parallel lineaments are located at the changes of regional trend which mark the Virginia Promontory and the New York Embayment.

c) Only a tentative statement can be made regarding the extent of crustal involvement; however, the evidence thus far suggests an ultimate thick-skinned origin, although the immediate expression is thin-skinned as in the transverse step ups (Fig. XV-3) suggested by Kulander and Dean (1978).

d) Isopach changes are known across the major lineaments in the Appalachians (Dennison and Johnson, 1971).

e) Basement controlled SL s

1. Active: All stratigraphic intervals should be affected, although the type and amount of effect will probably change with the interval, reflecting the variable nature of the activity through time.

2. Passive: All stratigraphic intervals should be affected if the lineament has been a site of subsequent motion; however, sedimentologic effects should be restricted to the basal units.

3. Supra-crustal SL s: Only those units above the detachment should be affected.

f) Folds may terminate or change abundance, size, shape or orientation across or within lineaments.

g) No effect on "s" surfaces is presently known.

h) The effect of lithology changes on the lineaments is not currently known.

i) The lineaments are independent of variations in P-T conditions.

j) The lineaments bear no relationship to isograds.

k) Major lineaments, such as the 38th parallel, contain belts of intrusives which parallel the lineament.

l) Not applicable.

5. History

a) The age of the SL s probably varies from structure to structure. In general, basement controlled SL s should be oldest since supra-crustal SL s can be no older than the deformation of the Appalachian foreland, whereas the basement controlled structures may be as old as the final consolidation of the Precambrian basement. For example, evidence has been presented by Dennison and Johnson (1971) that activity on the 38th Parallel Lineament dates to the early Paleozoic and is possibly older.

b) Studies of syndepositional effects have been used to establish the history of major SL s.

c) No studies of radiometric ages are known from any SL.

d) Not applicable.

e. First motion studies are not relevant for entire CSD's, since their motion is highly complicated; however, individual faults within them may have potential as sites of present day seismicity (e.g., Fletcher and Sykes, 1977; Fletcher et al., 1978).

6. Stress Field

Virtually nothing is known about the nature of the stress field associated with SL s.

7. Geophysical and Subsurface Characteristics

a. Basement controlled SL s may be sites of relatively high seismic activity. The New Madrid earthquake site lies on the 38th Parallel Lineament, while Fletcher et al. (1978) show evidence that it remains a belt of seismic activity.

b. Subsurface displacements have not been well documented, but are implied by the presence of facies and isopach changes associated with the major lineaments.

c. Gravity and magnetic anomalies are sometimes associated with the SL s. The anomaly trends may either parallel the SL s or be disrupted by it. For example, the Petersburg Lineament is marked by a gravity low which follows the lineament crossing a set of gravity highs attributed to imbricate thrust stacks in anticlines which plunge out along the lineament (Kulander and Dean, 1978).

8. Geomorphic Relations

Numerous geomorphic effects have been noted along SL s; primarily these are such phenomena as Ridge offsets, water and wind gaps and drainage anomalies. Anomalous topographic grain has also been noted, generally due to an increase in stream density (example, Parsons Lineament, Holland, 1976).

9. Methods of Identification: Since SL s are a complex of features, adequate documentation of their presence requires detailed geologic mapping of the variety of features which characterize them (see Section 3) as well as thorough statistical analysis of the data (e.g., Holland and Wheeler, 1977). Although frequently visible on LANDSAT or aerial photographs, not all SL s are. Geologic maps sometimes show SL s which have little or no expression on photographs or topographic maps. Unfortunately, there exists no generally accepted methodology for rapid mapping of SL s, largely due to a lack of sufficient understanding as to the precise nature of the structures.

10. Pitfalls in Identification: The principal pitfalls lie in an overenthusiastic use of aerial photographs and LANDSAT imagery, where a tendency develops to generate enormous families of spurious alignments (see Appendix D). An additional problem is a failure to consider that the zones are highly complex features; consequently a field study of only a few of the many possible manifestations of the phenomena may produce false negative results.

11. Possibility of Reactivation: Faults within a SL should be treated with suspicion, as a number of SL s are known to be seismically active. SL s also have long histories of activity; consequently reactivation of structures within the SL should be considered a possibility and studies should be made to judge its capability.

CHAPTER XVI

GROUP 12 FAULTS: FAULTS ASSOCIATED WITH LOCAL CENTERS

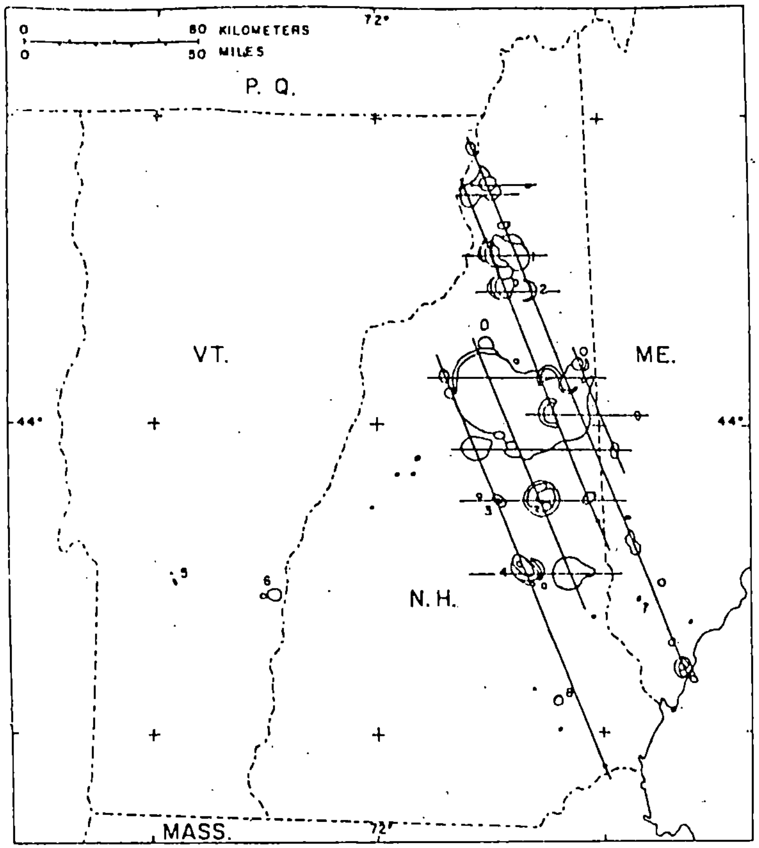
Several classes of structures forming small local disturbances have faulting associated with their origins. In addition, there is some circumstantial evidence linking some members of these groups to modern seismic activity. These associations include two of the most destructive earthquakes of eastern U.S. possibly localized near small plate plutonic bodies (Charleston and Cape Ann). A second class of possible quake-related structures includes meteorite impact or crypto-explosion structures. In terms of overall Appalachian tectonics, these two classes of structures are of minor importance but in terms of seismic risk analyses, they deserve proportionally much more serious consideration.

FAULTS ASSOCIATED WITH LOCAL INTRUSIVE CENTERS

Small intrusive bodies of late or post-metamorphic age commonly have faulting associated with their emplacement. They are also included in the list of prime suspects for the localization of present-day major seismic events (Sykes, 1978).

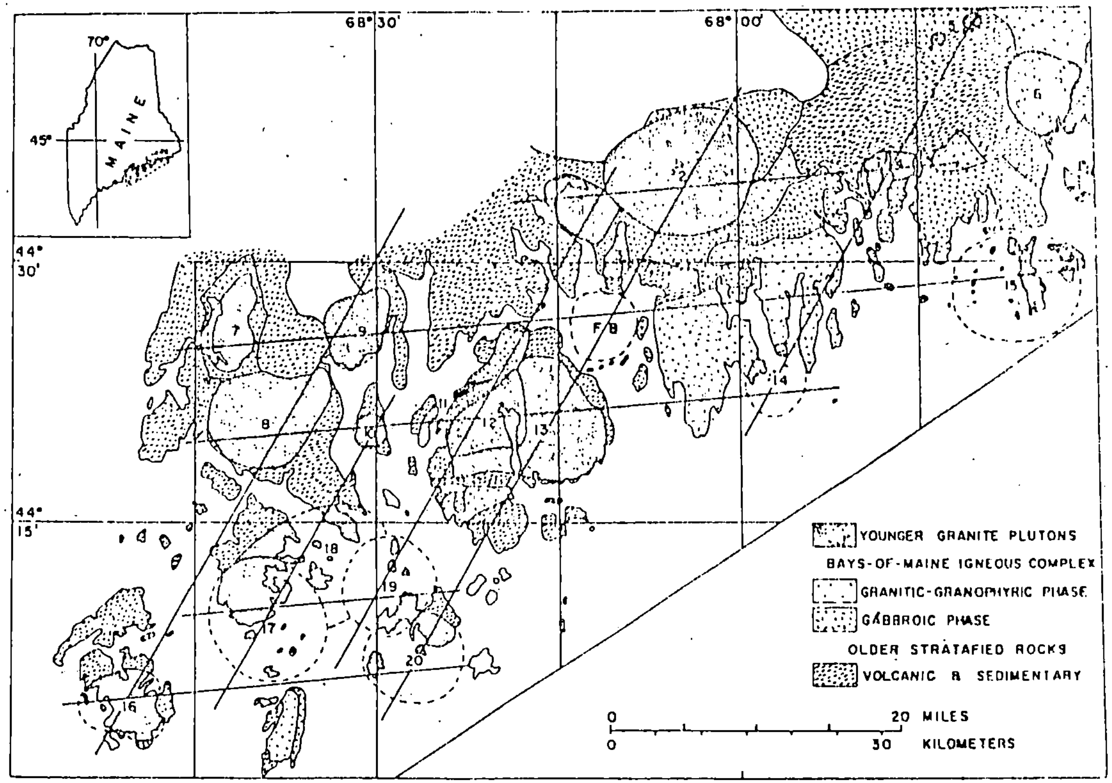
Best known of the late to post-metamorphic intrusive bodies is the White Mountain line of Jurassic and Cretaceous ring dikes and intrusives trending NNW across New England. A second series of analogous bodies is the group of Paleozoic coastal plutons of Maine. Both sets of intrusions may have been localized by regional fractures and have had subsidence faulting associated with their emplacement.

Chapman (1968) notes reticulate arrangement of the coastal plutons of Maine with dominant directions NNE and EW (Fig. XVI-1). He notes that the country rock near the granitic contacts appears to be dragged downward with severe shattering and brecciation. Some of the shattered zones are up to



(a)

Distribution of the White Mountain magma series. 1, Percy complex; 2, Pliny complex; 3, Red Hill complex; 4, Belknap Mountain complex; 5, Cuttingsville complex; 6, Ascutney Mountain complex; 7, Lebanon pluton; 8, Pawtuckaway complex. Heavy straight lines—pluton lattice pattern.



(b)

Distribution of the Maine coastal plutons. 1, North Sullivan pluton; 2, Tunk Lake pluton; 3, Sorrento pluton; 4, Harrington pluton; 5, Centerville intrusions (shape poorly known); 6, Jonesboro pluton; 7, South Penobscot pluton; 8, Sedgwick pluton; 9, East Blue Hill Pluton; 10, Long Island pluton; 11, Bartlett Island ring-dike; 12, Somesville pluton; 13, Cadillac Mountain pluton; 14, Corea pluton; 15, Great Wass pluton, 16, Vinalhaven pluton; 17, Stonington pluton; 18, Oak Point pluton; 19, Swans Island pluton; 20, Minturn pluton; FB, Frenchman Bay structural basin, probably formed by subsidence above an unexhumed granitic pluton. Patternless islands—geology not known. Plutons 4 and/or 6 may not belong to the younger granites. Heavy straight lines—pluton lattice pattern.

Figure XVI-1. Possible fracture control of location of White Mountain and coastal Maine plutons. From Chapman (1968).

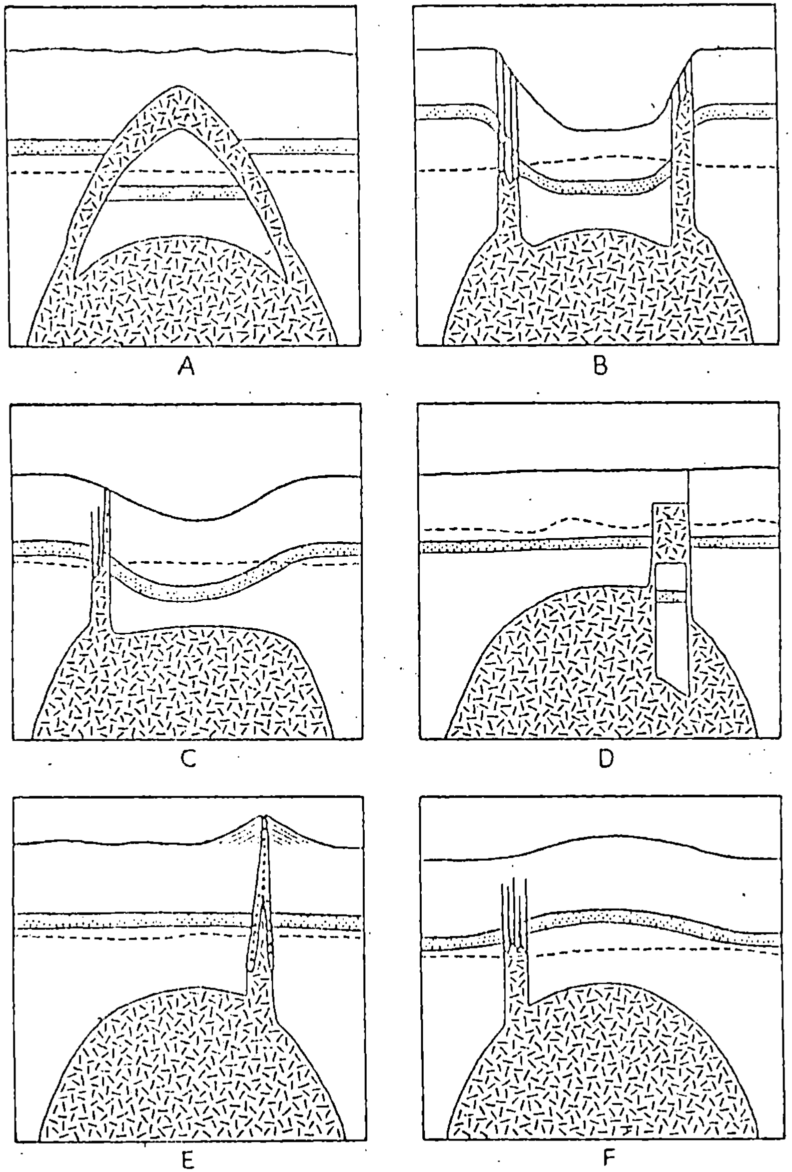
a half mile in width with fracturing increasing toward the contact to culminate in a thoroughly jumbled breccia mass. Blocks of breccia range up to 100 m in diameter, with hornfels and small granite dikes.

Chapman (1969) also notes reticulated patterns oriented WNW and EW associated with the Mesozoic White Mountain intrusives of New England and suggests that both the Maine and White Mountain sets of intrusions were localized along the intersections of regional deep-seated fracture systems. Similar to the Maine examples, dips of the White Mountain country rocks are inward toward the complex. The central regions of the complex are commonly downfaulted blocks of Moat Volcanics surrounded by ring dikes. Thicknesses of at least a mile of volcanics in these cauldron subsidences (Billings, 1945) indicate major vertical motions dropping and preserving small portions of a much more extensive volcanic pile which formerly covered the intrusive belt.

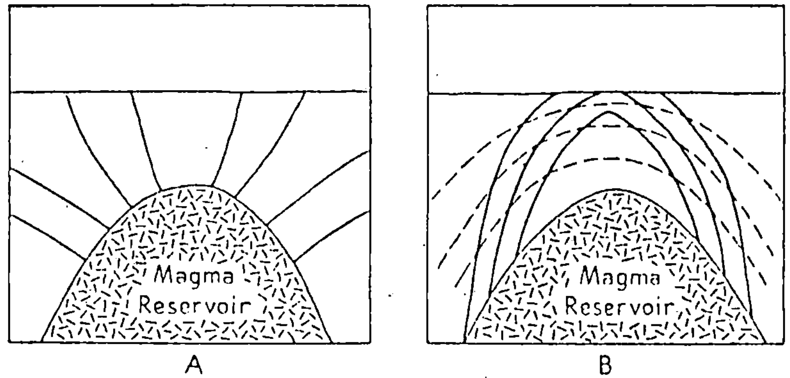
The fault contacts of the White Mountain magma series are not well exposed in general and for the most part are obscured by later stages of intrusion. Billings (1945) gives a general discussion of the emplacement mechanisms of these plutons including some of the faulting aspects (Fig. XVI-2).

Kingsley (1931) notes existence of two radial faults in the Ossipee Mountains of New Hampshire within the ring dike bounding the infaulted Moat volcanics against older granite. She describes one outcrop of the fault as granite grading into a "crush rock" with the fault itself marked by breccia intruded by quartz porphyry and basalt. Apparently, the fault was used as a volcanic conduit. She suggests that the magnitude of settling of this central cauldron was at least 5000 feet (Fig. XVI-3).

Billings, et al. (1946) in the Mt. Washington Quadrangle of New Hampshire map the very conspicuous Pine Peak fault separating and dropping the Mt. Washington block in the SE from the Pliny Range ring dikes and



a. Origin of ring-dikes. Broken line is present erosion surface.



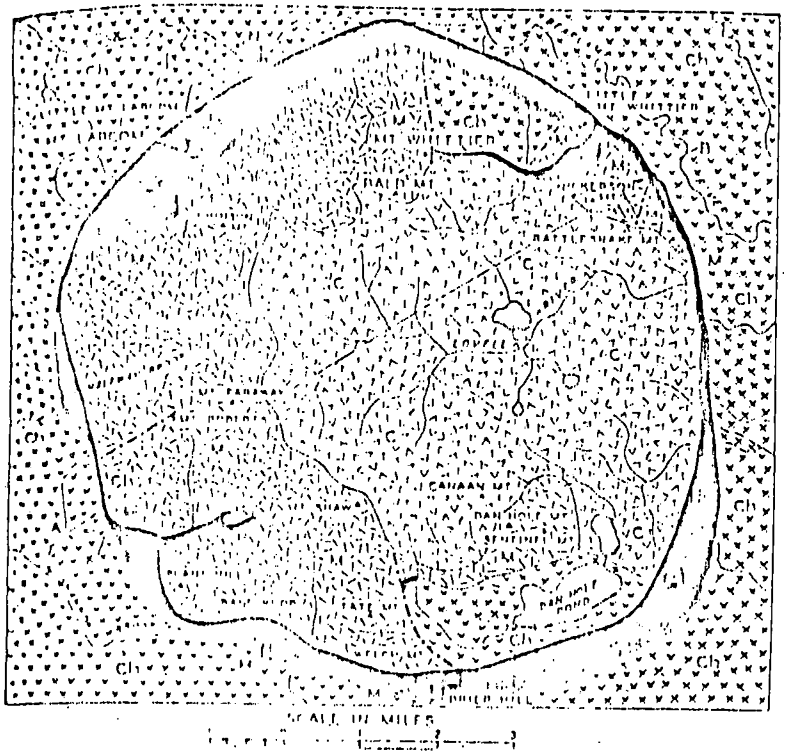
b. Fracture systems above a magma reservoir, after E. M. Anderson.

A. Magmatic pressure exceeds pressure exerted by surrounding rocks, causing tension fractures (solid lines).

B. Magmatic pressure less than pressure exerted by surrounding rocks. Tension fractures shown by broken lines. Steeper of two possible sets of shear fractures shown by heavy solid lines.

Figure XVI-2.

FRACTURING, RING DIKES AND CONE SHEETS ASSOCIATED WITH PROPOSED INTRUSION MECHANISMS OF THE WHITE MOUNTAIN PLUTONS. BILLINGS (1945)



CONWAY BIOTITE GRANITE

DEVONIAN ? — ALBANY PORPHYRITIC NORDMARKITE

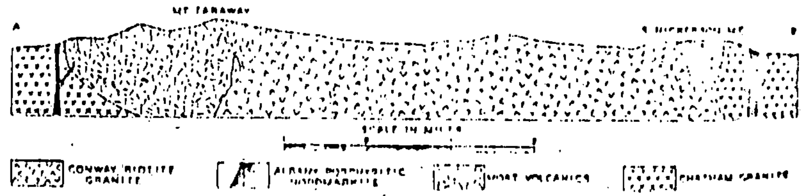
MOAT VOLCANICS

VOLCANIC NECK

PRE-CAMBRIAN ? — CHATHAM GRANITE

FAULTS

Areal geology of the Ossipee Mountains, N.H.



—Structure section through Mt. Faraway and South Nickerson Mountain.

Quaternary—Glacial till and outwash

Devonian (?) White Mountains batholith
- Conway biotite granite (interior stock)
- Albany porphyritic nordmarkite (ring-dike)
- Moat volcanics basalt, andesite, and quartz-porphyry flows; basaltic, andesitic, and rhyolitic tuffs and breccias; granitic breccia (central subsidence).

Pre-Cambrian (?)—Chatham two mica oligoclase granite (frame).

Figure XVI-3. Fault associated with intrusion of a White Mountain series pluton. From Kingsley (1931).

intrusions of the White Mountain Series to the NW. The fault is terminated on the SE by the Conway Granite and marked locally by wide zones of silicification. It does not seem to be closely related to the ring dike complex. Rather, it is sub-parallel to the Connecticut Valley - Bronson Hill line of structure, and more likely to be related to their tectonic setting than to local White Mountain intrusive centers.

In the central parts of the Belknap Mountain ring dike complex of New Hampshire, Modell (1936) describes a variety of cataclastic "flinty crush rocks", mylonites, ultra-mylonites, and pseudotachylites along an arcuate fault contact associated with subsidence of a central block. The younger intrusions follow this fault zone and have chilled margins against it. The outcrop patterns are suggestive of additional subsidence features following the same pattern.

More general discussion of dike systems associated with the White Mountain magma series is given by McHone (1978). Two major periods of igneous activity are concentrated in the early Jurassic (185 m.y.) and Cretaceous (125 m.y.). The dikes indicate changing orientation of the least principal stress axis with time. McHone does not discuss faulting associated with these dike injections although minor displacements are likely.

Among the older complexes, Chapman (1968) describes web joint patterns, and brecciated zones composed of radial and tangential fractures related to subsidence around the Mt. Desert Island complex. He suggests that the chilling of the complexes against their border faults implies rapid cauldron subsidence of huge blocks rather than slow magmatic stoping.

Continued motions during the magmatic emplacement stage are indicated by local faulting and diking of incompletely consolidated igneous rock and by shearing of crystal much in the Maine complexes.

YOUNGER FAULTING ASSOCIATED WITH LATE SMALL INTRUSIVE BODIES

A pattern of present-day fault activity may be associated with some small intrusive bodies of the Appalachians. This seismic activity includes some of the strongest shocks ever recorded in the region. Kane (1977) suggests a correlation of mafic and ultramafic bodies with centers of major seismic activity based on a correlation of these areas with local gravity highs. The center of the Charleston activity of 1886 includes several small gravity highs suggestive of shallow mafic intrusives. Basalt was recovered from a drill core taken from one of the highs (Rankin, 1978). In New England, part of the region of the White Mountain plutons included in a high seismicity area (Sykes, 1978) have associated gravity highs.

The reasons for this association of present-day seismic activity with Precambrian, Paleozoic or Mesozoic intrusive bodies are far from clear. Kane (1977) suggests that creep of rocks surrounding a more rigid mafic plug can cause the storage and sudden release of elastic energy in those rocks. The presence of serpentinization in the border zone of the mafic body would aid this process. In support of this, Kane notes that the major seismic activity in these regions is peripheral to the gravity highs rather than centered on them. On the other hand, Long (1976) proposed a variation of this model based on the same kind of data in which the mafic body was considered weaker than the surrounding rocks.

A further complication of several of the largest quake areas is the proximity of a continental margin and a buried Mesozoic basin. Mesozoic basins are interpreted as being just east of the Charleston and the Coastal Massachusetts areas (Rankin, 1977).

In addition to these, complexities of the largest quake areas lie on the possible projections of ancient transform faults. Sykes (1978) points out the association of the Charleston area with the Blake Spur fracture zone and the New England seismic region with the possible projection of the Kelvin fracture zone. He suggests a possible causal relationship with the seismic activity and the concentration of present-day stresses along much older zones of deep crustal weakness.

The above speculations on the possible association of modern seismic activity with much older small intrusive centers will require much more work to produce well defined mechanical models. Selection among the several hypotheses is beyond the present data limitations. These youthful faults, seemingly unrelated to the original emplacement mechanisms of the small bodies, nevertheless constitute a distinct group of Appalachian faults even though we do not understand as yet the details of their origins.

Meteorite Impacts

Within the U.S. Appalachians, meteorite impacts are more concentrated in the western and southern portions (Fig.II-II). Of all the Appalachians features, it seems safe to conclude these are the least likely to be reactivated by their original causal mechanism. The largest of these impacts, Flynn Creek, Tennessee, is 14 km in diameter (Roddy, 1968). The nature of impact geology has been extensively studied as part of the space exploration program (French and Short, 1968). The sites are recognized by circular nature, distinctive super-high pressure mineral assemblages (stishovite, coesite), lack of chemical equilibrium among the mineral phases, radial shatter cones in the surrounding rocks, throw-out debris, and distinctive circular and radial fault patterns (Fig. XVI-4).

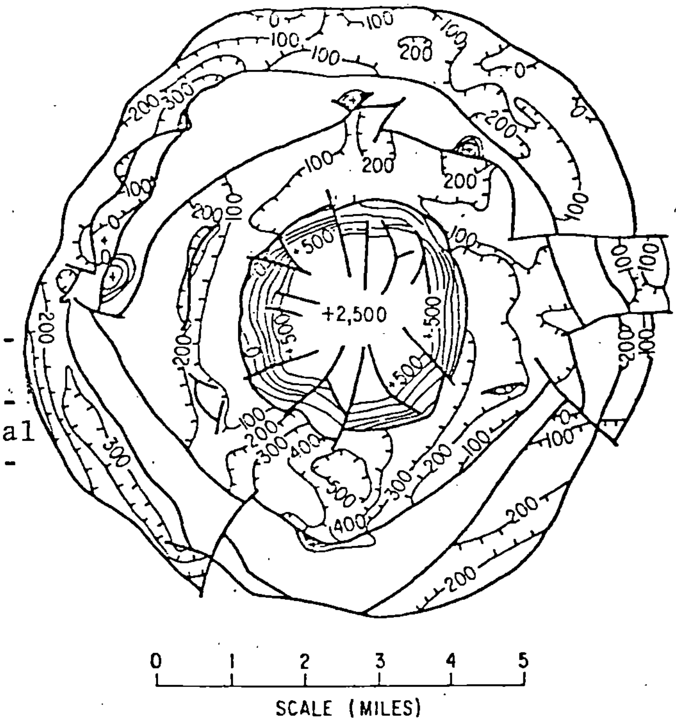
Pressures at the time of impact can reach a megabar with shock melted glass being injected pervasively along faults and many other fractures. A central zone beneath the impact may rebound from the shock to form a core with structural relief up to a km above a concentric series of horsts and graben. Shattered and brecciated materials may extend for a km or more beneath the impact site.

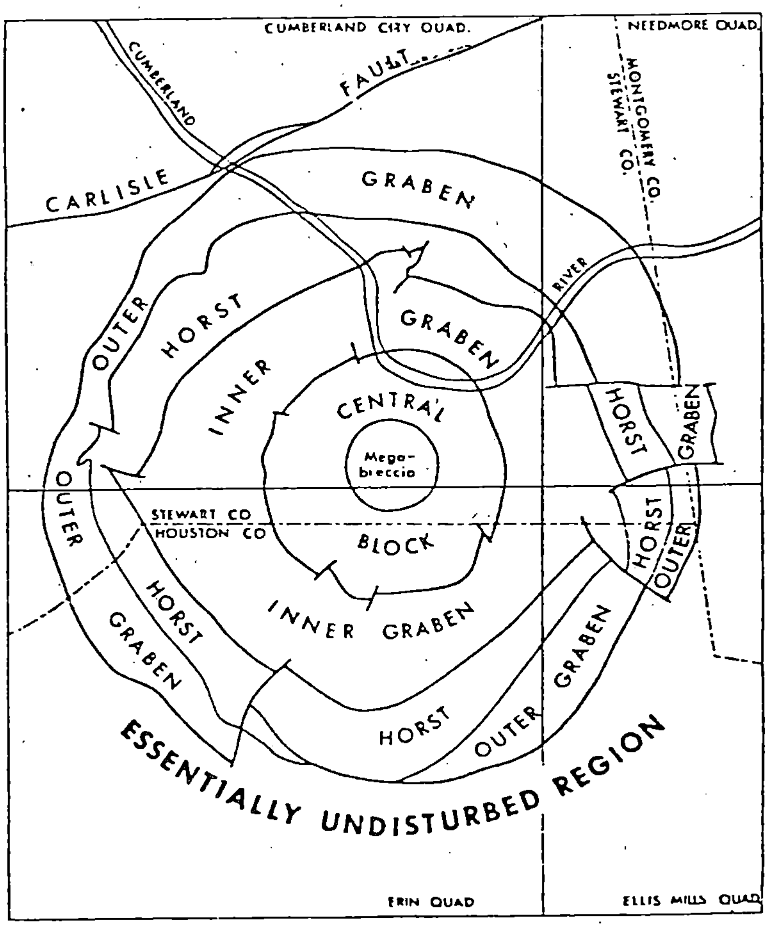
In addition to the well documented impact sites illustrated in Fig. II-II, another possible ancient site has been suggested in the Panther Mountain structure of the eastern Catskills by Isachsen (1977). The structure is marked by a circular drainage anomaly following zones of more concentrated jointing and by a slight negative gravity anomaly. It is interpreted by Isachsen as a possible ancient impact buried beneath the Devonian clastics and manifesting itself by upward propagation of joints above the deeper circular rim and walls.

None of the impact sites within the U.S. have marked concentrations of modern seismic activity associated with them but one nearby anomaly does exist. Only the Charlesvoix structure near Quebec City of all the Canadian impact features has marked concentration of seismic activity. Sykes (1978) suggests this may be a local phenomenon caused by a higher stress zone of the Saint Lawrence Valley being concentrated in the impact weakened rocks. Within the eastern U.S., the impact sites seem reasonably free from seismic activity concentration but probably should be monitored with a microseismic network before any critical siting decisions are reached.

Summary data and additional references on the impact sites can be found in French and Short (1968) and E. A. King (1976).

a. Structure of the Wells Creek area due to the cryptoexplosive event itself. This map exhibits the residual structure when regional structure patterns are subtracted.





b. Generalized tectonic sketch of the Wells Creek structure.

Figure XVI-4 The Wells Creek Structure. From Stearns, et.al. (1968).

XVII

GROUP 13 FAULTS: FAULTS RELATED TO GEOMORPHIC PHENOMENA

A. Generalized Description

Faults of small to moderate scale can be produced by a number of processes which are fundamentally geomorphic in nature. These structures are technically faults even though their relationships to true tectonic processes are distant at best. Nevertheless, their presence constitutes additional "noise" in the complicated small scale patterns of tectonic faulting present in most regions of the Appalachians. Most of the relevant geomorphic processes have been active in very recent time, and the possibilities of misinterpreting their effects are numerous. Their interpretation as true tectonic disturbances can cause unwarranted concern about the level of neotectonic activity in a region.

The possibility of continued motion on geomorphically produced faults obviously needs to be taken into account in the engineering design of any critical structures. However, problems of this type fall more in the realm of geotechnical engineering than in the analysis of seismotectonics. If a fault displacement can be demonstrated to be solely the result of some surficial process, it should be excluded from the usual seismotectonic restrictions required for site certification. However, many of these geomorphic effects can be concentrated along an older fault zone as a result of contrasting bedrock lithology, deeper weathering along a fracture zone, more water in a fault zone, weaker gouge in a zone, etc. Consequently, the mere identification or label of some structure as a geomorphically produced fault should not automatically exclude it from all tectonic considerations. However, once complete independence of these geomorphic structures from true tectonic structures has been established by deeper excavation, determination of map movement patterns independent of bedrock fault patterns, drilling, etc., then this group of faults and related structures should be excluded from the usual seismo-tectonic considerations for that site.

Saprolitic Faults

Deep saprolitic or lateritic weathering is common south of the Mason-Dixon Line and may be developed locally in Pennsylvania and New Jersey. It is particularly deeply developed on may older erosion surfaces of the Piedmont, reflecting the long time required for its production. The saprolites represent almost complete chemical decomposition of many of the minerals, particularly feldspar with preservation of the internal fabric of the rock mass, especially in the quartz and micas. Delicate fold and foliation structures remain visible even though the material can be crumbled in the hand. Typical weathering depths in these clay and iron rich soils can reach 30-50 meters.

As the saprolite mass forms, it becomes a distinct mechanical entity, capable of lateral spreading, creep, or landsliding. In addition, volumetric changes associated with mineral alteration and hydration place additional stresses on the saprolite mass. Relict joints or faults may be enhanced or reactivated by this process or new joint and fault surfaces may be produced. As a result, extensive slickensiding with displacements up to a few centimeters is a common feature of may saprolite exposures. Additional discussion of these features is given by St. John, et al. (1969). Once fractured, the saprolite tends to maintain ground water movement in the same channels, resulting in precipitation of iron and manganese in the joints and minor faults. Typically, these surfaces have spacings of a few 10s of meters.

Several criteria help distinguish saprolite faults from true tectonic types. The best method is to demonstrate by excavation that the faults in the saprolite have no corresponding planes of displacement in bedrock. Other evidence might be a statistical orientation study showing that joints, faults and slickensides in the saprolite have a different pattern from the corresponding classes of structures in the underlying bedrock. If these features in the saprolite also bear obvious relationship to local topographic creep or volumetric expansion directions, the case for non-tectonic fracturing is further strengthened. Presence of minerals other than Fe and Mn along the saprolite faults, unusually close local spacing of the saprolite fractures, or close parallelism with or development over bedrock fault zones are causes for additional scrutiny. If the slickensided surfaces can be demonstrated as purely the result of saprolitic processes, with movement vectors reflecting only creep and/or surficial expansion, the problem becomes one of soil mechanics and slope stability rather than seismic rock analysis.

Karst and other collapse structures

Removal of subsurface materials by either natural processes or human activities can cause vertical collapse of overlying rock or soils. Draining of water-filled systems can decrease further the support of the mass. In particular, a cycle of heavy pumping with consequent lowering of the ground water table in a karst region can cause clay-filled solution cavities to be reactivated. Within a few years of the water table drawdown, a rash of small to moderate-sized sink holes can develop. A case study of this process has been documented by Foose (1953) for the Hershey Valley of Pennsylvania.

Collapse is most likely along pre-exisitng steeply dipping fractures of any kind. The collapse planes are most likely to mimic normal or vertical faults. Slickensides on these surfaces in bedrock are rare because of low normal stress across the plane of motion. Association with dripstone and other cave features is common but no true hydrothermal mineralization should be present.

These cave related problems are most common in limestone regions, particularly in the Cambro-Ordovician rocks of the Great Valley just west of the Blue-Ridge-Reading Prong and in the limestone regions of the Appalachian folds and plateau. Discussions of the typical forms of karst features are given by Jennings (1971) and by Davis and Legrand (1972).

Not all caves and collapse features occur in carbonate terranes. Some cases occur by gravity creep of hillsides causing separation of blocks along joint and fault systems. Man-made caves constitute an additional complication. Throughout old mining districts of the Appalachians, collapse of underground workings can be a continuing problem.

A likely error in karstic or collapse regions, in terms of seismo-tectonic interpretation, is an older fault zone used as a boundary for a collapsing block being mis-identified as representing tectonic reactivation.

Glacio-Tectonic Structures

Glacial environments can create a host of structures easily mistaken for true tectonic features. A complete discussion of these structures is inappropriate here but a few of their more important aspects can be noted.

A general discussion of glaciotectonic structures is given by Banham (1974) who classifies them as: (a) compressional, in valley sides, in scarps and in islands or peninsulas between ice lobes and (b) tensional on slopes. He notes that glaciotectonic mechanics must recognize that: (1) ice of considerable weight can move very rapidly in geologic terms (2) strength of low permeability materials such as clays can be decreased greatly by water content (3) temperature is the main control of shear strength of the frozen rocks and sediments (4) over-riding ice can cause excess fluid pressure in water saturated materials with detachment and thrusting of slabs by the familiar mechanism of Hubbert and Rubey (1959).

Making use of the Rubey and Hubbert mechanism, large scale thrusting of bedrock slabs is possible. Kaye (1964) describes major imbricate thrusting of this type in coastal plain Cretaceous units at Gay Head on Martha's Vineyard. There high sea cliffs expose a number of slabs of Cretaceous units repeated by imbricate thrusting and complicated by an overprint of complex folding and faulting. Similar thrusting has been discussed by Hansen (1965) in Denmark, by Banham (1974) in coastal England, and by Moran (1971) in Saskatchewan. Horizontal dimensions of these glaciotectonic bedrock thrust slabs can be up to several kilometers with displacements of hundreds of meters.

In the process of overriding their own deposits, glaciers commonly develop folds and minor thrusts in the glacial material. Squeeze ups into slightly stonger units undergoing extensional fracturing are common. Older tills may have distinct joints developed within them with joints cutting clasts (Kuspch, 1955). Slickensided surfaces on till are common. Individual horizons may be swirled into "jelly roll" configurations.

Identification of fault or fold structures as being related to glacial overriding requires some knowledge of the local direction of glacial motion(s). These motions are indicated by bedrock surface striations, topographic indicators such as drumlin fields, and/or till orientation fabrics. Regional motions of glacial flow are given on the Glacial Map of North America (Flint, et al., 1959) but local variations around topography are common. Any glacially produced structures should be independent of bedrock fabric, relating in some logical way to the glacial deposits and to the directions of glacial motion.

Simple gravity collapse in ice contact and glaciofluvial deposits may also produce a variety of slump faults associated with loading, over-steepening of depositional fronts or sudden drawdown of a lake. Collapse of glacial deposits above buried ice masses can produce kettle holes with associated slump faulting.

Details of glaciotectonic and related structures can be found in bibliographies of the papers cited above. The glacial boundary crosses the Appalachians from Long Island to western New York state and thence to a line down the Ohio Valley (Fig. 11-12). North of this boundary glacially-produced structures are common in many surficial deposits. In addition, pseudo-tectonic permafrost features may occur south of the glacial border.

Permafrost structures

Extensive permafrost during the Pleistocene produced a variety of surficial structures throughout the Appalachians, both within and beyond the glacial border. The southward limit of Pleistocene permafrost is not well established. One model for the origin of the Carolina Bays of the Coastal Plain is as permafrost thaw lakes similar to those of the Arctic coastal plain of Alaska. (An argument against this interprelation is the characteristic raised rims of the Carolina Bays versus the absence of such rims in Arctic thaw lakes.) Felsenmeers (German for seas of rocks) may occur at higher elevations in all areas including the upland of the Southern Appalachians as a result of extensive frost shattering and heaving in both Pleistocene and recent time. Locally, these rock fields developed flow characteristics during the Pleistocene, somewhat analogous to rock glaciers as at Blue Rocks, Pennsylvania (Potter and Moss, 1969). A summary of permafrost features is given in books by Washburn (1973), Pewe (1969), and C.A.M. King (1976). In particular, the effects of former ice wedges, patterned ground and solifluction can mimic true tectonic structures. Ice wedging and lifting of bedrock sheets can produce effects along joints which are easily mistaken for faults. Deeper excavation and careful attention to map patterns or internal structures offer the best methods of distinguishing these structures.

Landslides and related forms of mass wastage

Landslides are among the more ubiquitous geomorphic features in regions of moderate to steep relief. Slickensides can be produced during their motion and may possibly be interpreted as being of tectonic origin. To be identified as landslide-generated, slicks should occur in landslide topography, bear some rational orientational relationship to the direction of motion of the mass, not be represented by similarly orientated structures in bedrock, and be devoid of any mineralization indicative of pressures or temperatures higher than these of the surface environment. Movement senses are commonly of a backward rotation of individual blocks, the well-known Toreva block (Reiche, 1937) of geomorphologists. A recent summary of landslides and their character has been edited by Coates (1977).

"Pop-ups" and other near-surface stress release

Small scale, near-surface structures of many types can develop locally as release mechanisms for in situ stress. Unloading of overlying confining materials is the common triggering mechanism as a result of glaciation, stream deepening, or quarry type operations.

"Pop-ups" are outcrop scale, sharp anticlinal release features occurring mostly in more competent units. They are most commonly interpreted as the result of relaxation from a regional compressive stress. The "pop-up" plane is generally less than 3 meters thick whereas the resulting anticlinal axis may be up to 50 meters long. The axes in a region tend to be sub-parallel with gradual variations in strike up to 30-40 degrees. The fold produced commonly has open space beneath its arch and is characterized more by brittle fracturing than by actual bending. Any pre-existing fractures are likely to be utilized as boundary planes within the fold. Structures of this type are common along the St. Lawrence and into western New York State in the Cambrian quartzites and the Lockport Dolomite. Their classic description is by Cushing, et al. (1910).

Near-surface sliding of rock sheets across each other during excavations and quarry operations, as described in Connecticut by Block, et al (1979) may be a related type of near-surface stress release. Block, et al (1979) report progressive offset of drill holes through an old mylonite zone in the center island of an Interstate Highway near Moodus, Connecticut. The displacement planes in that cut are parallel with the foliation of the bedrock, seemingly unrelated in direction to gravity forces acting on the face of the road cut, and are moving progressively at an average rate of 2.8 mm/yr. The motions appear to be progressive strain release from N-S striking compression of a regional nature. The fact that this area has a long history of disturbances and earthquake like "noises" lends some support to the Block, et al interpretation of these offset holes as modern tectonic manifestations. Although release of in situ stress seems to us an equally valid interpretation. The Block, et al (1979) interpretation does not mean that all offset drill holes or similar features should be regarded as neo-tectonic effects. Most offset drill holes are gravity slumping of joint blocks or frost heaves. Most others represent release of in situ stress by removal of the surrounding rock mass. Among the better known samples of the type of modern deformation produced by excavation is the Niagara Power Canal as described by Lee and Lo (1976) and Palmer and Lo (1976). There, the Lockport Dolomite, sandwiched between two shale layers, has considerably more residual stress than the adjacent shales. Turbines put into a deep cut early in this century have required repeated readjustments because of progressive movement of the dolomite. The deformation consisted of two parts: an instantaneous elastic release followed by continuing viscous deformation.

Near surface stress release features are a normal aspect of deep excavations and of many areas of the Appalachians. Their presence suggests at least moderate levels of residual stress in an area and calls for more careful and more complete in situ stress measurements than might ordinarily be made. Their presence should not automatically be considered as evidence of modern tectonic activity. However, the presence of micro-earthquake activity, in association with strong development of these release phenomena should be cause for concern.

XVIII

GLOSSARY

ALLOCHTHON: An allochthon is a rock unit which has been tectonically transported from its original site of emplacement (modified from Dennis, 1967).

BASEMENT: Crustal material generally inhereted from an earlier tectonic cycle. Commonly consists of crystalline rocks upon which sediments, with or without volcanic rocks, were subsequently deposited. These newly-deposited sediments may or may not be metamorphosed. Basement in the Appalachians may be Grenvillian (1100 Ma), Avalonian (700-800 Ma) or in some cases early Paleozoic. In the Alps it is Hercynian (250-300 Ma) and in the North American Cordillera it is middle Precambrian (Hudsonian, ca. 1700 Ma.).

BLASTOMYLONITE: A mylonitic rock (see mylonite) containing greater than 10% megacrysts. Typically the megacrysts result from neomineralization and or recrystallization (Higgins, 1971).

BLIND THRUST: A thrust fault that does not intersect ground surface.

BRECCIA: A coarse-grained cataclastic rock composed of large (greater than 2 mm), angular, and broken rock fragments that can be of any composition (modified from Gary, McAfee, and Wolf, 1972).

BUTTON SCHIST: A common term for rocks in which micaceous porphyroclasts or porphyroblasts form button-like structures upon weathering. This structure commonly results from the low-angle intersection of two s-surfaces (foliations, cleavages) producing button-shaped or lens-shaped fragments. Synonymous with: wavy schist, frilled schist, curly schist, phyllonitic schist, crumpled schist, puckered schists, eyed schist, eyed phyllonite, fish-scale schist, and oyster shell schist (after Higgins, 1971).

CATACLASIS: The process by which rocks are broken and granulated due to stress and movement during faulting granulation or comminution (Higgins, 1971). Cataclasis is a brittle process and cataclastic rocks (cataclasites) include: breccia, microbreccia, gouge, flinty crust rock, and pseudotachylites.

CLEAVAGE: All types of penetrative, secondary, planar, parallel fabric elements (other than coarse schistosity) which impart a mechanical anisotropy to the rock without apparent loss of cohesion (Dennis, 1967).

COHESION: The uniaxial tensile strength of a surface or zone. In this report we use cohesion to compare the tensile strength of a fault zone with that of the country rock. A different use of the term cohesion is found in soil mechanics literature (Jaeger and Cook, 1976; Gary, McAfee, and Wolf, 1972).

CONJUGATE: Paired surfaces which form synchronously and intersect so that one dihedral angle between the surfaces is acute while the other is obtuse. Conjugate fractures, conjugate axial surfaces, etc.

CONTINUITY: The state or quality of being continuous. With reference to faults, the strike continuity versus down dip continuity.

CONTRACTIONAL FAULT: Fault which results in relative shortening parallel to bedding (Norris, 1958). Synonymous with wedge.

DECOLLEMENT: Detachment along stratigraphic surfaces as a result of deformation (Dennis, 1967).

DEFORMATION: The net change of relative position, with respect to a fixed coordinate system, of every point within a body. The deformation may include rigid body translation and/or rigid body rotation with accompanying strain. Informally, deformation refers to the process by which the above changes occur, for example, a brittle deformation (Hobbs, Means, and Williams, 1976).

DIAPIR: A fold or plug-like flow structure whose mobile core pierces overlying less mobile rock (Dennis, 1967; Billings, 1972).

DISPLACEMENT: Each material point in an undeformed body may be connected to the same material point in the deformed body by a displacement vector. The total array of displacement vectors constitutes the displacement field (Hobbs, Means, and Williams, 1976). Informally, displacement can refer to the relative movement between two bodies, but is a non-precise term including both slips and separations (Gary, McAfee, and Wolf, 1972).

DRAG: Velocity discontinuity resulting from frictional resistance between two adjacent rock masses during differential movement.

DRAG FOLD: Minor folds produced in certain rock layers by differential movement of adjacent layers (Dennis, 1967).

EN ECHELON: An overlapping or staggered arrangement, in a zone, of geologic features which are oriented obliquely to the orientation of the zone as a whole. The individual features are short relative to the length of the zone (Dennis, 1967).

EPI-ANTICLINAL FAULT: A longitudinal or transverse fault associated with a doubly-plunging minor anticline and formed concurrently with folding (Gary, McAfee, and Wolf, 1972).

EXTENSIONAL FAULT: Faults which result in relative extension parallel to bedding (Norris, 1958).

FAULT: A fault is a tabular or planar discontinuity characterized by motion parallel to itself. The discontinuity might be marked either by loss of cohesion or by extreme ductile deformation.

FIBERS: Parallel arrays of elongate crystal growths marking the direction of extension along a fracture or fault.

FLINTY CRUSH ROCK: Silicified microbreccia or gouge; a cataclastic rock.

FLUXION STRUCTURE: A mylonitic foliation.

FOLIATION: A general term for a planar arrangement of textural or structural features caused by parallel alignment of inequidimensional minerals in any type of rock, e.g., cleavage in slate or schistosity in schist (modified from Gary, McAfee, and Wolf, 1972).

FRACTURE: A general term for any brittle break in a rock, whether or not it causes displacement. Fracture includes cracks, joints, and brittle faults (modified from Gary, McAfee, and Wolf, 1972). A surface along which loss of cohesion has taken place (Dennis, 1967).

FRACTURE CLEAVAGE: Closely-spaced jointing (Billings, 1972). A set of closely-spaced microfaults or fractures which divide the rock into a series of tabular bodies or microlithons (deSitter, 1964; Hobbs, Means and Williams, 1976).

FRICTION: The force resisting slip on a surface. For coefficients of friction, internal friction, dynamic friction, sliding friction, and static friction, see Jaeger and Cook (1976).

GASH FRACTURE (tension gash): Small scale tension fractures, having highly eccentric elliptical cross sections, occurring at an angle to a fault, which remain open or are filled by secondary mineralization.

GLACIAL OVER-RIDING: The process by which moving ice sheets exert shearing stress on the rocks beneath the ice. Glacial over-riding structures include minor faults and folds.

GOUGE: Clay-like rock material formed by crushing and grinding along a fault. Most individual fragments are too small to be visible to the unaided eye (Higgins, 1971). An ultra fine-grained cataclastic rock.

GROWTH FAULT: A fault in sedimentary rock that forms contemporaneously and continuously with deposition, so that the throw increases with depth and the strata of the downthrown side are thicker than the correlative strata on the upthrown side (Gary, McAfee, and Wolf, 1972). These faults may cut basement (rome trough) or they may be listric surfaces (Gulf Coast) which flatten at depth into a decollement zone.

IMBRICATE: The geometric array of a succession of nearly parallel overlapping thrust or reverse faults which are approximately ediquistant and have approximately the same displacement (modified from Dennis, 1967).

IN-SITU: In place, existing at the present time; e.g., in-situ stress is that stress state currently existing in rocks as opposed to paleo-stress.

JOINT: A joint is a fracture along which true or apparent displacement parallel to the surface is less than ten times greater than displacement normal to the surface.

KINK BAND: A sharply defined tabular zone, on any scale, within which planar fabric elements are abruptly rotated with respect to their orientation outside the zone.

LAG: A tectonic slide surface which structurally eliminates part of the known stratigraphic section (Dennis, 1967). Listric normal fault.

LIMB ATTENUATION: The tectonic thinning of the limb of a fold, either by flattening or by the development of a ductile fault or tectonic slide oblique to the limb. Limb attenuation is dominantly a ductile process.

LINEAMENT: Straight or gently curved, lengthy features of the Earth's surface, frequently expressed topographically as elongate depressions or lines of depressions; these are prominent on relief models, high altitude air photographs, and radar imagery. Their meaning has been much debated; some certainly express valid structural features such as faults and zones of intense jointing, but the meaning of others is obscure (Gary, McAfee, and Wolf, 1972). For an extended discussion see Appendix B.

LISTRIC: A fault plane with decreasing dip at depth; a shovel-like (generally concave-up) geometry; after the Greek for shovel -- listron.

MASS WASTING: The gravitationally-driven transport of surficial material down a topographic slope. Mass wasting has no tectonic significance except that some tectonic events can trigger mass wasting; it is included here only because some mass wasting (slump blocks) can be confused with faulting. Mass wasting differs from faulting because mass wasting does not extend to appreciable depth.

MEGACRYSTS: A nongenetic term for any crystal or grain in an igneous or metamorphic rock that is significantly larger than the surrounding groundmass or matrix. Megacrysts include phenocrysts, porphyroblasts and prophyroclasts (Gary, McAfee, and Wolf, 1972).

MILLING: The process of granulation and comminution of rocks in a brittle fault zone producing fault gouge. Lapworth thought milling was an important process in the production of the Moine mylonites; but this is incorrect because those mylonites were produced by ductile processes.

MULLION: Columnar rock structure bounded by discrete bedding or foliation surfaces, curved rather strongly about a single axis. The bounding surfaces are generally cylindroidal (modified from Dennis, 1967).

MYLONITE: A fine-grained, highly foliated rock, resutling from intense ductile strain where strain rate exceeds recovery and/or recrystallization rate. The strain is accomplished by the nucleation, glide, and climb of dislocations. The mylonitic foliation is invariably an axial plane foliation. Mylonites are finer-grained than their protoliths. Quartz-rich protoliths yield mylonites containing quartz ribbons flattened and extended in the foliation, and these quartz ribbons usually display recovery textures such as strain-free subgrains (Hatcher, 1978; Hobbs, Means, and Williams, 1976).

MYLONITIZATION: A process involving high ductile strain and incomplete recovery. Dimunition of grain size is characteristic of this process (Hatcher, 1978). Mylonitic rocks include: phyllonite, blastomylonite, mylonite, and ultramylonite.

NAPPE: A large allochthonous, sheet-like tectonic unit that has moved along a predominately subhorizontal floor (Dennis, 1967). An allochthon. Also may refer to a large-scale recumbent fold.

NORMAL: A line taken perpendicular to a plane, and whose orientation specifies the orientation of the plane.

NORMAL FAULT: A fault whose hanging wall has moved down relative to its footwall. Typically normal faults are brittle faults.

OBLIQUE: Across, not parallel to. Features may be parallel or oblique or perpendicular.

PALEOCRYOTURBATION: The past disruption of surficial materials caused by the expansion of water upon freezing, or by glacial over-riding.

PENETRATIVE: A structure is penetrative if it is repeated statistically at imperceptible distances on the scale of the domain under consideration, so that it effectively pervades the body and is in the same average orientation in every sample (Dennis, 1967). The concept is scale-dependent and a structure may be penetrative at one scale but not at another.

PHYLLONITE: A rock of phyllitic appearance formed by mylonitization of a schistose protolith (modified from Higgins, 1971).

PLASTICITY: That property of rocks and minerals whereby permanent (non-elastic, non recoverable) strain is achieved in a non-hydrostatic stress field. Plastic strain is permanent strain under constant non-hydrostatic stress (Jaeger and Cook, 1976). Plastic deformation is a constant volume deformation, that is, it arises only from the deviatoric part of the applied stress. The mechanisms of plastic deformation are dislocation glide, dislocation climb, and grain boundary sliding (Nicolas and Poirier, 1976). Plastic flow is a solid state process in contrast to viscous flow; nevertheless an effective coefficient of viscosity can be calculated for plastic flow even though the flow is non-Newtonian.

POP-UP: An outcrop scale antiform formed by natural or artificial erosional release causing the upbowing of a surficial bedrock slab.

PROTOLITH: The parent rocks from which metamorphic, cataclastic, or mylonitic rocks are derived.

PROTOMYLONITE: A mylonitic rock containing greater than 10% megacrysts. In contrast to blastomylonites, the megacrysts in protomylonites do not have rims of neomineralization and/or recrystallization. Megacrysts in protomylonites were being broken down at the time the texture was "frozen in."

PSEUDOTACHYLITE: A dark fine-grained, often glassy looking cataclastic rock which frequently occurs in discordant veins in fault zones. Although pseudotachylites usually are interpreted as the product of friction-induced melting, they have the microtextures of intense brittle deformation at high strain rates and low temperatures (Wenk, 1978).

RAMP: That portion of a bedding-plane thrust which cuts up-section producing a fold in the rocks of the thrust sheet. Generally, ramps occur when a thrust is crossing a competent unit. They are commonly more steeply-dipping than segments of the same thrust which follow bedding planes.

RECESS: An arcuate portion of an orogenic belt which is convex toward the craton. Synonymous with reentrant.

RECOVERY: The process which lowers the total strain energy of a crystal by dislocation climb, dilocation annihilation, polygonization, and annealing recrystallization. Recovery is a moderate to high temperature phenomenon, and the rate competition between strain hardening and recovery processes determines the texture of plastically deformed rocks (Nicolas and Poirier, 1976).

RESIDUAL STRAIN: Elastic (recoverable) strain stored in a rock because of the constraints imposed by surrounding rock, matrix, or cement. Residual strain is relieved when the rock or mineral grain is freed from its surroundings. For example, dissolving the cement from a sandstone allows individual sand grains to elastically recover their undeformed shape.

RESIDUAL STRESS: The stress equivalent of residual strain (Jaeger and Cook, 1976).

REVERSE FAULT: A steeply-dipping fault (more than 45 degrees) in which the hanging wall block moves up relative to the footwall block. Many thrust faults emerge from the ground as reverse faults (Billings, 1972). Reverse faults may be brittle or ductile.

ROTATION: Rigid body rotation describes a change in the spatial orientation of the bounding surfaces of a body measured with respect to a fixed coordinate system. Internal rotation involves a change in the angular relation between material lines within a body, and is a manifestation of shearing strain (Hobbs, Means, and Williams, 1976).

SALIENT: An arcuate portion of an orogenic belt which is concave toward the craton. Synonymous with promontory.

SAPROLITE FRACTURE: A joint or fault caused by surficial gravity creep or hydrational and decompositional expansion in thick iron-rich residual soils (saprolites).

SCARP: A relatively steep, smooth topographic slope which may be of fault origin (Billings, 1972). Undissected scarps suggest recent faulting. It is important to note that many physiographic scarps are not produced by faults.

SCHISTOSITY: A fissility of metamorphic origin, caused by parallel orientation of abundant platy or lath-shaped grains large enough to be seen with the unaided eye (modified from Dennis, 1967).

SHEAR SENSE: The relative motion of material on opposite sides of a shear surface, tending to cause clockwise or counter-clockwise rotation. Also used to describe the asymmetry of minor folds (Billings, 1972).

SHEAR STRENGTH: The shearing strength of a surface is the magnitude of shearing stress that surface can support without failure, under specified normal stress. The shearing strength of a body is the maximum shearing stress that body can support without failure, under a specified confining pressure. The shearing strength of anisotropic bodies varies as a function of the orientation of anisotropy with respect to the stress field (Jaeger and Cook, 1976).

SHEAR STRESS: A stress which acts in a plane and tends to cause one side of the plane to slip past the other side (Jaeger and Cook, 1976).

SHEAR ZONE: An imprecise term variously used for (1) a ductile fault zone, (2) a brittle fault zone, (3) a zone of fracturing and brecciation. The term should be abandoned in favor of more specific terminology.

SLICE: Mass of competent material removed from footwall and transported into a thrust zone.

SLICKENSIDES: Polished, smoothly striated surfaces developed on a brittle fault by friction-controlled mechanical abrasion. Slickensides are a product of cataclasis and must be distinguished from fibrous growths and pressure solution grooves.

SLIDE (TECTONIC SLIDE): A fault formed in the folding process by cutting out of the common limb between an antiform and synform.

SLIP LINES: Paths of relative displacement of adjacent constituent particles during deformation (Hansen, 1971).

SPLAY: Minor faults genetically related to a major fault but having slightly different orientation, especially near the ends of the major fault. Major faults frequently terminate in splays (modified from Gary, McAfee, and Wolf, 1972).

S-SURFACE: Any kind of parallel planar fabric element which is penetrative at the scale of the domain under investigation (Dennis, 1967). S-surfaces need not be metamorphic foliations, but usually are.

STABLE SLIDING: A type of frictional sliding which occurs at constant velocity under constant shearing stress. On a force-displacement curve, stable sliding is the region of constant near-zero slope (Jaeger and Cook, 1976).

STICK SLIP: A type of frictional sliding characterized by abrupt accelerations of sliding velocity and abrupt decreases in shearing stress. On a force displacement curve, stick slip is the region of sharp peaked oscillations, as the sliding surface accelerates then "locks up" (Jaeger and Cook, 1976).

STRAIN: The change in size and/or shape of a body in response to stress. There are three mutually perpendicular directions within an unstrained body which remain perpendicular in the strained state. These are the principal strain axes, either extensional or contractional, representing extreme values in change of the length of material lines. Because the principal strain axes remain perpendicular there is no shear in those directions. In all other directions there is a shear component present. There is no necessary correspondance between principal stress axes and principal strain axes, moreover, the total deformation may involve rigid body rotation; if so the final orientation of the principal strain axes will not correspond to the initial position (Jaeger and Cook, 1976; Hobbs, Means and Williams, 1976).

STRESS: The intensity of force per unit area, acting at every point within a body due to the existence of body forces and the application of surface forces on the boundaries of the body. At every point within a body there are three mutually perpendicular directions in which normal stress (σ) attains extreme (maximum or minimum) values. These directions are the principal stress directions and are designated: σ_1 (maximum principal stress) $\geq \sigma_2$ (intermediate principal stress) $\geq \sigma_3$ (least principal stress), where the relations are algebraic and compression is positive. In the principal stress directions, no shear stresses exist. In all other directions, normal stresses have values less than σ_1 but greater than σ_3, and shear stresses (τ) exist. Any plane not perpendicular to one of the principal stresses has both a normal stress acting perpendicular to it and shearing stresses acting with it. When $\sigma_1=\sigma_2=\sigma_3$ the stress state is hydrostatic and no shearing exists in any direction within the body (Jaeger and Cook, 1976).

TEAR FAULT: Strike-slip or oblique-slip faults which terminate a thrust fault or exist within a thrust sheet (modified from Dennis, 1967).

TECTONIC INJECTION: A mass of material which has been forcefully injected under tectonically-induced stresses into another mass.

TENSILE STRENGTH: The magnitude of the least principal stress (σ) at the instant of tensile failure. The term usually refers to the uniaxial tensile strength when $\sigma_1=\sigma_2=\sigma_3$ = tension. Tensile strength is a material property (Jaeger and Cook, 1976).

THICK-SKINNED: An informal term describing deformation, either folding or faulting, which extends into and involves crystalline basement.

THIN-SKINNED: An informal term describing deformation, either folding or faulting, which generally does not extend into crystalline basement. Recently, however, it appears that crystalline rocks (basement and non-basement) may be involved in low-angle thin-skinned thrusting (see for example Cook et al., 1979).

THRUST FAULT: A gently dipping fault (usually less than 30°, often almost horizontal) in which the hanging wall moves up relative to the footwall. The dips of thrust faults increase within ramp zones to values greater than 30°. Thrust faults may be brittle or ductile.

TRANSCURRENT FAULT: A dominant strike-slip fault of regional extent, whose strike is oblique or perpendicular to regional structural grain (Billings, 1972).

TRANSLATION: That type of deformation involving no strain within a body, but movement of the rigid body from its initial position along a straight path (Hobbs, Means, and Williams, 1976).

TRANSPOSITION: The deformation of a pre-existing s-surface (involving rotation and strain ± translation) into an axial plane foliation. Transposed bedding consists of compositional layers reflecting sedimentation, but the layers no longer have any superpositional significance (Hobbs, Means, and Williams, 1976).

UNLOADING STRUCTURE: A structure produced by a decrease in the vertical stress as the overburden is removed by erosion.

ULTRAMYLONITE: An aphanitic, very fine-grained mylonite whose individual grains can be detected only under magnification.

VERGENCE: The direction of overturning of folds, or the sense of asymmetry of folds (Hobbs, Means, and Williams, 1976). Synonymous with sense of tectonic transport, or sense of shear.

VIRGATION: Sheaf-like diverging of fold axes in an orogenic belt (Dennis, 1967).

WEAR GROOVES: Grooves on a frictional sliding surface produced by abrasion of opposite sides of the surface. Wear grooves are individually recognizable on a sliding surface but grade continuously into slikensides.

WEDGES: Small-scale step thrusts with displacements ranging from a few millimeters to a few meters (Cloos, 1964). Synonymous with contractional faults.

WRENCH FAULTS: A synonym for strike-slip faults, especially transcurrent faults. Unfortunately a fallacious concept, known as wrench fault tectonics, carries erroneous genetic implications in violation of Newtonian mechanics. The term should be abandoned.

XIX

SUGGESTIONS FOR FUTURE STUDIES

In assembling these data on the Appalachians, we were painfully aware of many gaps in the present knowledge of the region. The following are areas of considerable scientific and/or practical interest which could greatly advance the understanding of Appalachian tectonics and the behavior of faults contained herein.

(A) In situ stress measurements

Assessment of fault reactivation would be considerably enhanced by knowledge of the in situ stress at specific sites. However, present understanding of crustal stresses is poor. Measurements of in situ stress require that residual stresses be distinguished from tectonic stresses arising from current crustal movement. In addition, stress measurements are influenced by fractures, local topography, weathering, and man-made cavities. Proper evaluation of in situ stress data to separate spurrious components is presently difficult if not impossible. Further studies of present in situ stress techniques and development of new techniques will be necessary before earth stresses are more fully understood. Such studies will also increase the present scanty data density. Appendix A is an expanded explanation of the critical need for this class of studies.

(B) Evolution of fracture patterns across the Appalachian belt

Joint and lineament patterns are ubiquitious features of all mountains systems including the Appalachians. Many are superimposed on the ductile core region and consequently must reflect events and stresses in the later history of the belts. Others are part of the foreland and may reflect early or late brittle events and stress fields plus older structures propagated upward from basement. Thus, elements of these patterns represent some of the most recognizable structures related to the very late history of the region, the same time frame for which we have some of the least evidence of fault motions and the greatest need to know motion and stress history form a hazard viewpoint.

Unforunately, there are few areas of structural geology in which the link of laboratory and theory with field interpretation is more poorly known. Appendix D is a tongue-in-cheek critique of part of this problem. The fracture patterns of the Appalachians first need a clearer definition of the domain over which a given fracture type and orientation obtains. From associated structures having similar orientation and distribution as well as *in situ* STRESS STUDIES AS CLUES AS TO THE TIMING AND STRESS FIELDS responsible for that and associated pattern elements can be gleaned. We believe that once these fracture domains and origins are more clearly defined, they will represent a significant step forward in establishing the later stress and fracture history of the Appalachians and provide some additional constraints for seismo-tectonic zonation.

(C) Relationship between timing of deformation in core zone and foreland.

It is now generally recognized that the timing of deformation in the Piedmont and Blue Ridge relative to the foreland (Valley and Ridge), indicates that late Paleozoic Alleghanian deformation of the foreland has no recognized counterpart in the core. Moreover, it is apparent that, in at least the Southern Appalachians, the core zone has been translated westward a minimum of 250 km in the process of driving the deformation in the foreland. The lack of any recognized cuternide deformation or thermal events reflecting this translation represents a major gap in our understanding of Appalachian geology. As it seems unlikely (although not impossible) that the core zone could have driven this deformation without itself deforming, this suggests that major structures within the core zone could have been misidentified with respect to age. Thus the

Blue Ridge and Piedmont probably contain major Alleghanian structures, as well as Acadian and Taconic, which to date are the only ones recognized. A parallel question raised by this problem regards the nature of the mechanism by which this deformation occurred, a process which apparently failed to reset any age dates. This suggests that the deforming wedge of metamorphic and igneous rocks was subjected to a late stage cold deformation of unspecified nature. It can be demonstrated that the New England province which is a northern extension of the southern Piedmont and Blue Ridge may have been subjected to a similar type of translation and deformation, consequently serious questions regarding the interpretation of New England geology may be raised as well. Thus present interpretations of the structural history of the entire Appalachian core zone now seem open to question.

In order to resolve this problem, it will be necessary to both complete basic regional mapping in the southern Appalachians, as well as undertaking a detailed re-examination of core zone geology in selected traverses across the belt. Such traverses should attempt to link the Alleghanian structures in the foreland with their counterparts in the internal zone.

(D) Fracture and fault zone permeability

An understanding of fluid migration through crust is critical for the solution of problems including recovery of hydrocarbons, tapping of geothermal energy and disposal of nuclear waste. Because fracture and fault permeability is orders of magnitude higher than intact rock permeability (Kranz and others, 1979), migration of fluids along fractures and with in fault zones is an important component in the three processes mentioned above. Several aspects of fracture and fault permeability will require attention in future studies. Effective stress laws for joint aperture and thus permeability do not account for the behavior of joints and faults with a complicated stress history (Engelder and Scholz, 1980). Reaction of wall rocks with pore fluids also result in changes of joint aperture (permeability) are primary parameters controlling the permeability of fractures and fault zones. Secondary parameters include the surface roughness of joints, thickness of fault zones, and grain size distribution of fault gouges. The effect of these parameters on _in situ_ permeability will require detailed laboratory studies. There will be a need for the integration of lab results with field observations of fault zones and fractures by geologists with an eye for recognizing the effect of fluid flow through rock. Finally, larger scale field experiments will be required.

(E) Details of Evolution of passive margins applied to Eastern U.S.

The late history of the Appalachians is in large measure the tectonics of a passive continental margin evolution superimposed on an Alpine mountain system. Data and theory on this class of structures have been accumulating rapidly from many regions of the world including the Eastern U.S. Many of the details of presently active faults regional fracture patterns and _in situ_ measurements in the Appalachian region are manifestations of these tectonics. For example, the Coastal Plain hinges as well as the classic erosion surfaces of the Appalachians must be the products of major tectonic processes, the detailed nature of which are only partially understood. Linkage of offshore data with onshore geomorphic effects with stratigraphic studies, and with younger structures is an area which should continue to enjoy strong support.

(F) Recent advances in our understanding of both frictional sliding and pressure solution

Diffusion controlled creep phenomena suggest that surfaces generated by these different modes of deformation should produce distinctively different textural features. Preliminary field reconnaisance on both the Talas Fergana fault, Kirghizia, SSR, and the San Andreas supports this concept.

A possible test of this hypothesis could be made by examining textural characteristics of fault surfaces from different structural environments: 1) thrust faults postulated to be the product of aseismic creep; 2) known earthquake faults; 3) a reactivated basement fracture of long sustained, complex history. A systematic examination of these faults should reveal whether they can be distinguished on the basis of the deformation textures of the fault surfaces. A positive answer to this question would indicate a definite potential for the characterization of a fault surface as the product of seismic or aseismic activity solely on textural features.

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APPENDICES

Appendix A: IN-SITU STRESS MEASUREMENTS

The reactivation of any pre-existing fault depends upon the contrast between the mechanical properties of the fault versus country rock, and on the magnitude and orientation of the stress field with respect to the fault. Even with the "weakest" faults (brittle, unhealed), no shear motion is possible if the fault is parallel to a principal stress plane, because no shear stress exists in principal stress planes (Jaeger and Cook, 1976). When a fault does not lie in a principal stress plane it may still have an orientation with respect to the stress field unfavorable for reactivation.

Handin (1969) described the relationship between the Mohr-Coulonb failure envelope having a slope angle of ϕ (the angle of internal friction) and the sliding friction envelope having a slope angle of θ_s (the angle of sliding friction). Although sliding friction experiments are notoriously "noisey" and although much disagreement exists among authors regarding the details of the sliding process, general agreement does exist that for most rocks the angle of sliding friction is about 30^o (Byerlee, 1978; Stesky, 1978). Typical values over a wide range of rock types, pressures, temperatures, moisture contents, and sliding rates range from 17^o to 40^o ($0.3 \leq \tan \theta_s \leq 0.85$). For an extended discussion of variation in friction along natural fault zones see Engelder (1979b) which is included in this report as Appendix B. The angle of internal friction for most rocks is about 30^o ($10^o \leq \theta \leq 50^o$). Only for highly clay-rich fault gouges is there a major difference between the slopes of the failure envelope and the sliding envelope.

Handin's (1969) analysis shows that when the two envelopes are subparallel, there is a wide range of pre-existing fault orientations which cannot be reactivated, instead new faults develop in the intact rock (Fig. XX-1).

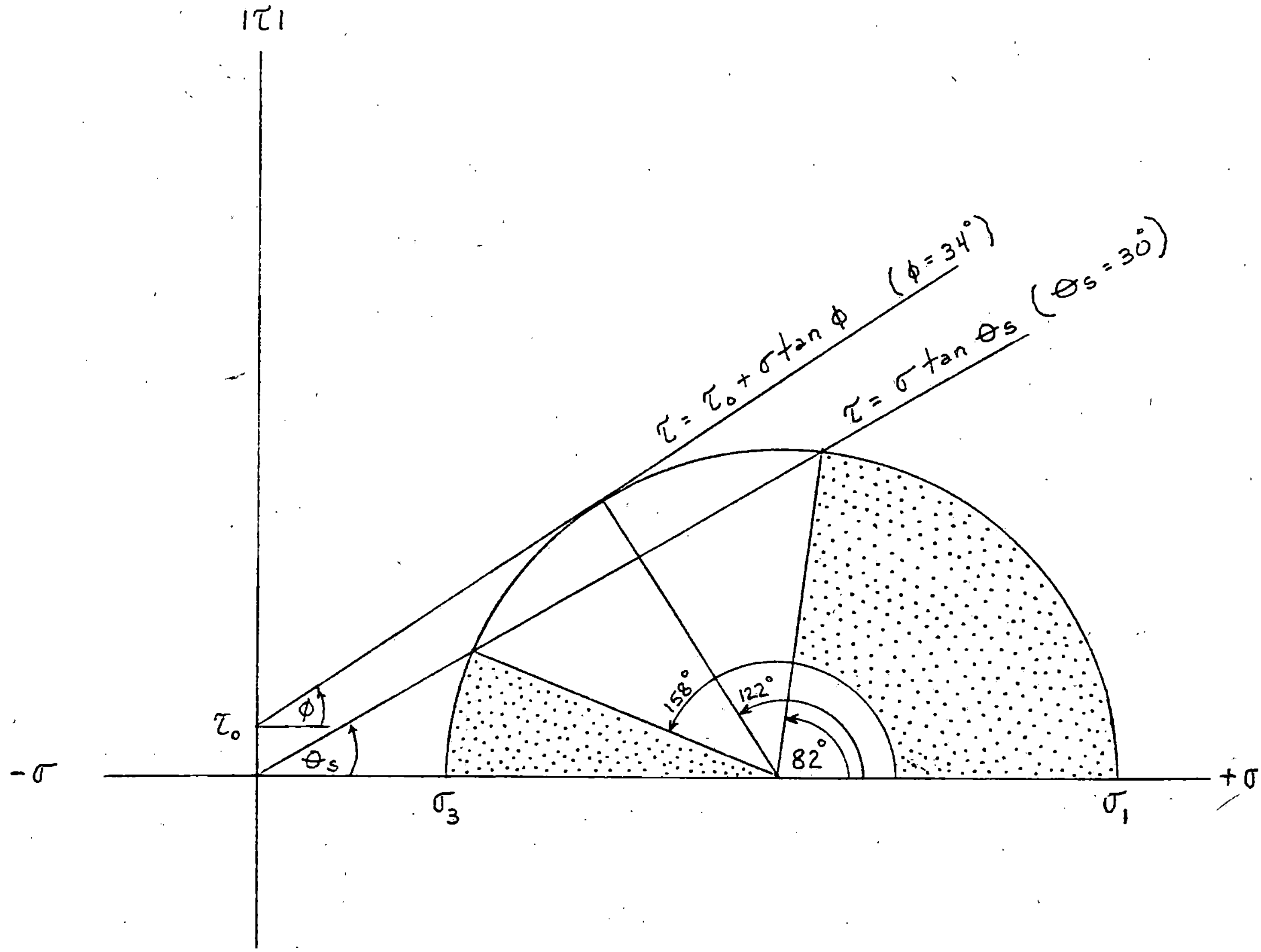

Figure XX-1

Mohr circle plots for the failure envelope for an intact rock ($\tau=\tau_o+\sigma\tan\phi$) and the sliding friction envelope for a fault in that rock ($\tau=\sigma\tan\theta_s$). The stippled areas represent the orientations of pre-existing faults which cannot be reactivated in the stress field illustrated. In this example faults inclined to the maximum principal compressive stress at angles of less than 11°, or more than 49°, will not be reactivated.

Conversely, pre-existing faults of favorable orientation will be reactivated.

A precise evaluation of "safe" fault orientation (those not subject to reactivation in a given stress field) requires experimental determination of ϕ and θ_s. In general, however, it is clear that faults inclined to the maximum principal compressive stress at angles of about 15 degrees or less, or at angles greater than about 60 degrees, are not likely to be reactivated. For some faults the "safe" zone may be even wider.

The foregoing discussion suggests that an assessment of fault reactivation would be considerably enhanced by knowledge of the in situ stress at any specific site. Three techniques have been utilized to measure orientation and/or magnitude of in situ stresses. The first relies on focal plane solutions of local earthquakes (Sbar and Sykes, 1973) and is the least satisfactory. There is no way of knowing whether a given earthquake involves reactivation of a pre-existing fault or a new fracture; consequently, the determination of the orientation of the maximum principal stress is non-unique. In general, focal plane solutions can define the quadrant containing the maximum principal stress but not its precise orientation (McKenzie, 1969).

The second technique utilizes strain relief methods, usually overcoring, and can yield both orientation and magnitude of the stresses. The chief advantage of this technique is its relatively low cost. The chief drawbacks are the fact that it is a surface or very shallow measurement, and that the orientation measurement has relatively large scatter. An error in the principal stress orientation of ±15 degrees precludes use of the Handin (1969) analysis of "safe" fault orientations.

The third technique involves hydraulic fracturing of the rocks surrounding a well, at any depth from near surface to thousands of meters. Routinely it is possible to determine the magnitude and precise orientation of the least principal compressive stress and the orientation of the greatest principal compressive stress. Under ideal conditions the magnitude of greatest principal compressive stress can be calculated; but this calculation depends on assumptions which may produce large error (Dunn and others, 1978). However, the Handin (1969) analysis does not depend on the magnitudes of the principal stresses, only on their orientations. These orientations can be determined unambiguously by hydraulic fracturing.

Several in situ stress measurements in a variety of tectonic settings, from active fault zones (Keys and others, 1979) to intracratonic basins (Bredehoeft and others, 1976; Haimson, 1976), suggest that below 100 to 200 meters both the maximum (σ_1) and minimum (σ_3) principal compressive stresses lie in or near the horizontal plane. The relations are: $\sigma_1 > \sigma_2$ = overburden weight $\geq \sigma_3$. The hydrofracture forms perpendicular to σ_3 and the strike of the hydrofracture is parallel to σ_1.

For most of the Appalachians the maximum principal compressive stress is approximately horizontal and trends ENE (Haimson, 1977; Sbar and Sykes, 1977; Zoback and others, 1978); however, the data are much too sparse to apply to a specific site. If in situ stress measurements by the hydrofracture technique were made in reference to a specific site, then the orientations of σ_1 in the vincinity of that site would be well documented. The orientation of faults in the same area could then be analyzed to determine which, if any, were likely to be reactivated under the existing stress field.

Appendix B: PROBLEMS OF DISTINGUISHING SEISMIC FROM ASEISMIC FAULTS

A major problem encountered when evaluating the seismic potential of an area is the determination of whether a given fault or set of faults is seismic or aseismic. Evidence used in making such judgements consists of such parameters as known seismicity, offsets of recent alluvial deposits, evidence of liquefaction, blowouts, etc, the presence of these features being generally accepted as the product of earthquake faulting. However, in areas such as the eastern U.S., evidence of this type is generally lacking and usually only the fault surface itself can be examined. Unfortunately, at present there exists no well defined set of characteristics whereby an earthquake fault may be distinguished from a ductile fault due to creep. However, fault surfaces contain information about the sliding process which is not yet understood.

It is our hypothesis that recent advances in our understanding of pressure solution and other low strain rate phenomena, combined with observations from experimental work on the textures associated with stick-slip phenomena, has the potential for developing textural criteria which may allow seismic faults to be distinguished from aseismic faults. The rationale underlying this hypothesis is that there is a difference in textural features of fault surfaces generated by stick-slip motion as opposed to those generated by creep, and that these differences have not been properly documented.

As has been pointed out by Elliott (1973, 1976) and Durney and Ramsay (1973), among others, one of the most common textural features of thrust fault surfaces in foreland mountain belts is crystal fibers which until recently have commonly been misinterpreted as frictional wear phenomena (slickensides). As these fibers are the product of diffusion-controlled processes, the motion on these surfaces is interpreted to be one of steady state creep at very low strain rates (on the order of 10^{-10}/sec or less) and thus aseismic. Recently, experimental work by Rutter and Mainprice (1978) has supported the hypothesis that pressure solution deformation is characteristic of low strain rates and plastic deformation. In their conclusions they point out that "studies of deep levels of ancient fault zones now exposed at the earth's surface should reveal the various deformation mechanisms which characterize fault zones at various depths. If the proposed process of cataclastic flow controlled by pressure solution sliding is important in nature, we would expect it to be particularly so in the intermediate depth ranges, between regimes dominated by seismicity on the one hand and plastic deformation on the other" (Rutter and Mainprice, 1978, p. 652).

Engelder (1974) has described microscopic wear grooves on slickensides bearing a striking similarity to wear grooves produced during frictional sliding experiments and has suggested that their presence is an indicator of paleoseismcity. In addition to wear grooves, experimental work indicates that true mechanical wear phenomena include such features as tectonic polishing, gouge and pitting (Paterson, 1978). There should be distinct differences between slickenside surfaces with wear grooves as documented by Engelder (1974) and slickenside-like surfaces which are in fact the product of pressure solution during aseismic slip.

To date, systematic studies of the features associated with fault surfaces in general have not distinguished between those features diagnostic of pressure solution and diffusional phenomena and those caused by brittle failure (e.g., Brock and Engelder, 1977). This is in large part due to the recent recognition of the importance of solutions in deformation, as it is only since the early 1970's that a significant number of papers have emerged on this subject (e.g., see review by Williams, 1977).

Based on the preliminary work that has been done on fault surfaces dominated by features characteristic of aseismic slip, there seems to be a variety of textures which characterize these surfaces and which are distinctly different than the features produced in frictional sliding experiments. If this suggestion is true, then there may exist the possibility of developing a set of textural criteria, observable in the field by which seismic and aseismic faults may be distinguished. Until this has been accomplished, however, geologists should not automatically assume that any surface bearing "slickensides" or even breccia is necessarily the product of earthquake faults. Instead, the textural characteristics of the fault surface should be carefully evaluated in light of recent developments on pressure solution creep as well as frictional sliding to avoid the frequent misidentification of fault surfaces as seismic when in fact they were aseismic.

Appendix C: SOME TERMINOLOGY FOR MYLONITES AND CATACLASTIC ROCKS

A variety of terms exist for structures and rock types associated with high degrees of strain. Unfortunately, many terms are relics of the older literature. Many others fail to take into account the range of metamorphic conditions that may be represented by several stages of deformation within a single rock. In particular, Higgins' (1971) professional paper on "cataclastic rocks" has much to commend it, but the proposed terminology mixes late stage cataclastic effects with the mylonitic phases to such an extent that many of the definitions seem unclear or unacceptable. Definitions used throughout the present paper are given in the glossary, but a more general framework for those definitions is presented here.

The character of highly strained or broken rocks is largely a function of the composition of the original rock mass, normal and shearing stresses across the failure zone, the metamorphic condition at the time of strain, the type of strains, the strain rate, and the degree of recovery in the minerals following the strain or breakage. The effects of strain are largely diminution of grain size, whereas those of recovery involve annealing of the strains within crystal lattices and the formation of new mineral grains. This competition between strain rate and recovery (largely a time, temperature, lattice energy, and fluid effect) determines much of the rock character and corresponding terminology (Fig. XX-2). Rapid strain at relatively low temperature with little or no recovery results in a cataclasite. When some recovery dominates, ordinary metamorphic rock terminology is used even though the total magnitude of strain can be quite large and involve a wide range of ductile phenomena. These distinctions between ductile flow, ductile faulting and brittle faulting are fundamental. A single hand specimen or fault zone may exhibit all three styles of behavior developed by superpositions at differing times in its history.

Brittle faulting occurs at high rates of deformation, low temperatures and low recovery rates. The typically formed rock types, if any, are: unconsolidated to poorly consolidated ground rock or gouge, microbreccia, and breccia. Commonly, the microbreccia and breccia are thoroughly silicified into a more homogeneous chert-like mass, traditionally described as "flinty crush rock." The brittle faults in which these rocks occur are typically on or in discrete well-defined planes or surfaces. Slickensides are common on surfaces as a result of two processes: mechanical wear grooves reflecting cataclasis under high frictional resistance to motion, and pressure solution grooves developed much as ice is selectively melted beneath the blade of an ice skate. Frictional heating of the surfaces might produce small amounts of very local melt. Essentially instantaneous quenching of the broken material and melt produces pseudotachylite or highly strained microbreccia with minor amount of glass (Wenk, 1978). Pervasive injection of psuedotachylite suggests instantaneous, large pressure differentials and fluidization of the broken and slightly melted material.

At slower rates of deformation, fibrous minerals connecting formerly adjacent points can grow within the fault surface. These fibers of quartz, calcite, serpentine, or other minerals are commonly misidentified as slickensides. It is important that the distinction between fibers and true slickensides be maintained, because the fibers indicate creep displacement so slow that a particular plane would not have produced an earthquake while the fibers were growing. Kink bands or discretely bounded zones of systematic angular rotation also occur under conditions separating brittle faulting from foliation development in ordinary metamorphic rocks (Fig.XX-2).

Mylonites represent the region of Fig.XX-2 of relatively high strain rates combined with appreciable recovery rates. Despite the Greek origin of the world (mylo = mill), the rock has little to do with clastic milling. It represents fundamentally a diminution of grain size accomplished by ductile strain as argued by Hatcher (1978). The flow planes are frequently termed fluxion structures, a synonym for mylonitic foliation. Larger crystalline masses contained within the metamorphic foliation are termed megacrysts. If they have formed largely by growth of a new mineral grain the prefix "blasto" is applied. The megacrysts formed by growth also are called "augen" (German, = eye). Thus augen gneiss and blastomylonite represent high strain rate lithologies gradational into typical high grade metamorphic rocks. Alternatively, the megacrysts may be formed by breakage of pre-existing mineral grains. If the broken and possibly rounded fragments are floating in a fine grained mylonite matrix with little or no sign of reaction with that matrix, the rock is a protomylonite (synonym = flaser gneiss). True mylonites show appreciable reaction rims between cataclastically produced megacrysts and the mylonitic matrix. Consequently they are much more closely related to protomylonites than to blastomylonites (in which the original megacrysts were produced by growth). With relatively complete reaction and absorption of the clastic megacrysts, an ultramylonite is produced. When quartz megacrysts are caught in the process and stretched to axial ratios of 10 to 1 or even 100 to 1, the term "ribbon quartz" is applied.

The history of metamorphism and deformation of a rock mass commonly extends over a long period of time during which several stages of high strain rate may occur under differing conditions. The result can be a complex array of superimposed strain and recovery structures. In general, the ductile deformations are widespread; the semiductile mylonite-type deformations are concentrated into zones up to hundreds of meters in thickness; the brittle features are concentrated into more tightly defined zones which may represent only a few percent of the total thickness of an older mylonitic zone. These late stage, brittle components of the total deformation are easily overlooked in the description and exploration of a major fault zone. Their volume is only a small part of the total zone; their nature encourages erosion and lack of exposure at the surface and lack of recovery in drill cores. Nevertheless, they are among the most critical features for seismic risk analysis. Too frequently, site analysis involves vast amounts of time and effort on defining and dating the ductile aspects of a major fault zone and ignores the critical brittle fault aspects of the late and possibly dangerous history of the zone.

The evolutionary history of rock from a major fault zone might follow a path through the stages of Fig.XX-2 as illustrated in Fig.XX-3. The main rock mass would pass through a series of deformations involving low strain rates as it goes to high metamorphic rank and back down to ambient conditions. Superimposed on this general pattern would be a number of brief pulses of fault-like, high strain rate. Frictional heating at higher strain rates might cause temporary slightly improved recovery as illustrated by curvature of the spikes to the right. Early breccias and gouge (A) or mylonite (B) on Fig. XX-3 would be homogenized and in part camouflaged by later metamorphism and ductile flowage. Mylonites and cataclasites produced after the metamorphic peak would be much more likely to survive and be identified. Once formed, they become metamorphic rocks which go through the same later stages of structural deformations and retrogressive metamorphism as all the other rocks in the mass. Some of the mylonites (D) would be likely to have a variety of younger S surfaces superimposed on them, be bent by kink bands, undergo passive and/or flexural folding and (E), be slickensided, or brecciated by late fault motions. Thus, the typical mylonite specimen should be considered the end result of a series of these deformations.

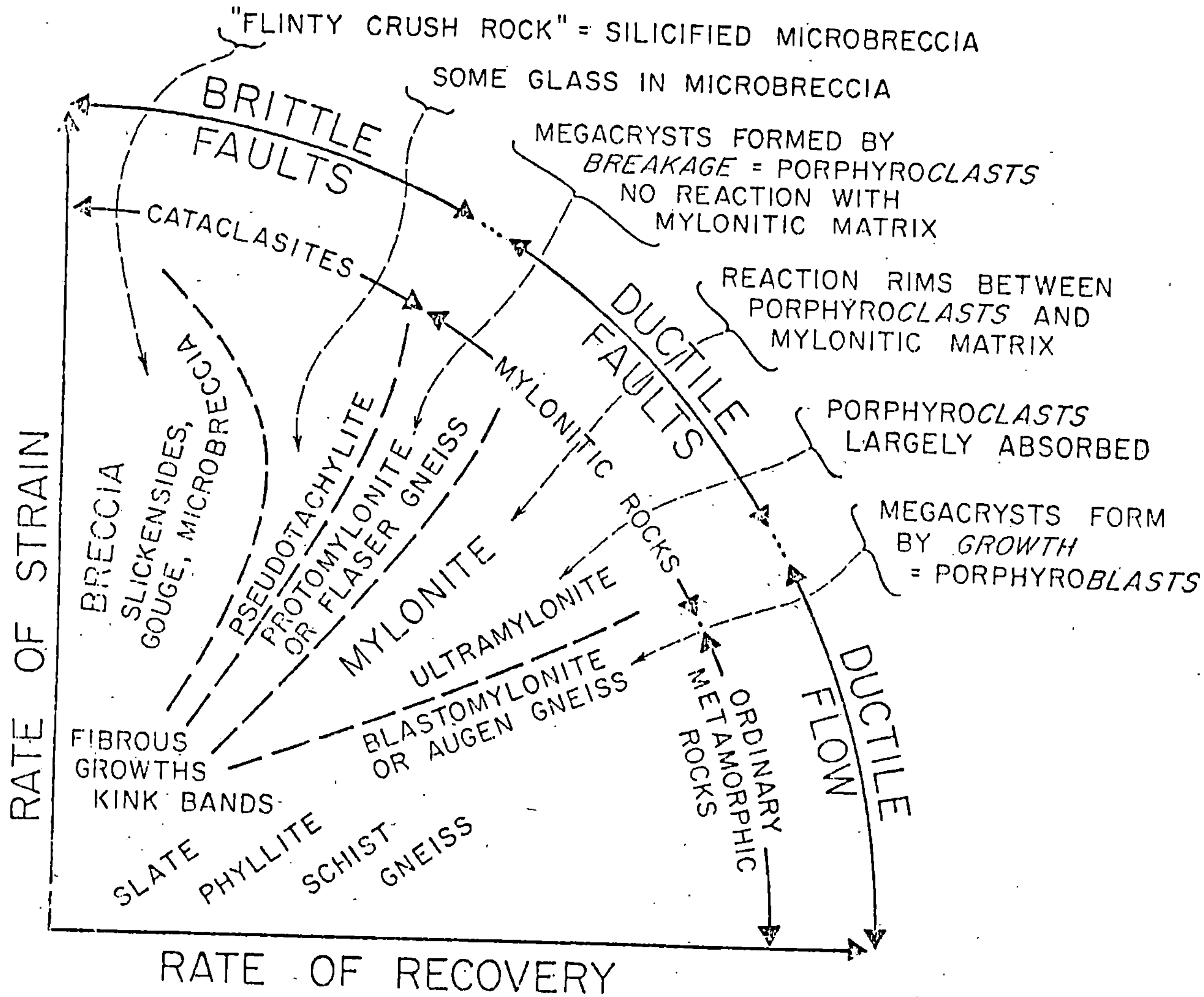

Figure XX-2 ANNEALING AND RECRYSTALLIZATION, TEMPERATURE AND FLUID DEPENDENT

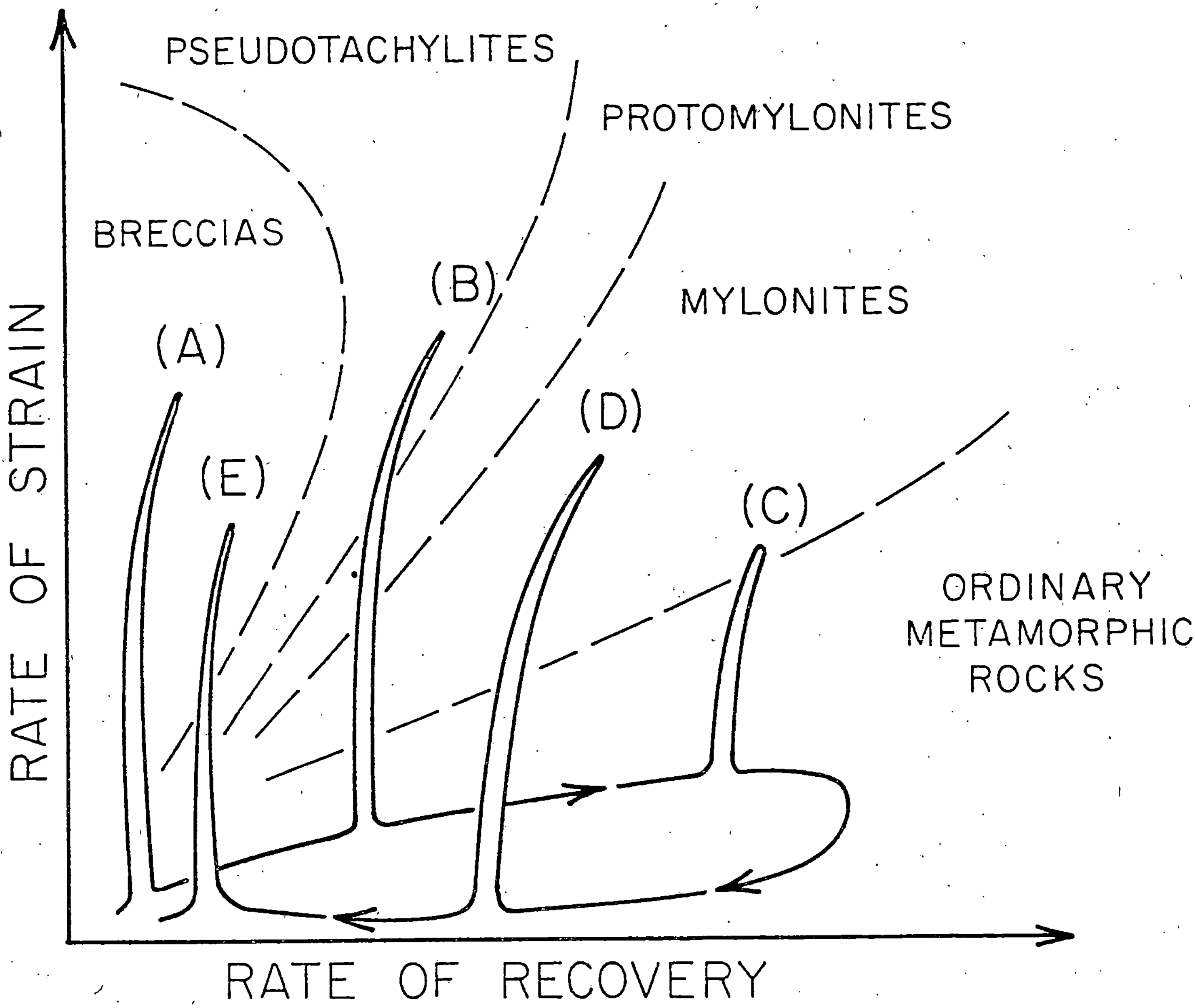

Figure XX-3

Diagram showing the range of cataclastic/mylonitic products with variations in strain rate and recovery rate.

These distinctions among the several cataclastic and mylonitic phases of deformation recorded in rocks within fault zones require careful observation both in the field and under the microscope as well as greater care in terminology. Lack of a general framework for terminology as well as failure to make the distinctions in the past has caused considerable confusion and needlessly complicated the task of seismic risk analysis.

Appendix D: LINEMANSHIP

Linear topographic, geologic or biologic elements reflecting in some way the bedrock and geomorphic characteristics of an area have been recognized by geologists for more than a century. Some pioneering linesmen, such as W. H. Hobbs at the turn of the 20th century, began systematic analysis of these linear features to win widespread recognition and general disbelief by the geologic profession. The advent of aerial photos spawned a prolific new generation of linesmen who demonstrated clearly that by squinting obliquely enough across air photos an infinite number of random lines could be drawn. From these roots evolved a new artform, Linear Geo-art. This art is displayed most commonly as maps with large numbers of straight lines interspersed with maps separating some of the lines according to azimuth, the whole crowned by a well executed wind rose plot. Like many other modern artforms, most linear Geo-art seeks to develop a pleasing pattern for the eye and leaves deeper significance to the mind of the beholder.

Recently, satellite imagery has attracted a new generation of geologists to develop further the potential beauty of this old artform. The new artists began to re-invent the line and to analyze it in a "scientific manner," apparently unaware of the existence of many rules of Linear Geo-art and the subtle, sophisticated methods of self and mutual delusion which generations of linesmen had developed before them.

With so many new practitioners, the possibility must be considered that a few of these tyro linesmen, through accident or design, might corrupt a thing of beauty into something of scientific significance. For the most part, the new linesmen simply need instruction in the artform to avoid such mischance. Accordingly, this paper lists some of the time-tested but generally unwritten guidelines for the practice of Linesmanship and Linear Geo-art. These guidelines, if followed carefully, should insure the long term preservation of this lovely type of art unblemished by any taints of science.

DEFINING THE LINES

The first task of a linesman is generation of "raw data" or lines, the more the better. It is not the quality of the lines which counts but rather their number and their potential for compilation into artistically pleasing patterns.

Rule 1: Given an array of points on maps or satellite imagery, aerial photographs, lines may be drawn through any pair of points.

a) Looking obliquely across a map in the direction of desired lineaments foreshortens distances along the line of sight. This permits connecting of two points which otherwise could not be joined in good conscience.

b) With sufficient cause, one point will suffice. The line is drawn through the point parallel to the most significant nearby lineament. This rule is known to all prospectors who can demonstrate that their prospect pit lies on an absolutely straight line passing through the headframe of the major mine in their district.

Rule 2: Given enough incentive, competent linesman should be able to find something uniquely significant about any random line drawn on a geologic map. However, it is generally better to have a reason for drawing a line. (Parallelism to an adjacent line is usually reason enough).

Rule 3: No line ever ends. Thus, projected far enough, the line must intersect some significant feature, proving the linear feature extends at least that far. (See Rule 23 for changing the points through which a line may project).

Rule 4: The width of a linear feature should be great enough to include all elements necessary to define the feature as a line.

(a) Lines with widths greater than their lengths (aspect ratio greater than 1) are considered poor practice.

Rule 5: Only those lineaments you personally discover on imagery are to be considered real without ground checking. All others need very careful documentation.

(a) Anytime two or more people can see the same lineament (which is rare), it is at least worth a scientific publication, and is usually worth drilling for oil, water, minerals, or whatever. This is difficult to get across to some of the more uneducated and conservative management types, who for some reason still insist that the poor geologist get out in the hot sun and wear out a perfectly good pair of boots to "re-prove" that most lineaments can't be detected on the ground and therefore field work is an expensive waste of time.

Rule 6: In detecting lineaments, the more sophisticated, modern, and expensive the equipment used, the more significant the data must be.

ARRAYS OF LINES AND THEIR DESCRIPTIONS

Systems of lines bearing some pleasing relationships to each other are an integral part of the art form. Differences as to what is most pleasing separate two main schools of linear artists, the parallel and the orthogonal schools. R. Hodgson has suggested (personal communication, 1978) that the distinction between the parallel and orthogonal schools may be conditioned in infancy by cribs with either vertical bars or diagonal mesh. A sub-group of the parallel school sees all lines as arcs of circles, preferably concentric circles. Whatever the school, the desired patterns or arrays must be developed carefully, preferably by biasing the lines as they are being drawn. Failing this, definitions of familiar English words may be biased to mold the description into the desired form as discussed in the following rules.

Rule 7: Two lines are "parallel" when they differ by less than 30 degrees of azimuth.

(a) The squeamish can use the terms "sub-parallel" or "close azimuthal relationship."

Rule 8: Enough random lines have been drawn on a map when it is possible to extract from the random pattern, sets of linear elements "parallel" to each other.

Rule 9: Eight fracture directions, each with an uncertainty of ± 15 degrees, are usually enough to include the full spectrum of 180 degrees of random line azimuths.

(a) Eight-fold symmetry has a certain elegance to it, particularly if azimuths of the lines are selected so as to be parallel with wrench faults on the other side of the globe.

Rule 10: "Orthogonal" lines usually meet at angles somewhat more than sixty degrees.

(a) If necessary "orthogonal" can mean any two lines which intersect. This is the basis for a general observation that most areas are characterized by "orthogonal" patterns of lineaments.

(b) Care should be used not to apply the definitions of Rules 7 and 10 simultaneously. "parallel" lines with an "orthogonal" intersection angle might strain the limits of even the flexible definitions given here.

Rule 11: Faced with a lineament having an azimuth halfway between two expected directions, competent linesmen can usually bend the feature into a straight line coinciding with one or the other of the directions.

(a) Truly great linesmen can make the lineament coincide with both directions. (Use of two different publications is recommended.)

PLOTTING OF DATA

Several forms of data plots are commonly used by linear artists. These deceptively simple plots can be engineered to a remarkable degree to develop or suppress components of the data, to produce aesthetically pleasing results, or to fit predetermined verbal descriptions of the data.

Rule 12: Histogram plots of aximuth-frequency should have a sufficient number of maxima so that two peaks can always be found with an "orthogonal" relationship.

(a) If the peaks on the histograms are not prominent enough, the vertical scale can be expanded until the peaks reach sufficient height to convince any skeptic they are real.

Rule 13: Unwanted peaks on bar graph histograms are easily removed by shifting the boundary between two bars. This splits the peak into two smaller bars and relegates the data to "noise".

(a) Use of a running average limits the artist somewhat in this practice of peak splitting but offers an advantage in return. By experimenting with different size intervals for the running average, one interval usually can be found which shifts a peak or merges several peaks into a single larger peak having a desired azimuth.

Rule 14: Auto-correlation and spectral power density plots of the data are indispensible. They give a certain mathematical elegance to a paper while concealing from the uninitiated the fact that you still had to correlate the azimuth-frequency histograms by eyeball.

Rule 15: A mismatch of 15 or 20 degrees in correlating peaks on the azimuth-frequency histogram can be camouflaged easily by plotting the data in wind rose form. A mismatch of 20 degrees of azimuth of a peak is barely recognizable on a wind rose plot having several other maxima. These plots are pretty, easily read, and rarely suspected of "engineering" by the casual observer.

Rule 16: Sophisticated population density contouring of the numbers of lineaments per square kilometer of certain areas has proven that fewer natural lineaments are observable in urban areas or over large lakes than in open country. Thus, computer processing of lineament maps derived from satellite imagery can find areas of low density of natural lineaments, and thus prove useful in location of previously unrecognized cities and lakes.

Rule 17: Scan lines are very useful in eliminating lineaments that are of no significance provided the flight line is perpendicular to the lineaments. On the other hand, the reverse effect can be obtained to enhance lineaments that are of a profound importance to a pre-established model, particularly if proper computer processing is applied.

(a) A similar, but more complex technique involves the use of properly selected sun angles or radar look angles to enhance, suppress, or change the azimuth of lineament trends by shadow illusion effects.

INTERPRETATION OF LINEAR PATTERNS

The interpretation of geologic lineaments into a larger tectonic synthesis is where the full talents of the artist can be brought into play. The objective is to develop a complex fabric composed of lesser patterns, each having its own elegant symmetry. Additional merit can be achieved if "plate tectonics" can be interwoven with the interpretation. For example, proper engineering of wind roses and histograms (rules 12, 13, and 15) can make data look similar or can aid in demonstrating the rotational aspects of plate motions between adjacent areas.

Rule 18: A useful simplifying assumption in lineament interpretation is that all "parallel" features are the same age regardless of scale or character.

Rule 19: Never specify the scale of a lineament in describing it. This knowledge may give the audience an unfair advantage in understanding your theory.

Rule 20: In relating lineaments to stress systems, a most useful simplifying assumption is the repeal of the laws of mechanics. Not too many readers will notice that your extension fractures strike perpendicular to maximum compression.

Rule 21: Never make distinctions among classes of lineaments or fractures while recording them. This take the challenge out of using statistics to separate the classes afterwards.

Rule 22: Lineaments should intersect all important geologic features in an area. This is the reason for having an adequate number of lines in your original random data. If a few features fail to lie on lineaments, this fact indicates an oversight in the original data generation. The oversight is readily corrected by drawing a line through the geologic feature parallel to the major fracture trend of the area (Rule 1 (6)).

Rule 23: Lines from your area should extend unchanged in azimuth at least across a continent. If a line does not project to the obvious point that you desire, find another map projection. Sooner or later a projection will be found on which a straight line will project to its proper place, prooving that the lineament goes through that point.

Rule 24: Never define the ages of "orthogonal" sets of lineaments too precisely. Differences of a few hundred million years between the intersecting sets are not very significant when compared to the elegence of such patterns.

Rule 25: Pattern is everything. As long as sets intersects with an "orthogonal" relationship, it doesn't matter if one set is a fault system and the other is wind streaking. The map area can be added to the growing register of regions with "orthogonal" linear patterns.

Rule 26: All lineaments represent the outcrop of vertical fault planes. Interpret all lineaments as faults no matter how strong the evidence is that they are mostly zones of enhanced joint development. The fault interpretation causes much more excitement, insures attention by a much wider audience and aids greatly in raising funds for continued practice Linear Geo-Art.

Rule 27: If you don't know what caused the lineament, it must have very profound significance.

Rule 28: If one line terminates against another, always assume that an older line has been cut off along a younger fault line. Never hint that an older fracture can form a boundary discontinuity for younger fractures to terminate against.

Rule 29: In interpreting lineaments, remember the first law of tectonics: "Bury it deep". Failing this make certain the proposed stresses are old enough to be "lost in the mists of time".

Rule 30: Each successive fracture episode is the very first to break an area. This assumption of eternal crustal virginity assures mechanical isotropy of an area and does not confuse readers with such complicated concepts as tectonic heredity and pre-existing influences on fracture directions.

Rule 31: Any truly great theory for the origin of lineaments is incapable of proof.

CONCLUSIONS

The art of lineament analysis is still alive and well within our science. The above rules should forstall any possible degradation of the art into a science. They should also help the geologic public to recognize the work of linesmen and to appreciate the subtleties of linear Geo-art as its examples continue to appear in abundances in our scientific literature.

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16. ABSTRACT *(200 words or less)* The characterization is a synthesis of available data on geologic faults in the Appalachian foldbelt regarding their description, generic implications, rate of movement, and potential as geologic-seismic hazards. It is intended to assist applicants and reviewers in evaluating faults at sites for nuclear facilities. Appalachian faults were found to fall into 13 groups which can be defined on either their temporal, generic, or descriptive properties. They are as follows: Group 1, Faults with demonstrable Cenozoic movement; Group 2, Wildflysch type thrust sheets; Group 3, Bedding plane thrusts - décollements; Group 4, Pre- to synmetamorphic thrusts in medium to high grade terranes; Group 5, Post metamorphic thrusts in medium to high grade terranes; Group 6, Thrusts rooted in low crystalline basement; Group 7, High angle reverse faults; Group 8, Strike slip faults; Group 9, Normal (block) faults; Group 10, Compound faults; Group 11, Structural lineaments; Group 12, Faults associated with local centers; and Group 13, Faults related to geomorphic phenomena. Unhealed faults (groups 1, 6, 8, 9, and 12) must be considered candidates for reactivation. Healed brittle or ductile faults (groups 4, 5, and 10) are not places of mechanical discontinuity and are unlikely candidates for reactivation. The remaining groups (2, 3, 7, 11, and 13) should be individually assessed as to their potential for reactivation.

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