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A CHARACTERIZATION AND CLASSIFICATION OF GEOLOGIC FAULTS IN THE APPLACHIAN FOLDBELT.

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C. Fault Classes

1. Bedding plane thrusts -- Decollements.
2. Faults penecontemporaneous with wildflysch.
3. Thrusts rooted in low grade to unmetamorphosed crystalline basement.
4. Block faults.
5. Faults associated with local centers (diapirs, cauldron subsidence, intrusions, and crypto-volcanic structures).
6. Pre- to synmetamorphic faults in medium to high grade terrane.
7. Postmetamorphic thrusts in medium to high grade terrane.
8. Strike slip faults.
9. Complex faults with long, repeated movement history.
10. Enigmatic faults, inferred faults such as the 38th parallel lineament.
11. Geomorphic faults with Tertiary history overprinting older Appalachian structures.
12. Faults with demonstrable Cenozoic movement.

Table I below summarizes the movement history of each of the twelve fault classes. The vertical extent of each line represents the time during which faults of this class were active, while the width of each line represents the degree of activity during various time intervals.

Fault Classes Most Subject to Reactivation

Fault classes 3,4,5,8, and 12 are brittle faults, either unhealed or filled (this terminology is defined in Section II. below); consequently, these faults are planes or zones of mechanical discontinuity with respect to the country rock 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 coun-

try rock (see Appendix XIX.A. for a discussion of critical fault orientations with respect to in situ stress orientation).

Particular attention must be given to Class 5 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, Class 9 faults have long histories of reactivation and at least some portions of their total movement histories were brittle. Moreover, there is some modern seismicity on both the Ramapo and Brevard faults; consequently these faults must be considered as possible candidates for further reactivation.

E. Fault Classes Least Subject To Reactivation

Fault Classes 6, 7, and 9 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 lower shearing strength than the country rocks. Jackson (1973) has demonstrated as much as 62% reduction in shearing strength for mylonites compared to their source rocks, when 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 Classes 6, 7, and 9. Typically the brittle features constitute the more easily eroded and less well exposed portions of these fault zones,

so some care must be exercised in determining the likelyhood of reactivation.

F. 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 erosion 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 begins 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.

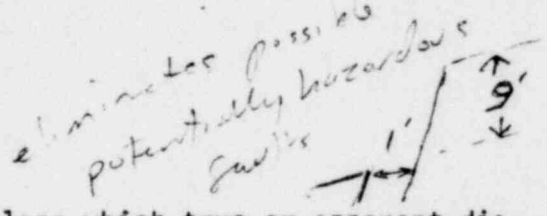
G. Relation of Seismicity to Surface Breaks

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).

II. DEFINITION OF KEY TERMS

The usual distinction between a fault and a joint or fracture is scale-dependent. A feature mapped as a fault at a scale of 1 inch equals 10 feet might be treated as a joint at a map scale of 1 inch equals 1 mile. We prefer a definition which is independent of map scale. Also, features variously described as "shear zones" or "zones of displacement" or "dislocation zones" may or may not be treated as faults, even though they clearly involve shear motion. We prefer less ambiguous terminology and will adhere to the following definitions throughout this report.

A. Fault



A fault is a surface or tabular zone along which true or apparent displacement parallel to the surface or zone is at least ten times greater than displacement normal to the surface or zone.

1. Ductile fault - A ductile fault involves no loss of cohesion normal to the fault at the time of last motion. Cohesion as used here refers to the tensile strength of the fault surface or zone in contrast to the unfaulted rocks on either side.

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.

into a wholly sedimentary section.

i. P-T Conditions - Class 3 faults form at metamorphic conditions of greenschist facies or below, implying temperatures below 300-400°C and maximum pressures of a few kb.

j. Relat onships 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 Class 3 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.

l. 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 Class 3 faults is different with location in the orogen. Generally the age decreases toward the south with Taconic Class 3 thrusts in the Berkshires (Ratcliffe and Harwood, 1975) and Reading Prong (Drake, 1970), and 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 (1968) 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

CLASS 4: BLOCK FAULTS

A. General description

Faults of this class are steeply dipping faults that extend to and disrupt basement (antithetic faults in headwall 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 class have probably developed at several times in the history of the Appalachians: in the late Precambrian associated with crustal extension and rifting (Bird and Dewey, 1970) within the Grenville crust, during latest Precambrian - Cambrian time associated with the Avolonian activity in the northern Appalachians (McCartney, 1969) and the Carolina Slate belt in the southern Appalachians (Long, 1979), during Pennsylvanian-Permian activity in the Narragansett-Boston-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 class 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 class.

The Mesozoic subclass contains the overwhelming majority of faults in Class 4. 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 subclass.

Class 4 faults are common throughout the Piedmont Province and in the coastal plain subsurface (Fig. 36). All high angle faults within the

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 37). 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 38). Lindholm (1978) suggested the local orientation of foliation may have affected the trend of the fault, producing a curvilinear trace. From a detailed study of the fault trace, Reinemund (1955) suggested that the Jonesboro fault is cut and offset by cross faults which had significant strike-slip component and these faults were subsequently intruded by diabase dikes (figure 39). 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 40). 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

B. Description of Fault Class

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 verticle.

(ii) along strike - Tends to parallel regional strike of basement. Most lack significant curvature, but may locally show curvature due to local anisotrophy. Composites or coupling of contemporaneous straight segments can give a regional indication of curvature.

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 41.

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 develope 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 anisotrophy.

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 stabilities 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 subclass major motion is not known with certainly, some may represent reactivation of older (Paleozoic faults). Major motions are Triassic and Jurassic. Motion frequently occurred during sedimentation. Seismic focal mechanisms indicate that in central Appalachians some mesozoic boarder faults may be ~~are~~ still active - but elsewhere most are apparently inactive.

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 effects 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 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 Principle Stresses - σ_1 is vertical and σ_3 is normal to strike at time of faulting. Slickensides and seismic first motion studies indicate that stress orientation can and in some cases have 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 axis 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 - Where networks are sufficiently dense, microseismicity has been found associated with the faults.

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 class. Faults of this class 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. contradictory to 7(d) above

c) Zones of silicification, zeolite mineralization, micro breccia can be 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 draps 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 class 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.

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 (Fig. 3). 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 class brought with them masses of ultramafic rocks and/or pieces of oceanic crust. The ophiolite sheets of the Bay of Islands in

Elaborate or provide ref.

Newfoundland (Williams, 1973) probably escaped metamorphism by being thrust onto the foreland. Those of the Baie Verte area were not so fortunate. The latter may be the history of many of the ultramafic bodies of the central and southern Appalachians.

4. History

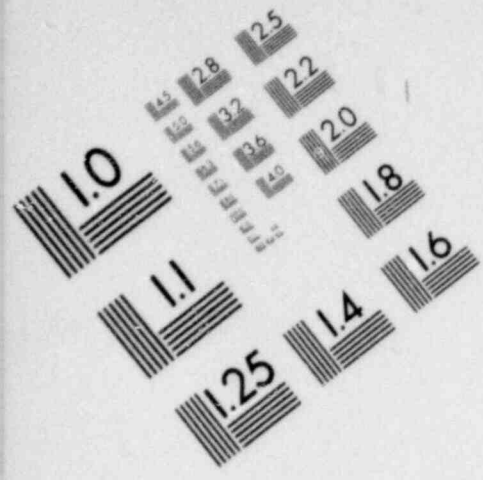
a. Age of Inception - The recognizable premetamorphic thrusts were generated immediately prior to the metamorphic/thermal peak, while the synmetamorphic thrusts formed during the thermal event. Timing of thermal events is different in different parts of the orogen. The Greenbrier and Hayesville faults 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 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 site 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



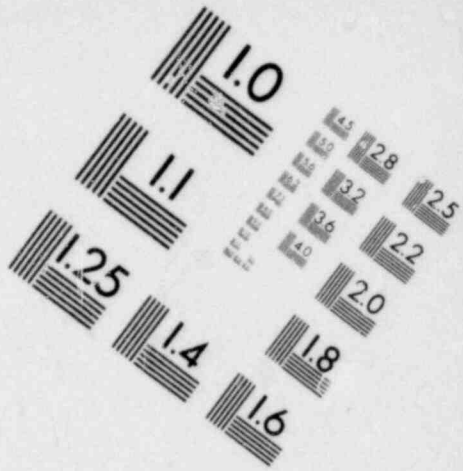
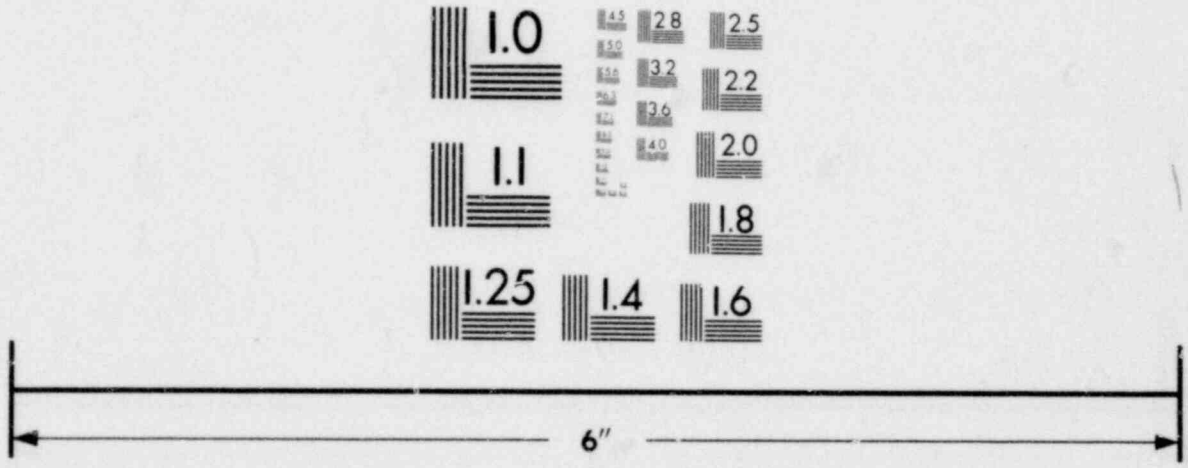
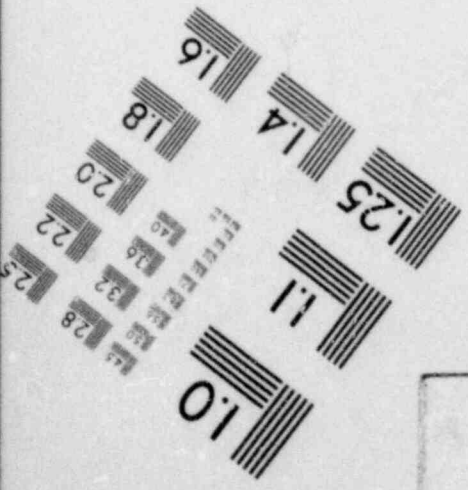
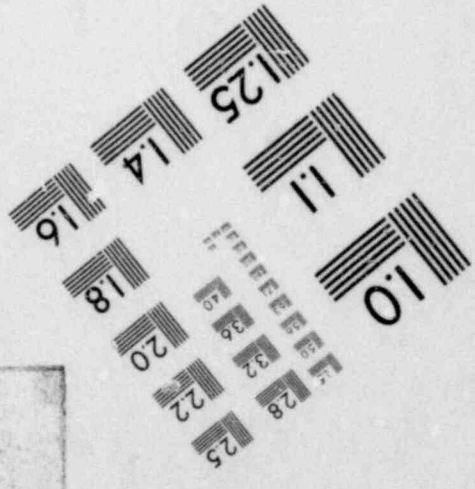


IMAGE EVALUATION TEST TARGET (MT-3)



MICROCOPY RESOLUTION TEST CHART





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 homogenous, planar, fine-ground 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 class.

   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 are not a major cause for concern, 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

Class 7 LATE-TO POST-METAMORPHIC THRUSTS IN MEDIUM TO HIGH GRADE TERRANES (PALEOZOIC CYCLE)

A. General Description

Thrusts of this class are generally crystalline thrusts in which there has been enough motion (minimally) to juxtapose metamorphic isograds (Fig. 53). 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 decollement 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 classed as complex faults.

Some Class 7 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 class. All a e faults of the metamorphic core of the Appalachians.

Subclasses of Class 7 include: (1) those faults with abundant mylonites which juxtapose Paleozoic isograds; (2) faults without mylonites; and (3) erosional remnants of allochthonous sheets.

Examples of Class 7 faults include the Linville Falls fault in the Grandfather Mountain window in North Carolina (Bryant and Reed, 1970a, 1970b), the Hollins Line fault of Alabama (Tull, 1978), the Alto allochthon of Georgia and South Carolina (Hatcher, 1978b), the Bowen Creek-Ridgeway faults of Virginia and North Carolina (Conley and Henika, 1973), Inner Piedmont nappes (Griffin, 1971, 1974) and the west side of the Berkshires (Ratcliffe and

identification very difficult, even though the chronology of deformation and mechanics may be identical to that of other faults of this class.

(d) Planes or zones of prograde or retrograde low grade metamorphism 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 Class 7 faults is unlikely, except along high angle segments.

12. Best References on Class 8 Faults

Bryant and Reed (1970b)

Conley and Henika (1973)

Griffin (1974)

Hatcher (1978a, 1978b)

Ratcliffe and Harwood (1975)

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

If the zones of seismicity crossing the Appalachians in New England and South Carolina were related to cross-structural faults of the type associated with the latitude 40°N fault zone, then we should expect reactivation of a zone such as the latitude 40°N likely.

List of Type Examples

a) Cross Mountain, Tennessee

b) Sideling Hill, Pennsyl[illegible]a (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 subclass are described elsewhere in this report as complex faults. Some complex faults have demonstrable strike-slip displacements based on offset of local rock units. One example is the Ramapo fault system of New York that has 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. 66).

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 known at present. The field relationships as presently understood are presented in Figure [9]. The area was mapped by the writer at a scale of 1 in.: 1000 ft during investigation which spanned a three-week period. ...
>
> The mylonite zones shown on Figure [9] are all marked by strong development of minor folds showing right-lateral shear sense and near vertical fold axes. Evdience 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. [9], 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 67 shows major tear faults

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.

a statement that could apply to any fault fissure slide. Seems unnecessary & out of place here.

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. 71). Faults of this subclass 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 structures have greater strike length and are not so obviously related to the folds.

Faults of this subclass 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

σ_2 = 15.86 MPa, and σ_3 = 6.21 MPa. Schaeffer and others, in press, 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 pa.t of the movement history (Acadian and 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 and others, 1978; Cook and other, 1979, in press) 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 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 faults of the Brevard zone

Then they are [illegible]

4) Relation to Country Rocks

a) The Ramapo fault system is parallel to regional grain except at northern termination.

b) Located in the New York promonitory.

c) Thick-skinned.

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

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

f) Not Applicable.

g) In the fault zone mylonite foliation parallels the fault zones.

h) Fault character varies in a complicated manner depending on both lithology and age of faulting.

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

j) Acadian isograds superimposed on the northern end of the fault zone. Mesozoic faulting cuts the isograds (Fig. 83).

k) 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. to 371 m.y.

1) 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 Mesozoic of 73 m.y.

d) Related to erosional unloading - Unknown.

e) Last motion - Seismicity along the fault zones indicates that the Ramapo system is still active (Fig. 84).

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 accommodate several faulting modes.

d) Present in situ stress - See b.

e) Seismic first-motion studies - Aggarwal and Sykes show that modern seismicity is in response to a northwestern maximum compressive stress (Fig. 84).

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 patter.

9) Methods of Identification - Not Applicable.

10) Pitfalls in Identification - Not Applicable.

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.

5. History

   a. The age of the CSD's probably varies from structure to structure. In general basement controlled CSD's should be oldest since supra-crustal CSD'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 (1977) 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 CSD's.

   c. No studies of radiometric ages are known from any CSD.

   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 CSD's.

7. Geophysical and Subsurface Characteristics

   a. Basement controlled CSD'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.

lack of sufficient understanding as to the precise nature of the structures.

10. Pitfalls in identification: The principal pitfalls lie in an over-enthusiastic use of aerial photographs and LANDSAT imagery, where a tendency develops to generate enormous families of spurious alignments (see Appendix B). 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 CSD should be treated with suspicion as a number of CSD's are known to be seismically active. CSD's also have long histories of activity, consequently reactivation of structures within the CSD should be considered a possibility and studies should be made to judge its capability.

CHAPTER XIV

CLASS II: FAULTING 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 at any site. However, these problems fall more in the realm of ~~soil mechanics and civil~~ 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 older fault zones as a result of bedrock contrasts, deeper weathering along fracture zone, more water in the fault zone, weaker gouge in the 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 class of faults and related structures should be excluded from the usual seismo-tectonic safety considerations for that site.

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 cause for additional scrutiny. If the slickensided surfaces can be demonstrated as purely the result of saprolitic processes, with movement vectors reflecting only creep, the problem becomes one of soil mechanics and slope stability rather than seismic risk analysis.

Describe in much greater detail the mechanism of saprolite faults

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 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-existing steeply dipping fractures of any kind. The collapse planes are most likely to mimic normal or vertical faults. Slickensides in bedrock are rare because of low normal stress across the plane of motion. Association with dripstone and other cave formations is common but no true hydrothermal mineralization should be present.

These cave related problems are most likely 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.

The most likely error in Karstic or collapse regions, in terms of seismotectonic interpretation, is the mis-identification of a fault zone used as a boundary for a collapsing block to represent 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: (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. In the Appalachians Kaye (1964) suggests major imbricate thrusting of this type in Cretaceous units on Marthas Vineyard. Spectacular examples of this type of structure occur in Denmark at Mons Klint, south of Copenhagen. There, a 125 m high sea cliff exposes a number of slabs of Cretaceous chalk repeated by imbricate thrusting with intercalations of glacial till, complicated by an overprint of complex folding and faulting (Hansen, 1965). Similar thrusting has been discussed 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 up to hundreds of meters.

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 examples of the type of modern deformation produced by excavation is the Niagra power canal as described by Lee and Low ( ). 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 excavation 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 microearth activity, as in the Moodus area, in association with strong development of these release phenomena should be cause for concern.

This leads the reader to believe that the Moodus noises are directly related to the offsets. This isn't true. The offsets are in the Honey [illegible] area while Moodus noises [illegible] Mt. Tom area - several [illegible] dis[illegible]

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 rock).

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

j. isograde - Faults cut indiscriminately across metamorphic isogrades.

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).

This interpretation was later shown to be in error & fault could be dated as post 50 my - VSG press release. (see Stafford report)

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 principle 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. but this is true ~~the~~ along fall zone where there are no mapped faults

5. 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 igh resolution seismic reflection seismology to determine offsets of basement and stratigraphic surfaces.

EPI-ANTICLINAL FAULT: A longitudinal or transverse fault associated with a doubly plunging minor anticline and formed concurrently with the folding (Gary, McAfee, and Wolf, 1972).

EXTENSIONAL FAULT: Tension fault (Gary, McAfee, and Wolf, 1972). A tension fault must, of necessity, form in the σ_1-σ_2 plane at right angles to σ_3. This precludes any shear motion because the fault lies in a plane of zero resolved shear stress. The term should be abandoned, because any shear motion must be superimposed on a pre-existing fracture.

FAULT: A fault is a surface or tabular zone along which true or apparent displacement parallel to the surface or zone is at least ten times greater than displacement normal to the zone. This definition is not scale-dependent. Compare with Billings (1972), Dennis (1967), Gary, McAfee, and Wolf (1972). see earlier comment

FIBERS: Parallel arrays of elongate crystal growths marking the direction of extension along a fracture or fault.

FLINTY CRUSHED 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 in any type of rock, e.g., cleavage in slate or schistosity in schist (Gary, McAfee, and Wolf, 1972).

IMBRICATE: The geometric array of a sucession of nearly parallel overlapping thrust or reverse faults which are approximately equidistant 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. Include no displacement

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: 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 oblique to the limb. Limb attenuation is dominately a plasticity process.

benefits not worth the cost

XIX.

APPENDIX A

A. Critical Need For 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 repsect 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-Coulomb 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° (Byerlee, 1978; Stesky, 1978). Typical values over a wide range of rock types, pressures, temperatures, moisture contents, and sliding rates range from 17° to 40° ($0.3 \leq \tan \theta_s \leq 0.85$). For an extended discussion of variation in friction along natural fault zones see Engelder (1979). The angle of internal friction for most rocks is about 30° ($10° \leq \phi \leq 50°$). Consequently, 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. XIX-1). Conversely, pre-existing faults of favorable orientation will be reactivated before new faults can develop.

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Comments prepared by
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Comments on "A Characterization of
Geologic Faults in the Appalachian Foldbelt"

1. Page 5, Fault Classes. The placing of faults into the 12 categories listed here appears to be inconsistent and redundant.

a. Fault classes 1, 2 3, 6 & 7 are all similar (low angle thrusts) and should probably all be under one class, each with a subclass status.

b. A possible course, and probably the most useful way for licensing, is to divide them up under headings as to potential for reactivation such as: brittle, unhealed faults; faults with demonstratable Cenozoic movement; and faults with apparent seismicity as one major category. Faults that have a pre-metamorphic displacement history only belong in category of faults with the least likelihood of reactivation, etc.

c. Another way to categorize faults can be based on senses of movements, such as strike slip, reverse, normal, etc.

2. Page 5. Table 1 that is referred to on this page is missing from the report.

3. Page 6, 3rd paragraph. Regarding the statement that there is some modern seismicity on both the Ramapo and Brevard faults, some scientists have associated seismicity with the Ramapo and Brevard faults, but the association of seismicity with these structures is controversial and has not been demonstrated.

4. Page 7, item 4. Unsheared minerals that fill microcracks related to a fault may not be indicative of last movement on that fault. Only those minerals that cut the fault plane itself can be used for absolute dating of an upper limit for last movement.

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5. Page 9, item A. The definition for a fault given here would eliminate some potentially hazardous faults. For example, the faults at Nine Mile Point, one of which has experienced about 1 foot of displacement normal to the fault plane versus 6 feet movement along the fault plane, would not be considered a fault at all by this definition.

6. Page 70, item f. What is the basis for speculating that the faults discussed here "may flatten into subhorizontal basement faults with depth?" Also, what is the significance?

7. Page 72, item 3. Most of the mapped faults cutting Cretaceous Coastal Plain strata are reverse faults, and not normal faults, which apply to this Class.

8. Page 73, item 5a. The statement that some Mesozoic border faults in the central Appalachians "are still active" is too strong as this has not been proven. "May still be active" is more appropriate.

9. Page 74, item 6a. Reference is made to seismic activity associated with the Ramapo fault zone as indicating that stress orientation has changed with respect to this fault. The interpretations of focal mechanisms in the region of the Ramapo vary a lot. Some focal mechanism solutions are consistent with the interpretation of geologic data regarding sense of last movement along the Ramapo and others are not.

10. Page 74, item 7a. The statement that "where networks are sufficiently dense, microseismicity has been found associated with the faults," is an over-statement. Microseismic monitoring have been carried out in areas where there are mapped faults or other anomalies (Stafford fault, North Anna nuclear site, Shearon Harris nuclear site, and South Port, NC) with negative results, and microearthquake activity has been detected in other areas where there are no mapped faults (Blue

Mountain Lake).

11. Page 75, item 9b. This statement appears to contradict 7d.

12. Page 76, item 11. Why are the faults of this category located along the Coastal Plain hinge line regarded as being more prone to reactivation than faults in other areas? There is relatively little seismicity in the areas of these faults even though geologic data shows that movement on some of them extends into the Plio-Pleistocene. More elaboration is needed here.

13. Page 93, item 9g. The phrase "(except in drill cores)" should be deleted because brittle deformation zones are also likely to be missed in drill cores.

14. Page 93, item 10a. Discuss why synmetamorphic faults, although not a major cause for concern, should be avoided if given a choice.

15. Page 109, 1st paragraph, last sentence. The statement that there may be unrecognized major strike-slip faults associated with the Carbonifeous of New England should be elaborated on. Were the recent mapping of the area of the Clinton-Newbury and Bloody Bluff - Mystic fault systems by Barosh et al, geophysical studies by Weston, and other investigations considered in making that assessment?

16. Page 111, 3rd paragraph. The statement made in this paragraph is a little premature since it has not been established that there is a major latitude 40°N fault zone.

17. Page 115, 1st paragraph. The statement made in the last sentence seems unnecessary and out of place here because it would apply to many geologic features such as an unhealed fault, regardless of age, fault gouge zone, landslide plane, fissure, collapse structure, glacial pop-up etc.

18. Page 131, item k). The statement that the Cortlandt complex is cut by the Ramapo fault zone is misleading. The main trace of the Ramapo fault passes west of the Cortlandt. It is more accurate to say that faults of the Ramapo system cut the Cortlandt complex.

19. Page 131, item 6b. Stresses in the vicinity of the Ramapo fault zone as determined by Dames & Moore were variable and gave no consistent picture as to the state of stress in this area. However, the horizontal component of maximum compression appeared to be somewhat consistent, varying between northeast and eastwest.

20. Page 131, item 5e. T he statement that seismicity along the Ramapo System indicates that it is still active should read that "it may still localize earthquakes."

21. Page 132, item 8. The Ramapo fault zone forms the boundary between the Newark basin and the Hudson Highlands, not the Newark-Gettysburg basin and Highlands. This implies that the Ramapo extends from New York to Maryland, and this has not been shown to be true.

22. Page 132, item 7a. This paragraph is completely erroneous and misleading as it implies that the 38th Parallel Lineament is highly active because the New Madrid earthquake site is on it. The New Madrid earthquake area is south of the 38th Parallel, and seismic activity and structure are oriented almost normal to it.

23. Page 140, item 10. Expand and provide the bases for the statement that a number of CSD's are known to be seismically active. None of those discussed in this section are demonstrated to be uniquely seismically active.

24. Page 141, 2nd paragraph, 2nd sentence. Delete "soil mechanics and civil engineering," and insert "geotechnical engineering."

25. Page 142, Saprolitic Faults. Describe in greater detail and cite references concerning the mechanisms for development of saprolitic faults independent of tectonic faulting.

26. Page 144, 1st paragraph. Delete "clay filled" in front of solution cavities," because clay filled solution cavities are the least likely to be reactivated.

27. Page 150, last paragraph. In this association of the Moodus noises with the ongoing offsets in the Honey Hill fault zone, it should be pointed out that the 2 areas are not spatially related but separated by several miles.

28. Page 158, item 5c. It should be added in this consideration of the Belair fault that the evidence of Holocene movement as first interpreted was in error, and that the only thing that could be said based on the data was that last movement occurred within the last 50 million years (USGS news release - 18 Nov., 1976)

29. Page 159, item a. It should be stated in this paragraph that the Stafford, Brandywine, Bellair, etc. are aseismic. As it stands, the statement implies that these and other high angle reverse faults are within or near relatively active central Virginia seismic zone and are therefore active.

30. Page 160, item 8e. This statement applies to the entire Fall Zone where crossed by rivers, whether there is recognized faulting or not.

31. Page 181, Definition of Fault. See comment number 5 above.

32. Page 195, Appendix A. At many sites it may be desirable and even necessary to perform in-situ stress measurements, but because of the state-of-the-art (uncertainties in the results and what they mean) and the large expense of hydro-fracturing, it is not reasonable or even desirable to require this technique at every site. The strong recommendation to require this should be deleted.