Geology of the Starksboro Area, Vermont

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LOCATION AND PREVIOUS MAPPING

The field area is centered in the Lewis Creek watershed in the township of Starksboro, Vermont (Pl.1, L-4). It encompasses the northeastern part of the Bristol 7.5' quadrangle and the northwestern part of the Mt. Ellen 7.5' quadrangle.

Cady and others (1962) mapped the Mt. Ellen quadrangle at a scale of 1:62,500. Cady mapped the eastern part of the Bristol quadrangle for the Geologic Map of Vermont (Doll and others, 1961). Four formations and two members were recognized: the Late Precambrian Pinnacle and Underhill Formations; the Fairfield Pond Phyllite and Forestdale Dolomite Members of the Underhill Formation; and the Lower Cambrian Cheshire and Dunham Formations. They interpreted the Pinnacle Formation as the core of the Lincoln anticline with younger rocks of the Underhill Formation in depositional contact on both limbs. The Underhill Formation on the east limb was also considered to be a finer grained stratigraphic equivalent of the Pinnacle Formation.

Tauvers (1982, 1982b) mapped the Lincoln area to the south of the Starksboro region. He and I (DiPietro, 1982) developed a stratigraphy in the Pinnacle Formation and mapped thrust faults in the Underhill Formation on the east limb of the Lincoln anticline (Pl.2). The Fairfield Pond and Forestdale Members on the west limb of the Lincoln anticline could not be correlated with the Underhill Formation. As a consequence, the upper phyllitic part of the Fairfield Pond Formation was mapped as a separate formation. The Forestdale Dolomite and overlying metagreywacke were mapped as units in the upper member of the Pinnacle Formation.

STRATIGRAPHY

The formations in the field area are separated into a western and an eastern sequence. The western sequence consists of the Pinnacle, Fairfield Pond, Cheshire and Dunham Formations. The eastern sequence consists entirely of the Underhill Formation and is separated from the western sequence by the Underhill and Jerusalem thrust faults. The Late Precambrian Pinnacle and Underhill Formations are rift clastic deposits that overlie, with profound unconformity, the Precambrian-Y North American basement (Rankin, 1976; Doll and others, 1961). The Cheshire and Dunham Formations constitute the lowest part of the Cambrian - Ordovician shelf sequence in Vermont. Figure 1 shows the correlation of the western sequence with Doll and others (1961) and with Tauvers (1982). A detailed stratigraphic column of the western sequence is shown in Figure 2.

The rocks are metamorphosed to the biotite grade. Cady and others (1962) mapped the garnet isograd along the eastern boundary of the area. All map units strike a few degrees west of north and dip east. Graded beds indicate that the west limb of the Lincoln anticline is overturned.

Western Sequence

Pinnacle Formation. The Pinnacle Formation is divided into lower, middle and upper members. All three members are variable from north to south and each consists of two or more map units. The facies variations and distinguishing features of each member are summarized in Figure 3. Most of the rock in the Pinnacle Formation consists of schistose sandstone or semischist, which I refer to as metagreywacke.

Lower Pinnacle Member

CZpl - Undifferentiated quartz-sericite metagreywacke and phyllite (Type loc. Pl.1, C-5 and I-7). The lower member consists predominantly of massive, medium grained, schistose, shiny light grey, brown weathered, quartz-sericite-chlorite-albite metagreywacke with blue quartz pebbles and brown weathered disseminated carbonate. The rock is quartz-sericite rich with albite generally making up less than 10 percent. Biotite is rare. Phyllite, schistose quartzite and mica schist are present locally. This unit becomes thicker to the north. The lower part contains wide intervals of fine grained, grey or green, fissile, sericite-chlorite-quartz-epidote phyllite and schist which become more abundant north of the field area. The lower member overlies the basal Pinnacle conglomerate in the Lincoln area (Fig.1).

CZpll - Laminated magnetite schist (Type loc. Pl.1, E-8). This unit is a fine grained, greenish-grey, sericite-chlorite-quartz-epidote schist characterized by abundant white quartz laminations and secondary magnetite. It is similar in appearance to the laminated schist (CZul) except that it lacks biotite, contains abundant magnetite and, in general, is compositionally less variable. Contacts with the surrounding quartz-sericite metagreywacke (CZpl) are not exposed.

Middle Pinnacle Member

CZpm - Undifferentiated quartz-albite-sericite metagreywacke and phyllite (Type loc. Pl.1, D-4 and O-6). The Middle Pinnacle Member is a very massive, resistant, granular, medium and coarse grained, quartz-albite-sericite-chlorite-biotite metagreywacke with albite pebbles, local conglomerates, graded beds and intraclasts. South of Lewis Creek it is medium-to-dark grey with biotite, but becomes more schistose light-to-medium grey north of Lewis Creek. Here, blue quartz is more common and biotite is sparse. Mica schist, magnetite-rich layers, lower member-type metagreywacke (CZpl) and sandy laminations similar to those in the laminated schist (CZul), are present locally. Interlayered sericite-chlorite-quartz-epidote phyllite and schist are not common but become more abundant north of Lewis Creek. The lower contact is gradational over an interval of 10 to 30m and is well-exposed at locations E-5 and L-7 (Pl.1).

CZpmg - Graded bed unit (Type loc. Pl.1, E-5 and F-5). This unit consists of beds (<30cm) grading from pebbles to fine sand that are overlain, with sharp contact, by thin (<10cm) layers of phyllite. These turbidite sequences are interlayered with lower and middle member-type metagreywacke (CZpl, CZpm) as well as discontinuous phyllite.

CZpmc - Conglomeratic unit (Type loc. Pl.1. G-4 and N-7). The conglomeratic unit consists of discontinuous lenses of pebble and cobble conglomerate up to 10m thick. Graded as well as poorly-sorted beds are present. Clasts are subrounded to rounded and are predominantly matrix supported. In observed order of abundance, the clasts are quartz-plagioclase gneiss, plagioclase, plagioclase gneiss, blue quartz and polycrystalline white quartz. The plagioclase is largely altered to albite. The interlayered metagreywacke (CZpm) is medium grey at location N-7 (Pl.1) and dark grey with intraclasts at location G-4 (Pl.1).

Upper Pinnacle Member

Forestdale-type phyllite and metagreywacke (Not a map unit. Type loc. Pl.1, Q-6). Lustrous silver-green phyllite and metagreywacke are present throughout the upper member south of Lewis Creek. Because these rocks occur below, within and above Forestdale Dolomite, they are referred to as Forestdale-type phyllite or metagreywacke. The term "Forestdale-type rock" refers strictly to metagreywacke and phyllite, not to dolomite. Forestdale-type rock is not a map unit. Units which contain Forestdale-type rock are mapped by the presence or absence of a specific rock type. Forestdale-type rocks are lustrous silver-green, fine-to-medium grained, quartz-sericite-chlorite-albite-iron oxide phyllite and metagreywacke that weather dark (dull) green. All gradations from fissile micaceous phyllite to very sandy metagreywacke are present. Secondary magnetite is common.

CZpug - Coarse metagreywacke and phyllite (Type loc. Pl.1, F-3 and R-6). The distinctive rock in this unit is a coarse, green to light grey, quartz-albite-sericite-chlorite metagreywacke with abundant blue quartz clasts and a spaced (5mm) S1 schistosity. Albite and white quartz clasts are also common. Carbonate layers and flakes of muscovite are present locally. Biotite is absent. The coarse metagreywacke is more abundant (>70 percent) north of Lewis Creek where it is interlayered with predominantly dark green, fissile, chloritic phyllite. Medium and fine grained, dark green, chloritic metagreywacke are common south of Lewis Creek. The coarse metagreywacke, in this area, becomes less abundant and pinches out south of the field area (Tauvers, 1982). The lower contact is gradational over an interval of 8 to 30m and is well-exposed at locations L-5 and D-4 (Pl.1). It becomes increasingly gradational to the north and may become impossible to delineate north of the field area.

CZpuc - Fine metagreywacke and phyllite (Type loc. Pl.1, D-3 and Q-6). This unit consists predominantly of lustrous green, chloritic, Forestdale-type phyllite and metagreywacke. Dark green varieties are also common. It is distinguished from the underlying and overlying units by the lack of both coarse metagreywacke and carbonate layers. Sandy metagreywacke is common south of Lewis Creek whereas phyllite is more common to the north. Biotite is absent in this unit.

CZpuf - Forestdale Dolomite (Type loc. Pl.1, J-3 and Q-5). The Forestdale Dolomite consists of white to buff, sandy dolomite, interlayered with Forestdale-type phyllite and metagreywacke. The dolomictic layers are typically 5 to 15cm thick and rarely greater than 30cm. Layers of Forestdale-type rock are much thicker, locally up to four meters. Dolomite weathers tan-to-dark brown and forms deep reentrants between the resistant phyllitic layers. In some areas, dolomite is hidden beneath phyllite and unless the rock is broken, it can be overlooked. The dolomictic layers become less abundant and pinch out into dark green fissile phyllite (CZpuc) north of Lewis Creek.

CZpufm - Massive Forestdale Dolomite (Type loc. Pl.1, R-6). Three meter thick layers of white to buff, brown weathering, sandy dolomite alternate with four to ten centimeter layers of Forestdale-type rock at location R-6 (Pl.1). The massive dolomite occurs only in this one isolated area and is gradational to the main body of Forestdale Dolomite. Thick layers of sandy dolomite are more common south of the field area (Tauvers, 1982).

CZpuu - Chloritic metagreywacke and phyllite (Type loc. Pl.1, B-2 and R-5). South of Lewis Creek, the chloritic unit consists of highly variable, grey or green, chloritic, fine and medium grained metagreywacke and phyllite with Forestdale-type rock common near the base. Secondary magnetite is abundant in this area but biotite is absent. North of Lewis Creek, the lower part changes facies to CZpub, CZpul and CZpuq. The upper part consists predominantly of Forestdale-type rock but is more coarse grained with layers rich in blue quartz pebbles. Carbonate layers (identical to the Forestdale Dolomite), biotite and secondary magnetite are locally present. The lower contact of this unit is gradational.

CZpub - Biotite bearing metagreywacke and phyllite (Type loc. Pl.1, E-3 and I-3). The lower part of the biotite-bearing unit consists predominantly of massive, granular, dark grey, medium and coarse grained, albite-quartz-chlorite-sericite-biotite metagreywacke that resembles the Middle Pinnacle Member. The upper part is finer grained and consists of green-to-dark grey, chloritic phyllite and metagreywacke. Cross beds, graded beds, blue quartz clasts, albite clasts, detrital carbonate and small (<3cm) intraclasts, are present locally. This unit becomes thicker, darker grey and more massive to the north. The lower contact, at location J-3(Pl.1), is sharp (<2m), and graded beds are common at the base.

CZpul - Thinly layered unit (Type loc. Pl.1, J-3). The thinly layered unit consists of Forestdale-type rock interlayered with thin (<2 cm) fine-to-medium grained, white, quartz-albite-rich, sandy layers that are spaced less than 15cm apart. Secondary magnetite is abundant in this rock and although present in the chloritic unit (CZpuu) south of Lewis Creek, it is a mappable unit only in the East Mountain area. Its lithic identity is lost at location I-3 (Pl.1) where continuous exposure shows that it changes facies into the underlying and in part, stratigraphically equivalent biotite-bearing unit (CZpub). The thinly layered unit is a transitional facies between the fine grained chloritic unit (CZpuu) and the coarse grained biotite bearing unit (CZpub). The lower contact with the biotite bearing unit is sharp (<2m).

CZpuq - Quartz-pebble metagreywacke (Type loc. Pl.1, K-3 and D-2). The distinctive rock in this unit is a greenish, coarse to pebbly quartz-albite-chlorite metagreywacke. Blue quartz is extremely abundant and the rock is locally a quartzite. Blue quartz is less abundant at location E-2 (Pl.1) where this rock closely resembles the coarse metagreywacke in CZpug. The quartz-pebble metagreywacke is interlayered and surrounded by greenish chloritic rock that is typical of the chloritic unit (CZpuu).

Summary and Stratigraphic Trends of the Pinnacle Formation

The Pinnacle Formation is divided into three members which change facies along strike (Fig. 3). These changes indicate that the lithic character of each member is time transgressive and can occur at different stratigraphic intervals. For example, layers of dolomite occur both above and below the stratigraphic horizon that is mapped as Forestdale Dolomite. Another significant aspect of the Pinnacle Formation is that identical stratigraphic sequences appear at different stratigraphic intervals. For example, the CZpm-CZpug-CZpuc sequence is nearly identical to the CZpub-CZpuq-CZpuu sequence that occurs north of Lewis Creek (Fig. 2). Graded beds in both rock sequences indicate that this repetition is stratigraphic and not structural. The total thickness of the Pinnacle Formation in the Starksboro area is between 1.5 and 2.2km. The maximum thicknesses are shown in Figure 2.

CZf - Fairfield Pond Formation (Type loc. Pl.1, B-2 and R-4). The Fairfield Pond Formation consists of homogeneous, fine grained, grey and green, sericite-quartz-chlorite-albite phyllite. The phyllite is soft and commonly fissile, but sandy layers are present locally. The lower contact is sharp (<2m) at location B-2 (Pl.1) but phyllite and metagreywacke are interlayered at location R-4 (Pl.1).

Cheshire Formation.

Ccp - Phyllitic member

(Type loc. Pl.1, S-3) The phyllitic member consists of interlayered dark grey phyllite (CZf-type) and argillite (Cca-type). White sandy lenses or stringers are common and may represent deformed trace fossils. The lower contact appears gradational but is disrupted by the Hinesburg thrust.

Cca - Argillaceous member

(Type loc. Pl.1, E-2 and S-3) The argillaceous member consists of grey, quartz-feldspar-sericite-chlorite argillite with thin phyllitic partings, rippled beds, trace fossils and local quartzite beds. It also contains potassium feldspar which is not present in pre-Cheshire Formation rocks. The lower contact appears gradational but is disrupted by the Hinesburg thrust.

Ccm - Massive quartzite member

(Type loc. Pl.1, C-2) The massive member consists predominantly of massive white-to-pink quartzite and is generally structureless. The lower contact is interlayered over an interval of ten meters and is well-exposed at location B-2 (Pl.1).

Dunham Formation - Cd (Type loc. Pl.1, J-2). The lower part of the Dunham Formation is exposed and consists of pink or brown weathering, sandy dolomite with thin phyllitic partings and local trace fossils. The lower contact with the Cheshire Formation is sharp (<3m) and is exposed at location J-2 (Pl.1).

Eastern Sequence

Underhill Formation. The Underhill Formation structurally overlies and truncates the east limb of the Lincoln anticline. It consists of two fault slices: the Jerusalem slice and the Underhill slice.

Underhill Slice

CZu - Undifferentiated quartz-sericite schist and metagreywacke (Type loc. Pl.1, C-14 and K-13). The Underhill slice consists predominantly of fine grained, light grey, brown weathered, quartz-sericite-chlorite-albite schist interlayered with thin (<1m), medium grained metagreywacke of similar composition. The metagreywacke contains blue quartz clasts and brown weathered disseminated carbonate. It is identical to the more massive sequences of Lower Pinnacle Member metagreywacke (CZpl). This unit also contains greenstone, schistose quartzite, mica schist and greenish chloritic schist with thin (<1cm) sandy calcareous layers. Albite and biotite are locally abundant in metagreywacke south of Beaver Meadow Brook (Pl.1, H-15).

CZua - Coarse metagreywacke and amphibolite (v) (Type loc. Pl.1, C-12, D-15, and H-14). This unit consists of massive, dark grey, coarse grained, quartz-albite-biotite-chlorite-sericite metagreywacke interlayered with dark grey, amphibole-albite-epidote-quartz-magnetite-chlorite-sphene amphibolite. The metagreywacke is lithically similar to the Middle Pinnacle Member (CZpm) and to the biotite bearing metagreywacke (CZpub). Contacts with the surrounding quartz-sericite schist (CZu) are sharp but believed depositional.

CZub - Biotite-rich metagreywacke and greenstone(v) (Type loc. Pl.1, K-1). The biotite-rich unit consists of dark grey, medium and fine grained, quartz-albite-biotite-chlorite-sericite metagreywacke and schist interlayered with amphibole-chlorite-epidote-quartz-albite-biotite-sphene greenstone.

CZug - Greenstone (Type loc. Pl.1, M-12). This rock is a massive spotted green, white and black, epidote-chlorite-quartz-amphibole-biotite-albite greenstone. Locally it is less massive, epidote-quartz rich and interlayered with the biotite-rich unit (CZub). The abundance of quartz suggests that the mafic volcanic material was mixed with clastic sediment.

Jerusalem Slice

CZul - Quartz laminated schist (Type loc. Pl.1, I-10, N-7 and N-10). The laminated schist consists of grey or green, fine grained, sericite-chlorite-quartz-epidote-albite schist with abundant, very continuous, white laminations that define S1. The laminations consist predominantly of recrystallized quartz and are metamorphic in origin. A few are sandy and may represent original bedding. Quartz veins are abundant and commonly impregnate the rock. The laminated schist contains biotite and imbricated pods and layers of Middle Pinnacle Member metagreywacke (CZpm) along the Jerusalem slice on the east limb of the Lincoln anticline (eg. Pl.2, E).

Correlation of the Eastern Sequence with the Western Sequence

The Underhill slice and Lower Pinnacle Member contain identical sequences of metagreywacke. The major difference between the two rock units is that the metagreywacke in the Lower Pinnacle Member occurs in layers of 10m or more whereas layers of metagreywacke in the Underhill slice are commonly less than one meter and separated by wide intervals of quartz-sericite schist. The Underhill slice is also somewhat more variable with metabasite and albite-biotite rich metagreywacke. These rock types are not found in the Lower Pinnacle Member. The abundance of similar rock types however, suggests the Underhill slice is a finer grained facies equivalent of the Lower Pinnacle Member (Fig.1). Stratigraphic equivalence cannot be proven because lithic units in the Pinnacle Formation are time trangressive and cyclic.

The Jerusalem slice is closely associated with the Middle Pinnacle Member. Laminated rock, similar to the quartz laminated schist (CZul), occurs locally in the Middle Pinnacle Member and both rock units are truncated by the Underhill slice at location H-10 (Pl.1). The major difference between the two is that the laminated schist is much finer grained. Because of their close association, the laminated schist is interpreted as a finer grained facies equivalent of the Middle Pinnacle Member (Fig.1). The Jerusalem slice may represent a stratigraphic facies of the Middle Pinnacle Member that is similar in origin to the thinly layered unit (CZpul) and chloritic metagreywacke (CZpuu) facies of the biotite bearing unit (CZpub) in the Upper Pinnacle Member.

Environment of Deposition

Tauvers (1982) interprets the basal Pinnacle conglomerate as an alluvial-fan deposit and interprets the overlying Pinnacle Formation rocks as submarine fan, mass flow or turbidite sequences. The presence of graded beds, phyllitic intraclasts, resedimented carbonate deposits, and massive conglomeratic sand layers, support a submarine fan origin for the Pinnacle Formation in the Starksboro area (Walker, 1978).

There are two distinct but very closely related end member rock types in the pre-Cheshire Formation rocks: 1) albite-biotite rock (CZpm, CZpub, CZua, CZub) and 2) quartz-sericite rock with local carbonate (all other rock units). The albite-biotite rock types are commonly massive and coarse grained. They may represent a proximal facies of the quartz-sericite rock. This possibility is supported by the abundance of albite in the underlying Mount Holly Complex (Tauvers, 1982) and the association of albite-biotite rock with metabasite in the Underhill Formation.

Large-scale stratigraphic trends are present in the Pinnacle Formation. The lower member becomes thicker (>500m) and finer grained to the north. The stratigraphic trend from the Lower to Middle Pinnacle Member, is coarsening upward (Fig.2). This sequence is interpreted as a large prograding submarine fan.

The stratigraphic trend of the Upper Pinnacle Member varies from north to south. It fines upward south of Lewis Creek, but contains the intervening Forestdale Dolomite (Fig.2). North of Lewis Creek, it fines upward to a sharp contact (at the base of the coarse grained biotite bearing unit, CZpub) and then, an almost identical, but much thinner, fining upward sequence repeats itself (Fig.2). This may represent abandonment or migration of the lower-middle member submarine fan lobe and the interfingering of a second submarine fan.

Active rifting ceased by the end of Upper Pinnacle Member time. The fine grained Fairfield Pond Formation represents an abrupt change from the highly variable coarse grained deposits of the Pinnacle Formation. Rippled beds and vertical burrows in the overlying argillaceous Cheshire (Cca), suggest near sea level deposition. The Fairfield Pond Formation therefore, is interpreted as a shallow water, slow subsiding basin deposit. The phyllitic Cheshire (Ccp) may represent a shallowing upward sequence to the argillaceous Cheshire. The phyllitic Cheshire also marks, for the first time, the influx of sediment rich in potassium feldspar. This compositional change suggests a major shift in source area. The upper Cheshire Formation (Ccm) and Dunham Formation mark the beginning of the stable continental shelf that existed until the Ordovician Taconian orogeny.

Structural complications make the eastern sequence somewhat more difficult to interpret. The lithic similarity to the Lower Pinnacle Member, suggests a similar, but more distal, source area for the Underhill slice. Metabasite in the Underhill slice suggests local volcanic or volcaniclastic source areas not found in the Lower Pinnacle Member. The Jerusalem slice may represent a distal intrabasinal mud or possibly, a facies peripheral to the main depocenter of the Middle Pinnacle Member submarine fan.

STRUCTURAL GEOLOGY

Two major deformational events are recognized in the Starksboro area. The first (D1) is associated with the dominant regional foliation (S1), the development and westward overturning of the Lincoln anticline (F1), biotite grade metamorphism (M1), and late-F1, syn-M1, westward displacement of the Underhill, Jerusalem and Hinesburg thrusts. Radiometric dates indicate a Taconian age for D1 (Harper, 1968; Lanphere and others, 1983). The second deformational event (D2) is associated with open to overturned, upright folds (F2), axial plane crenulation cleavage (S2), chlorite grade metamorphism (M2), and large-scale warping of the Lincoln anticline. Minor deformational events include poorly-developed open or kink folds (F3), east-west fracturing and dike intrusion.

Fold Events

F1 Folds. The Lincoln anticline is a doubly plunging, west vergent, F1 fold, that encompasses the entire western sequence (Pl.1). The west limb is sheared by the Hinesburg thrust. The east limb is truncated by thrusts in the Underhill Formation. The Underhill thrust does not follow the plunge of the fold (Pl.2). This suggests the Lincoln anticline was doubly plunging prior to late-F1 thrusting. Older rock units in the core of F2 synclines on the west limb, indicate that the Lincoln anticline was overturned prior to F2.

The dominant planar element in the field area is the penetrative S1 foliation, which strikes generally north and dips 50 to 90 degrees east (Fig.4b). The morphology of S1 in pre-Cheshire Formation rocks, varies from fissile to schistose to spaced as the percentage of mica decreases. S1 is expressed as thin phyllitic partings in the Cheshire and Dunham Formations but is non-pervasive or absent in the massive Cheshire quartzite (Ccm). Minor shear zones are commonly developed parallel to S1 (eg. Pl.1, P-5).

Mineral lineations of mica or quartz are present on most S1 surfaces. They rake between 60 and 90 degrees to S1 and plunge east-southeast (Fig. 4d). This orientation is parallel to slickensides along the Underhill and Jerusalem thrust faults, which suggests that the mineral lineations define the regional transport direction of the rock.

Small scale F1 folds are rare and observed only in the Pinnacle and Underhill Formations. They are tight to isoclinal, doubly plunging folds, with thickened hinge areas and amplitudes generally less than one meter (Fig.4c). S1 is axial planar to these folds which do not affect the map pattern.

S1 and its Relationship to the Lincoln Anticline. Except for minor F1 fold hinges, S1 is parallel (or at an imperceptibly small angle) to bedding on both limbs of the Lincoln anticline. The clearest examples are the thin (<3cm) sand layers in the thinly layered unit (CZpul). The sand layers are oriented parallel to S1 and, although boudined and pulled apart, are not folded by F1. Notwithstanding the parallelism of bedding to S1 across the Lincoln anticline, cross section C-C'(Pl.1) indicates that the limbs of the fold are at an angle to the axial surface. The cross section is constrained by field data that indicates bedding decreases gradually from near vertical in the Cheshire and Dunham Formations to about 70 degrees east in the Middle Pinnacle Member on the west limb of the Lincoln anticline. The dip of beds on the east limb however, changes abruptly to between 40 and 60 degrees east. Displacement on the Hinesburg thrust is minor in this area (Pl.1, cross section C-C'). The Lincoln anticline therefore, is structurally connected to and part of, the relatively undeformed Cambrian - Ordovician shelf sequence to the west. The parallelism of bedding and S1 on both limbs of the Lincoln anticline is due to the early development and persistence of a bedding plane foliation in the Pinnacle Formation. Thus, S1 is interpreted as a foliation that developed parallel to bedding rather than axial planar to the Lincoln anticline. It is possible however, that an axial plane foliation is developed in the hinge area of the major fold. Such a foliation would represent a S1.5 surface.

F2 Folds. F2 folds are conspicuous throughout the field area. They range in amplitude from less than one centimeter to 200m or more. Major F2 folds (amplitude >50m) are responsible for variations in both the strike and map width of each rock unit (Pl.1). They are tight, upright, doubly plunging folds with steep overturned west limbs and narrow fold hinges (Fig. 5). Major F2 folds warp and tighten the Lincoln anticline so that the Lower Pinnacle Member (CZpl) is exposed on the east limb rather than in the core (Pl.1, cross section C-C').

Minor F2 folds (amplitude <50m) are not prevalent except near the hinge area of major folds. They are tight and similar in geometry to the major folds with open folds developed in the limb areas. F2 is disharmonic in the laminated schist. Fold axes diverge by as much as 90 degrees in a single outcrop. F2 is well-developed in all rock units except the Cheshire and Dunham Formations west of the Hinesburg thrust. Much of the F2 shortening in these formations was apparently taken up by D2 shear along the Hinesburg thrust.

The S2 axial plane cleavage is generally restricted to the hinge areas of major folds and tight minor folds. It commonly occurs as a spaced crenulation or pressure solution cleavage that locally develops into a slip cleavage. It is rare in the Middle Pinnacle Member and occurs locally as a fracture cleavage in the Upper Pinnacle Member and the argillaceous Cheshire member (Cca). S2 is well-developed in phyllitic rock, especially the Fairfield Pond Formation where it commonly forms a dominant foliation.

Metamorphism

Figure 6 summarizes mineral growth relative to S1 and S2 cleavage development for both clastic rock and metabasite.

Detrital Mineralogy. Quartz and albite are present as detrital grains throughout the field area. The albite is altered from original Ca-plagioclase. Individual grains vary in size from fine sand to cobbles. Larger grains are strongly undulose with sutured grain boundaries that are surrounded by fine recrystallized subgrains. Detrital K-feldspar and biotite are restricted to the Cheshire Formation. One relict igneous mineral was found in the metabasite. This is a red-brown hornblende that occurs in the greenstone (CZub and CZug).

Syn-S1 Mineralogy. Much of the detrital feldspar and quartz were recrystallized during the development of the penetrative S1 schistosity. The recrystallized grains are fine sand sized and not as strongly undulose or as highly sutured as the relict grains. Other syn-S1 minerals include sericite, chlorite, biotite, epidote, sphene, magnetite, carbonate, hornblende, actinolite and ilmenite.

Syn-S1 epidote, actinolite and hornblende in the metabasite are commonly zoned. Zoned hornblende occurs in the amphibolite-bearing unit (CZua) and in the biotite rich unit (CZub). Zoning is patchy but early S1 cores are generally light greenish-blue and late-S1 rims deep blue-green. Blue-green hornblende also occurs as unzoned grains. Syn-S1 actinolite occurs in greenstone (CZug and CZub) where it pseudomorphs relict hornblende. Individual grains locally show patchy zoning. In general, cores are light aqua-green and rims are light pale green. The former actinolite is rare.

Post-S1-Pre-S2 Mineralogy. Biotite, blue-green hornblende, chlorite, muscovite and spessartine occur as randomly oriented, euhedral grains that truncate S1. The edges of grains commonly deflect S1, indicating that growth occurred late to post-S1. Late to post-S1 mineral growth was not found west of the Pinnacle Formation.

Syn-S2 Mineralogy. M2 mineral growth is generally confined to S2 cleavage surfaces and commonly involves only quartz, sericite, chlorite and carbonate. Sphene, epidote, iron oxide and tourmaline are rotated into S2, become stretched and granulated and then emerge without recrystallization.

Mylonitic Recrystallization. A well-developed mylonitic foliation is present along the Underhill thrust. The foliation is defined by laminae of fine grained, recrystallized quartz, albite, biotite, chlorite, sericite, epidote and zoned hornblende. The mylonite foliation truncates S1 but is folded by F2. This indicates that displacement occurred late-S1 during biotite grade, M1 metamorphism. Biotite locally grows across the mylonite foliation. This indicates M1 persisted until the late stages and locally outlasted the thrust event. The thrust, therefore, does not truncate M1 metamorphic zones.

Hinesburg Thrust Zone

The Hinesburg thrust was mapped by Keith (1932) to explain the stratigraphic discontinuity that extends from Starksboro northward to the Winooski River Valley. Both Keith (1932) and Cady (1945) postulated that it continues to the south but found no evidence for faults. Evidence, presented here, suggests that the Hinesburg thrust continues south of Starksboro village as a shear zone with minor displacement. This zone was mapped by Tauvers (1982) who reports slickensides, transposed worm burrows and stratigraphic repetition in the lower part of the Cheshire Formation, in the Lincoln area.

The Hinesburg thrust in the Starksboro area, is placed along the base of the argillaceous member of the Cheshire Formation (Cca). Fault zone evidence is well-exposed in the area north of Starksboro village. Here the phyllitic Cheshire member (Ccp) is absent. The Fairfield Pond Formation (CZf) thins and locally pinches out. The argillaceous Cheshire member (Cca) thins and pinches out north of the field area. Quartzose rocks in the argillaceous Cheshire (Cca) locally contain a strong intersecting (phacoidal) cleavage. The fault appears parallel to the regional S1 foliation.

The trace of the Hinesburg thrust at locations S-3 and H-2(Pl.1) is marked by interlayered phyllite and argillite. Fault zone features are absent but a fault zone is suggested by the truncation of the phyllitic member (Ccp) and the thickness variations in the Fairfield Pond Formation(CZf). Local shear may have extended to the Fairfield Pond Formation - Pinnacle Formation contact in areas such as J-3(Pl.1), where the Fairfield Pond Formation is thin.

One significant aspect of the argillaceous Cheshire member, along the trace of the Hinesburg thrust, is the common occurrence of phyllitic partings up to 10cm thick. This is believed to represent a fault zone pressure solution cleavage. A pressure solution cleavage is also suggested by transposed trace fossils in the phyllitic Cheshire member that lack a strong mineral lineation. Syn-D1 quartz veins attest to the selective solution of quartz.

The Hinesburg thrust developed from the sheared overturned limb of the Lincoln anticline (Pl.1). This relationship, and the parallelism of the thrust to the regional S1 foliation, suggests displacement occurred late-F1 during M1 metamorphism. Displacement on the Hinesburg thrust is between .5 and 2km in the field area but increases northward to at least 10km in the Hinesburg area.

Underhill Thrust Zone

The Underhill thrust is the best defined and most significant thrust in the area. The Jerusalem slice (CZul) is considered a large lithic sliver that formed during emplacement of the Underhill slice.

Mylonite foliation and lithic slivers of metabasite are well-exposed along the Underhill thrust between locations J-10 and N-12 (Pl.1). The fault trace is poorly exposed outside this area but was crossed at locations I-10, G-10 and C-9(Pl.1). It is placed east of all known exposures of laminated schist (CZul) at location I-10(Pl.1) and separates thick sequences of metagreywacke (CZpl) from finer grained schist and metagreywacke, of similar composition (CZu), at locations G-10 and C-9(Pl.1). The contact is interlayered at locations I-10 and G-10 but is abrupt at location C-9.

Mylonitic Foliation. Mylonite along the Underhill thrust is a syn-M1, incipient to pervasive foliation that truncates the earlier S1 schistosity (Pl.2). Two compositional types are recognized: 1) mylonitic country rock, which represents sheared metagreywacke, phyllite, schist and metabasite; and 2) quartz mylonite, which represents sheared quartz veins. They occur interlayered in sequences that range from a few centimeters to five meters thick. Mylonite is present 250m east of the fault trace and makes up more than 90 percent of the outcrop within 20m of the thrust at location C(Pl.2). The mylonite foliation appears parallel to the regional S1 foliation of the surrounding country rock.

Mylonitic Country Rock. Three stages are recognized in the progressive development of mylonite foliation in country rock: 1) incipient, 2) well-developed and 3) pervasive. Mylonites that show a continuous grain size reduction from country rock toward the center of the shear zone, contain all gradations between these stages. Those in knife-sharp contact with country rock contain a well-developed or pervasive mylonite foliation. In this discussion, a "section" refers to a cut perpendicular to the dominant foliation in the rock. A section is either perpendicular or parallel to the mineral lineation.

<u>Incipient Stage.</u>

Rocks at the incipient stage of mylonitization are distinguished by a strong intersecting (phacoidal) foliation in sections both perpendicular and parallel to the mineral lineation. In other examples, a spaced mylonite foliation truncates intrafolial folds of S1 (Pl.2, Fig.7). The rock is not strongly foliated and a pervasive mineral lineation is not developed.

<u>Well-Developed Stage.</u>

Mylonite at this stage is strongly foliated, non-schistose and well lineated. The earlier S1 foliation occurs as discontinuous lenses and stringers. The intersecting (phacoidal) foliation is well-developed only on sections perpendicular to the mineral lineation. The foliation on sections parallel to the lineation is planar and compositionally layered compared to the incipient stage.

<u>Pervasive Stage.</u>

Mylonite at this stage is strongly foliated and very fine grained. S1 is obliterated, but a few albite porphyroclasts (<400 microns) are present. A pervasive mineral lineation is defined by elongate quartz-rich rods or layers. Mica wraps around the quartz-rich layers (or rods) so that sections parallel to the mineral lineation show strong compositional layering and sections perpendicular to the mineral lineation show a well-developed phacoidal foliation (Pl.2, Fig.8). Individual quartz and albite grains are generally less than 100 microns and elongate parallel to the mineral lineation. They are undulose but are not highly sutured.

The relative sense of shear obtained from intrafolial folds and deformed mineral grains, is predominantly east over west. Intrafolial fold axes, slickensides and quartz rods plunge down dip and trend roughly S 66 E.

Quartz Mylonite. The quartz mylonite is characterized by a pervasive mylonite foliation with slickensides and quartz rods (Pl.2, Fig.9). It is the most common mylonitic rock at the fault contact and is always in knife-sharp contact with country rock.

In thin section, the quartz mylonite consists of greater than 95 percent quartz with sericite and lesser amounts of iron oxide. Quartz varies in grain size from very coarse (>1.5mm) to very fine (<50 microns). All grains are undulose. Larger grains are strongly undulose, contain deformation lamellae and sutured grain boundaries. Individual grains are équant on sections perpendicular to the mineral lineation (Pl.2, Fig.10) but strongly elongate on sections parallel to the lineation (Pl.2, Fig.11). The larger grains are surrounded by shear bands of fine recrystallized quartz that define the mylonite foliation.

The lack of feldspar, abundance of quartz and the occurrence in very thin layers with knife-sharp contacts, suggests that the quartzite represents sheared quartz veins.

Regional Extent. The mapped lateral extent of the Underhill thrust is 21km (Tauvers, 1982, this report). It probably extends northward along the Pinnacle - Underhill Formation contact on the Geologic Map of Vermont (Doll and others, 1961). This trend separates the predominantly clastic Pinnacle Formation to the west from finer grained, metabasite-bearing rock east of the thrust. To the south, the Underhill thrust may continue along the Hoosac - Underhill Formation contact. Stanley and Ratcliffe (1983) correlate the Underhill thrust with the Hoosac Summit - Middlefield thrust zone along the eastern border of the Berkshire massif in western Massachusetts. Large horizontal displacement (>15km) is suggested by: 1) the presence of large lithic slivers (including metabasite and the Jerusalem slice), 2) tectonic klippen 3km west of the fault trace and 3) the absence of volcanic rock in the Pinnacle Formation.

Major F1 Folds in the Underhill Slice. Compositional layers in the Underhill slice are parallel to S1. The Underhill slice is underlain by a major thrust fault and is not part of the Lincoln anticline. Metagreywacke in the Underhill slice shows a greater degree of deformation than similar metagreywacke in the Lower Pinnacle Member. The micaceous foliation is well-developed with through-going anastomosing bands that separate distinct lenses of recrystallized quartz and albite. This contrasts with the Lower Pinnacle Member in which the micaceous foliation is generally expressed as interstitial flakes. The percentage of recrystallized grains relative to detrital grains is also greater in the Underhill slice. These relationships suggest that the Underhill slice is tightly folded relative to the Pinnacle Formation. It is possible that the Underhill slice represents a recumbent fold with a sheared lower limb (i.e. the Underhill thrust). The dominant foliation in this formation, therefore, may be the S1.5 axial plane foliation into which the S1 bedding foliation has been rotated. The S1.5 foliation becomes pervasive at the base of the recumbent fold where it forms the mylonite foliation in the Underhill thrust zone. D1 deformation apparently progressed from east to west so that the Underhill slice was already tightly folded and the axial plane S1.5 foliation was well-developed, prior to the development of a S1.5 foliation in the Pinnacle Formation. This geometry, of recumbent folds floored by thrusts overlying less deformed rock, is similar to structures reported in the Taconic allochthons (Zen, 1961, 1972). Thus, the Underhill thrust may represent the root zone for the (now eroded) northern extension of the syn-metamorphic high Taconics (Stanley and Ratcliffe, 1983).

Jerusalem Thrust Zone

The Jerusalem slice consists of undifferentiated quartz laminated schist (CZul; Fig.12, Pl.2). It is exposed as a belt on the east limb of the Lincoln anticline and as erosional outliers at locations N-7 and N-10(Pl.1). Field and petrographic evidence suggest that shear related to emplacement of the Jerusalem slice was not restricted to the laminated schist - Middle Pinnacle Member contact but was distributed throughout the laminated schist within the Jerusalem slice itself.

The erosional outliers occur on topographic highs in knife-sharp contact with the structurally underlying Middle Pinnacle Member. There is no change in texture or gradation in either rock unit as the contact is approached. The contact is parallel or at a very low angle to S1 and is folded by F2. The outliers do not plunge into the ground either to the north or south, change facies with the Pinnacle Formation or reappear as a belt on the west limb of the Lincoln anticline.

Tectonic imbrication and mylonitization is evident along the belt on the east limb of the Lincoln anticline. The laminated schist, in this area, contains discontinuous pods and layers of Middle Pinnacle Member metagreywacke which commonly contain a well-developed phacoidal foliation.

Thin sections of laminated schist, taken anywhere in the Jerusalem slice, show the same general fabric (Pl.2, Fig.13). There is strong metamorphic differentiation of quartz-rich and mica-rich layers; grain size in well-developed quartz laminations is less than 100 microns and mica-rich layers commonly contain lenses and stringers of quartz or epidote. These characteristics are typical of mylonite along the Underhill thrust but are rare in fine grained country rock in either the Underhill or Pinnacle Formations.

Quartz laminations in the laminated schist are closely associated with quartz veins. Both are extremely abundant and are seen in outcrop and in thin section to grade directly into each other (Pl.2, Fig.13). The transition from a quartz lamination to a quartz vein (grain size >1mm) is directly related to the percentage of mica at grain boundaries. The grain size of quartz in a lamination is less than 100 microns where interstitial mica is abundant but becomes considerably larger (forming quartz veins) where mica is absent. All gradations may exist in a single lamination depending on the distribution of mica. The quartz veins truncate rather than deflect the surrounding micaceous foliation. This suggests that quartz growth occurred late to post-S1 (i.e. late M1).

Significantly, a sliver of laminated schist along the Underhill thrust (Pl.2, B) grades directly into a quartz mylonite. It was previously argued that the quartz mylonite represents sheared quartz veins. The close association of quartz laminations to both quartz veins and quartz mylonite, suggests that the quartz laminations themselves represent sheared quartz veins. This interpretation is supported by the presence, in quartz veins, of fine grained shear bands that cut across the larger strongly undulose grains (Pl.2, Fig.13).

The presence of sheared quartz veins suggests that silica-rich fluids migrated into the fault zone during active shear. Fluid migration is also suggested in mylonitic metagreywacke by the presence of overgrowths and fibrous infillings along brecciated albite porphyroclasts (White, 1976). The knife-sharp contacts of the laminated schist and quartz mylonite with country rock, may also be indicative of fluid migration. Thus, the laminated schist is interpreted as an originally fine grained rock that has been tectonically modified by distributed shear along mylonitic zones represented by the crystalline quartz laminations. The sheared fabric of the quartz mylonite relative to the recrystallized fabric of the laminated schist, suggests that displacement continued along the Underhill thrust after distributed shear in the Jerusalem slice had ceased.

The room needed to accommodate the observed quartz veins and laminations may have been created as the thrusts overrode the cross-synclinal trough of the doubly plunging Lincoln anticline (Pl.2). The trough was filled by the Jerusalem slice and was accompanied by silica-rich fluid intrusion.

Structural Evolution

The major structural events are summarized in Figure 14. D1 deformation began during the Taconian orogeny with the onset of metamorphism, initial flexure of the Lincoln anticline and the incipient development of a bedding plane foliation (S1) in the Pinnacle Formation (Fig.14a). With continued deformation the Lincoln anticline became upright and doubly plunging. The bedding foliation was accentuated on the limbs of the Lincoln anticline but may have been destroyed in the hinge area during the development of an axial plane foliation (S1.5, Fig.14b). Late-F1 faulting occurred along the Underhill thrust perhaps along the sheared lower limb of a recumbent fold. During westward displacement, the Underhill thrust incorporated lithic slivers of metabasite and the Jerusalem thrust was formed. The Lincoln anticline became west vergent at this time, broadly folding the overlying thrust slices (Fig.14c). Shear along the overturned limb resulted in formation of the Hinesburg thrust. M1 metamorphism ceased during the final emplacement of the Underhill slice. There may have been a time gap before the initiation of D2 but this deformational event is also believed to be Taconian in age. It is responsible for large scale warping of the Lincoln anticline which produced the present configuration (Fig.14d, compare with cross section C-C'(Pl.1)).

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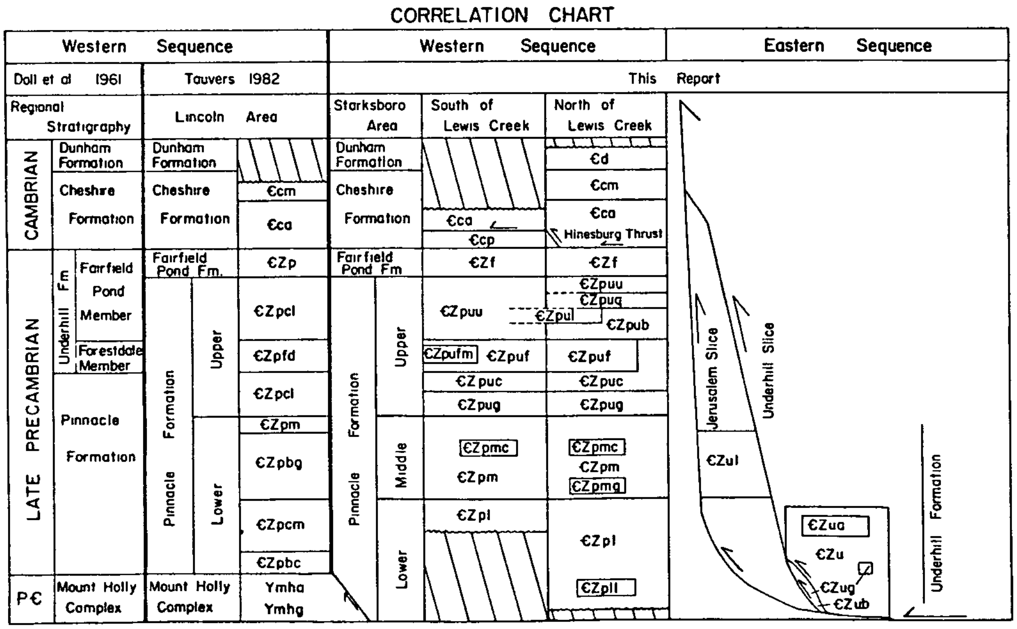


Figure 1. Stratigraphy and correlation chart for the Starksboro area. Half arrows indicate the direction of relative displacement of either the hanging wall or foot wall along faults.

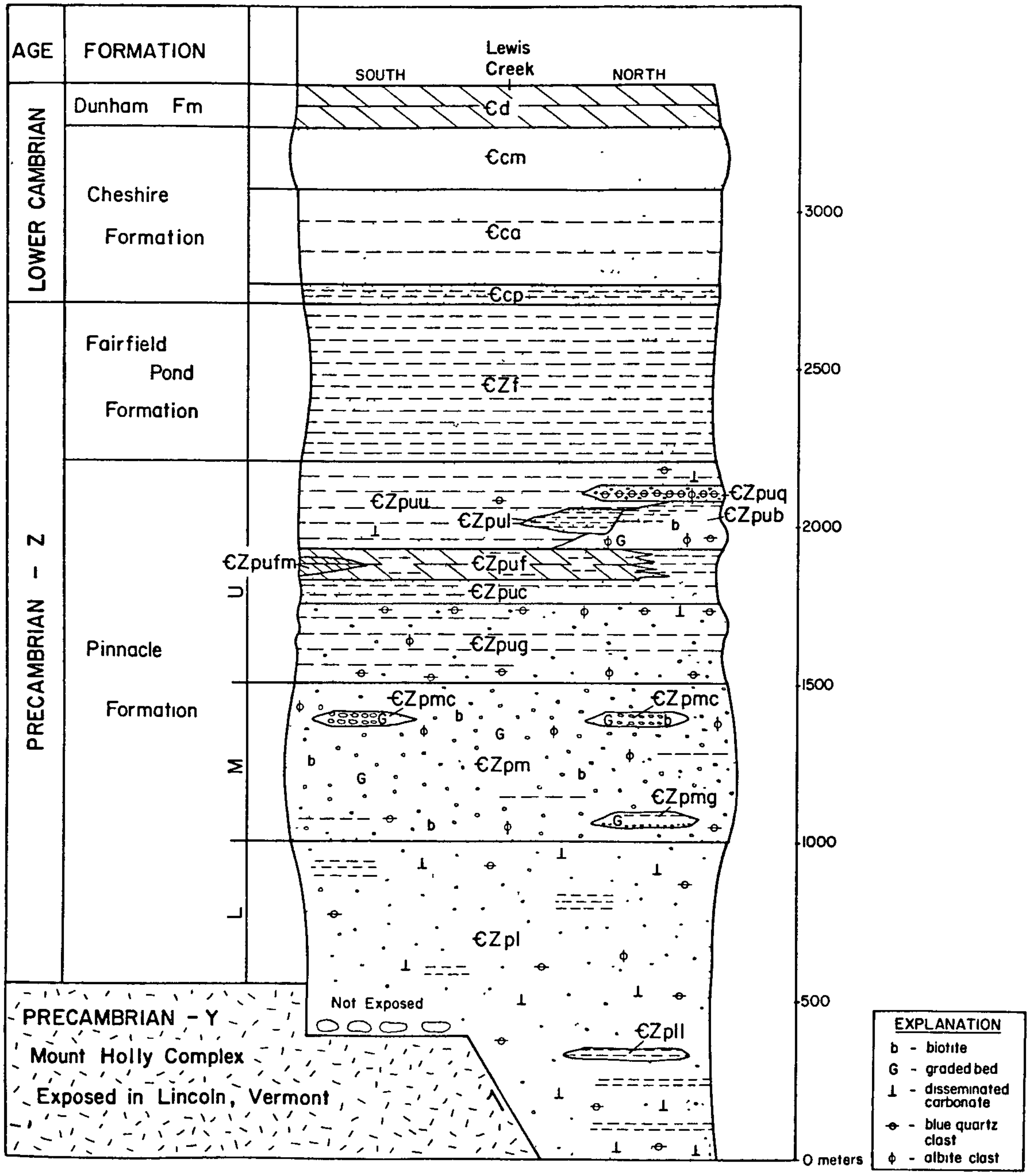


Figure 2. Detailed stratigraphy of the western sequence. Half arrow on the foot wall indicates displacement on inferred Late Precambrian normal fault.

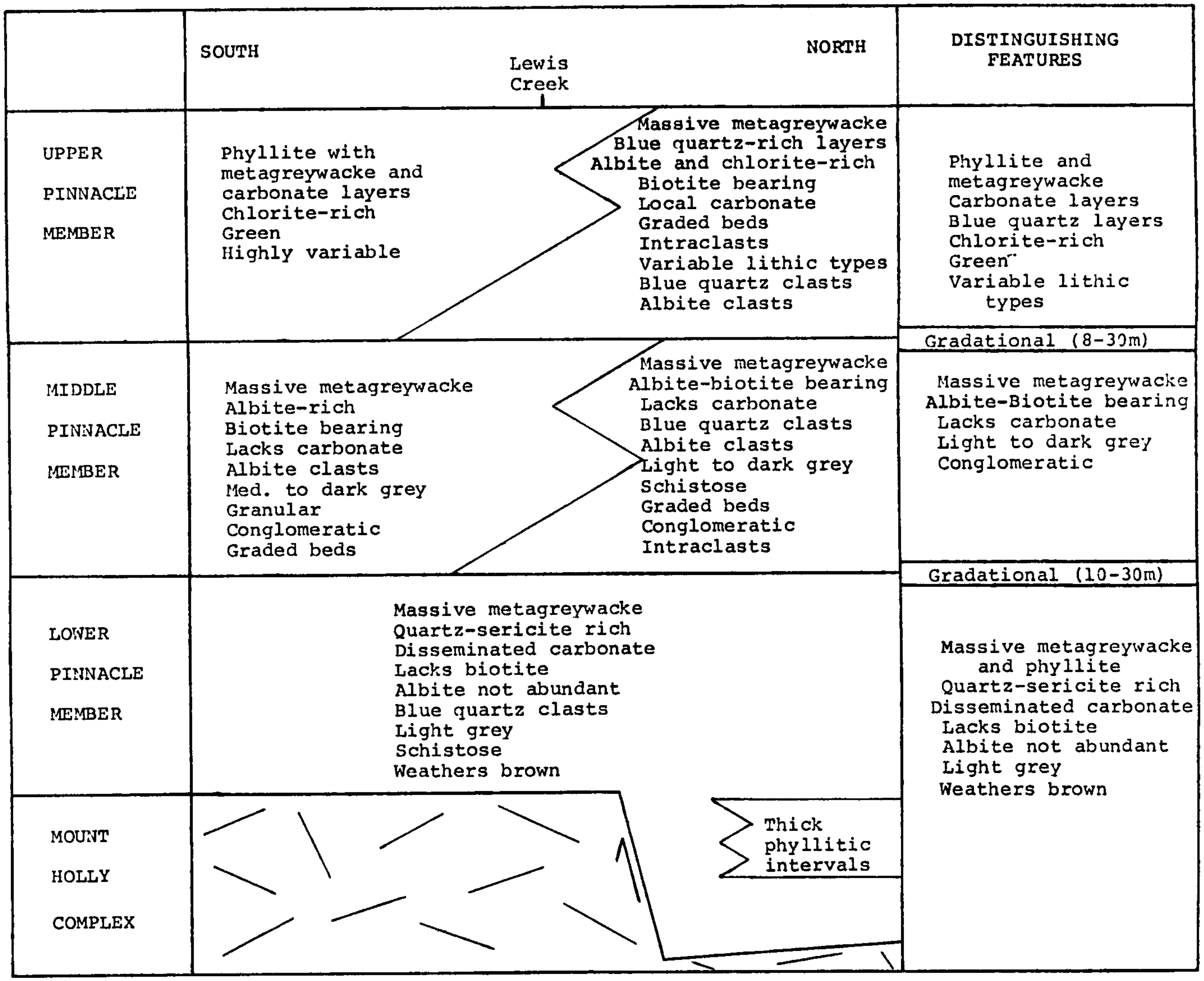


Figure 3. Summary of south-to-north facies changes and distinguishing features in the Pinnacle Formation. Half arrow symbol is same as figure 2.

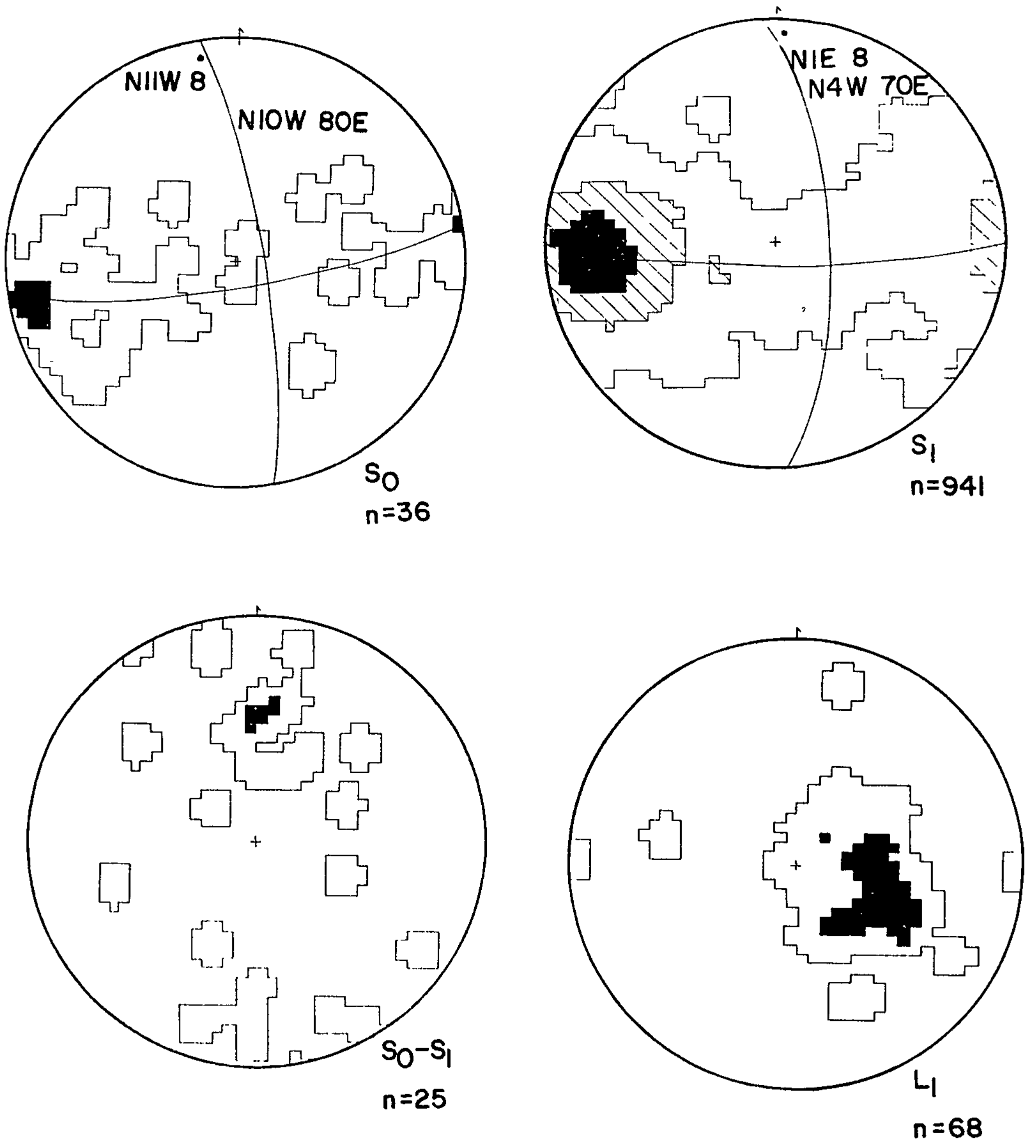


Figure 4. Lower hemisphere equal area projections of D1 structural data. a) 36 poles to bedding (S0). Contour interval is 3 and 8 percent per 1 percent area; b) 941 poles to S1. Contour interval is 0.1, 2.0, and 9.0 percent per 1 percent area; c) 25 S0-S1 intersection lineations. Contour interval is 4 and 12 percent per 1 percent area; d) 63 mineral lineations. Contour interval is 2 and 9 percent per 1 percent area.

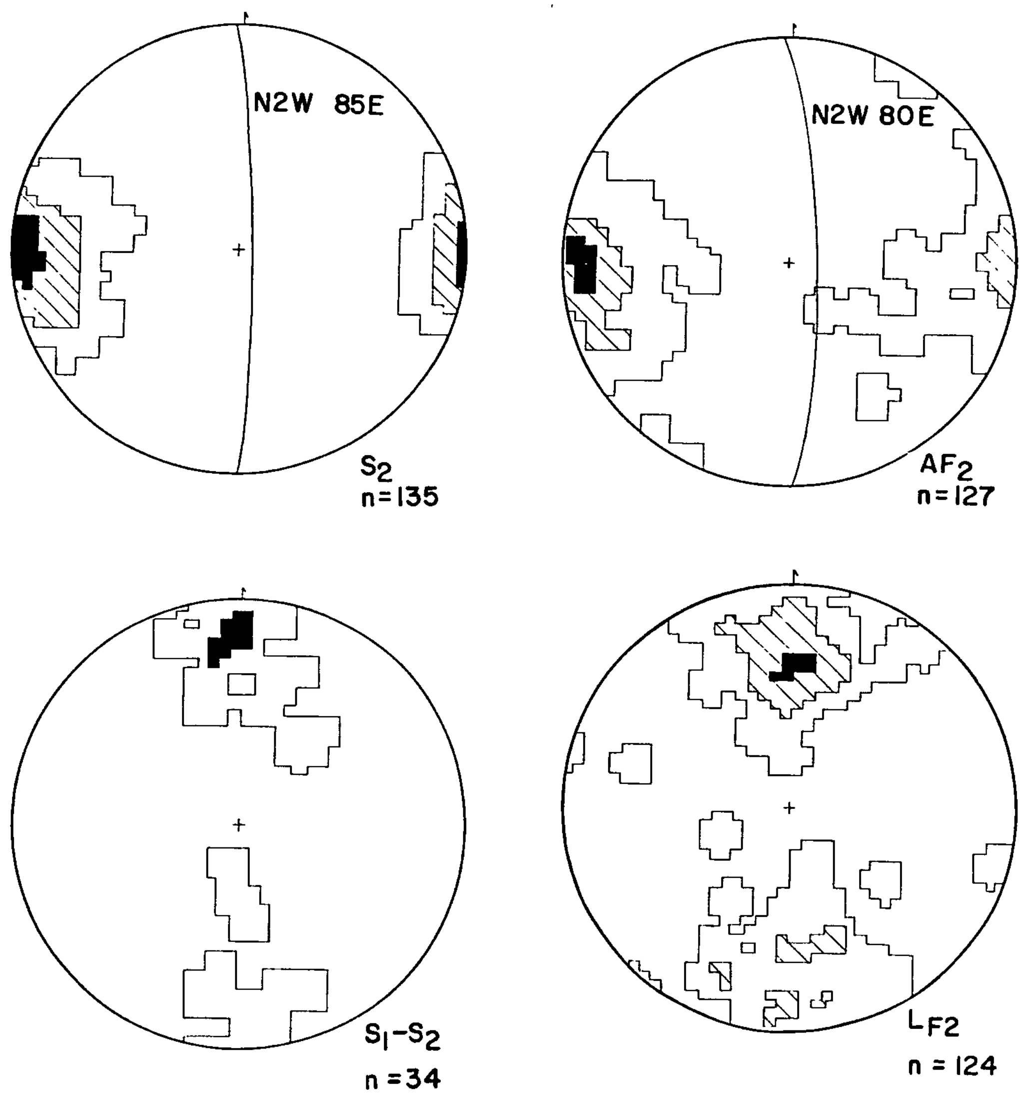


Figure 5. Lower hemisphere equal area projections of D2 structural data. a) 135 poles of S2. Contour interval is 0.7, 6.0, and 18.0 percent per 1 percent area; b) 127 polesto F2 axial surfaces. Contour interval is 0.8, 6.0, and 17.0 percent per 1 percent area; c) 34 S1-S2 intersection lineations. Contour interval is 3 and 15 percent per 1 percent area; d) 124 F2 fold hinges. Contour interval is 0.8, 4.0, and 14.0 percent per 1 percent area.

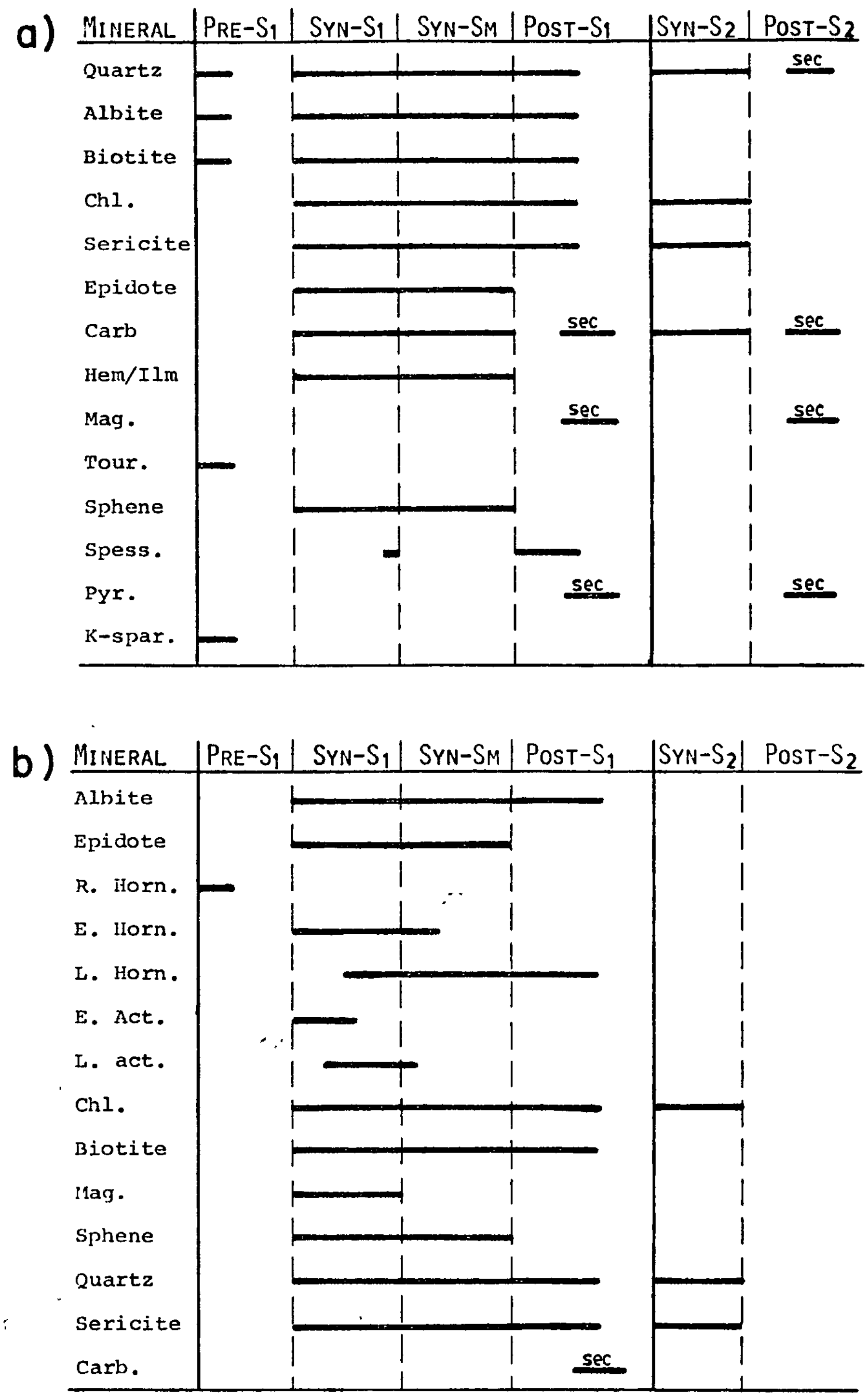


Figure 6. Relative time - mineral growth chart for a) clastic rock and b) metabasite. Sm represents the mylonitic foliation. Sec indicates secondary mineralization.

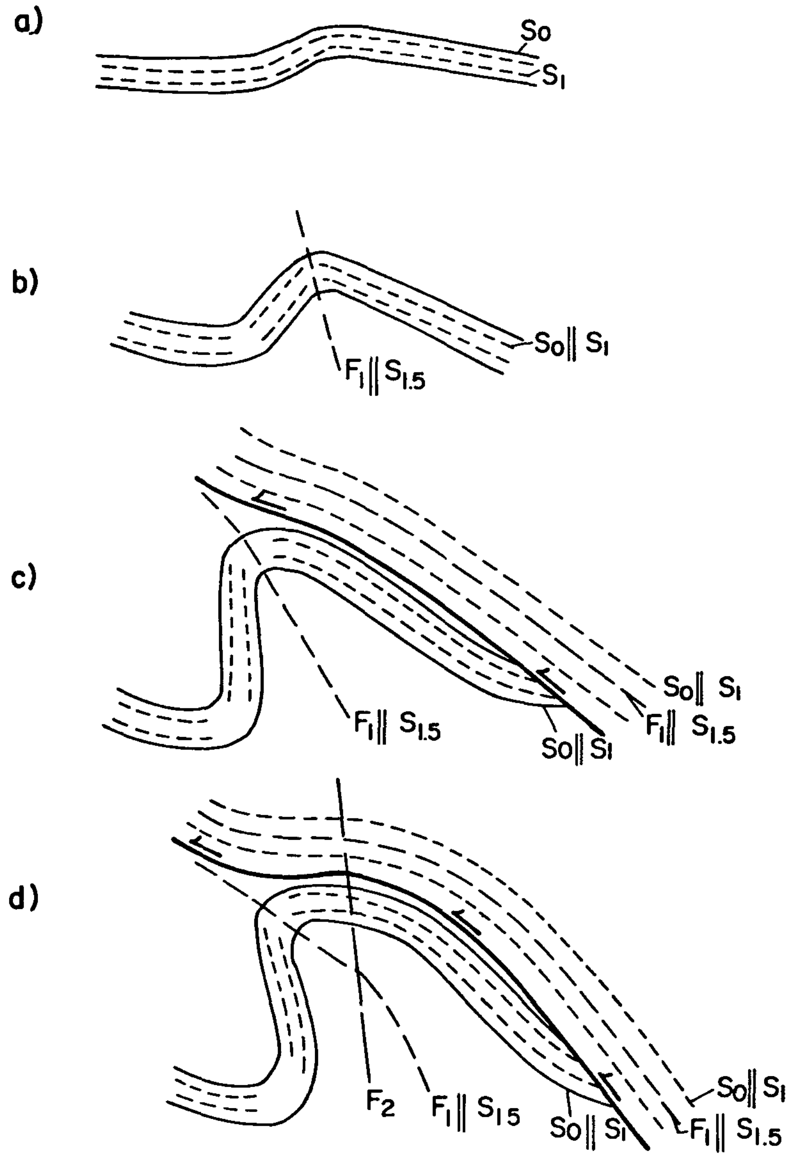
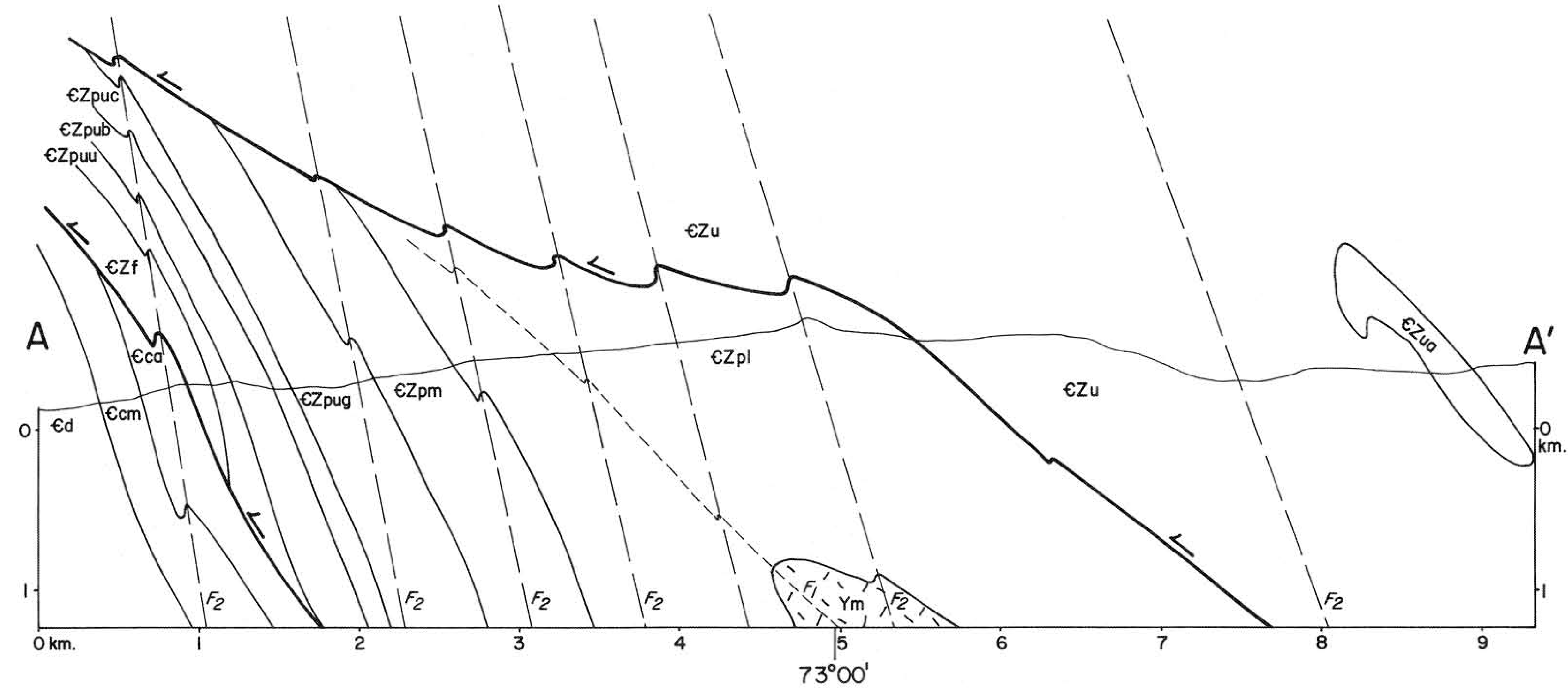
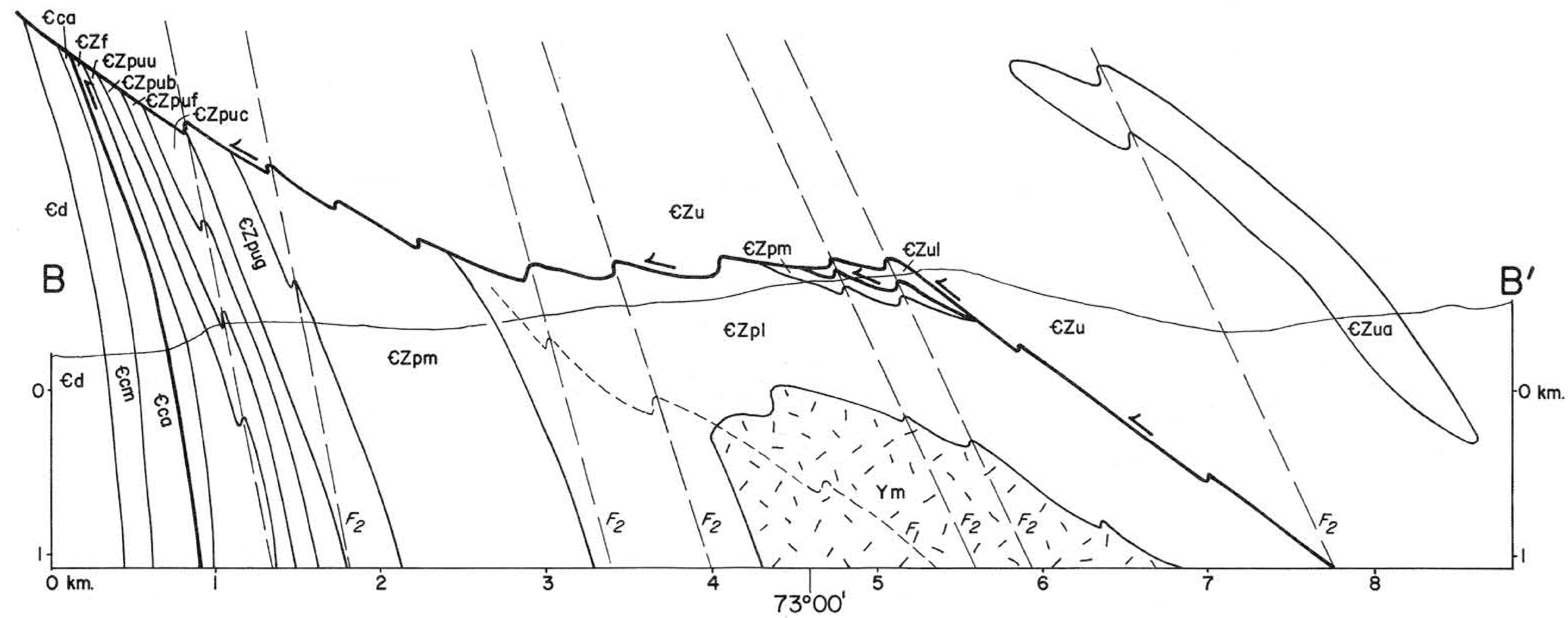
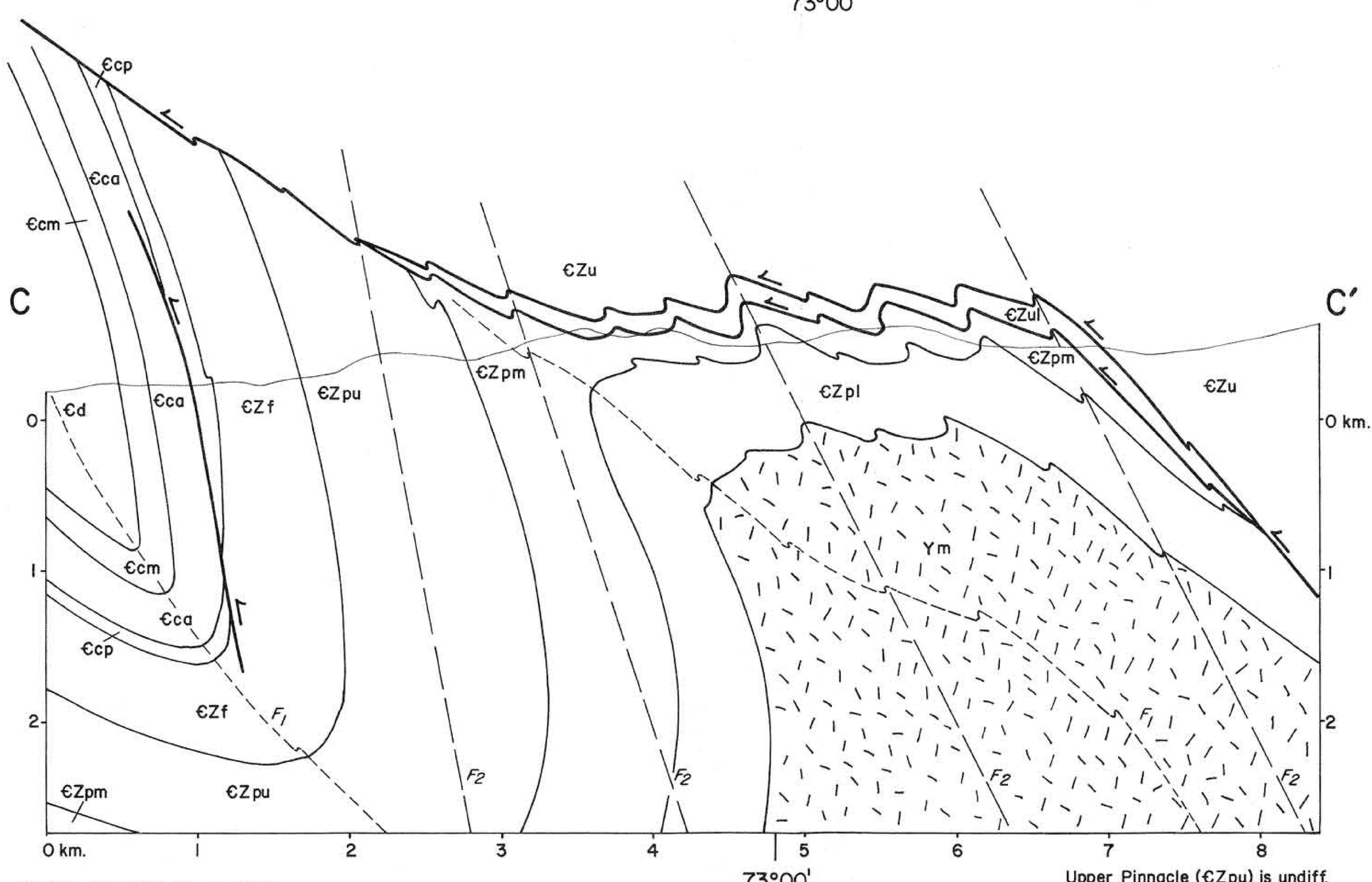


Figure 14. Progressive development of the Lincoln anticline. a) Initial flexure of the Lincoln anticline and the development of a foliation (S1) parallel to bedding (SO) in the Pinnacle Formation. b) Development of an axial plane foliation (S1.5) in the hinge area of the Lincoln anticline (F1). c) Truncation of the Lincoln anticline by the Underhill fold-thrust nappe. The bedding foliation (SO and S1) in the Underhill slice has been rotated into parallelism with the axial plane foliation (S1.5) of the nappe (F1). d) Large-scale warping (F2) of the Lincoln anticline.



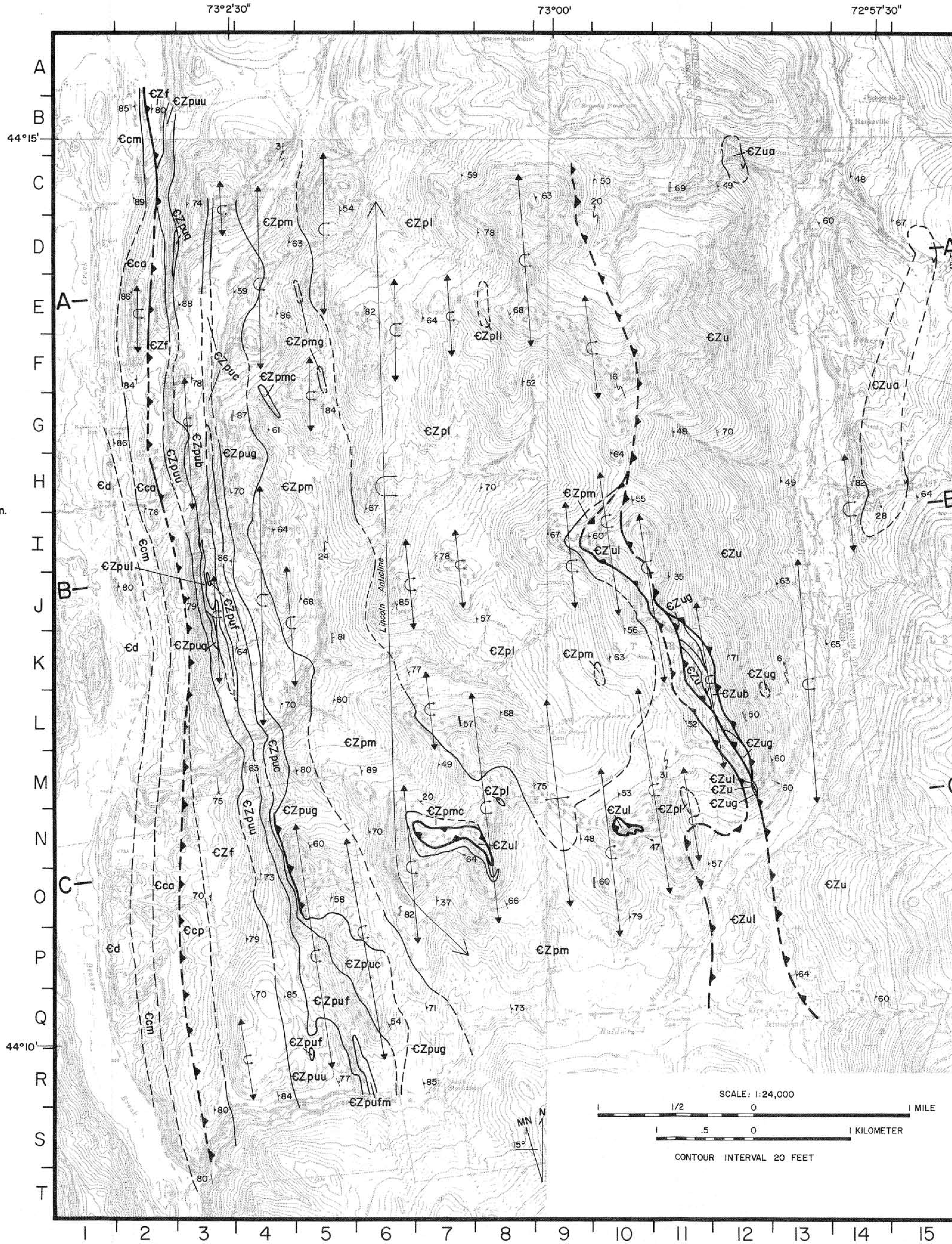




Geology of the Starksboro Area, Vermont

JOSEPH A. DIPIETRO

PLATE 1



EXPLANATION

WESTERN SEQUENCE

L. CAMBRIAN

- €d DUNHAM FORMATION
- CHESHIRE FORMATION
  - €cm Massive quartzite member
  - €ca Argillaceous member
  - €cp Phyllitic member

LATE PRECAMBRIAN

- €Zf FAIRFIELD POND FORMATION
- PINNACLE FORMATION
  - Upper Member
    - €Zpuu Chloritic metagreywacke
    - €Zpuq Quartz-pebble unit
    - €Zpub Biotite-bearing unit
    - €Zpul Thinly bedded unit
    - €Zpuf FORESTDALE DOLOMITE
    - €Zpufm Massive dolomite
    - €Zpuc Fine metagreywacke
    - €Zpug Coarse metagreywacke
  - Middle Member
    - €Zpm Quartz-albite-sericite metagreywacke
    - €Zpmc Conglomeratic unit
    - €Zpmg Graded bed unit
  - Lower Member
    - €Zpl Quartz-sericite metagreywacke
    - €Zpll Laminated magnetite schist

EASTERN SEQUENCE

LATE PRECAMBRIAN

- UNDERHILL FORMATION
  - Jerusalem Slice
    - €Zul Quartz laminated schist
  - Underhill Slice
    - €Zu Quartz-sericite schist
    - €Zua Coarse metagreywacke and amphibolite (v)
    - €Zub Biotite metagreywacke and greenstone (v)
    - €Zug Greenstone

- Well defined contact
- Inferred contact
- Thrust contact (teeth on upper plate)
- Mylonitic foliation
- Axial trend of major F_2 anticline
- Axial trend of major overturned F_2 anticline
- Outcrop
- A–A' Line of section
- A Location (Plate 2)
- 81 Bedding (So)
- 35 Overturned Bedding
- 45 S_1 foliation
- 12 S_2 foliation
- 31 F_1 axial surface
- 23 F_2 axial surface
- 13 F_1 fold hinge
- 20 F_2 fold hinge (clockwise rotation)
- 41 F_2 fold hinge (counterclockwise rotation)
- Intersection lineation
- Mineral lineation

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PLATE 2

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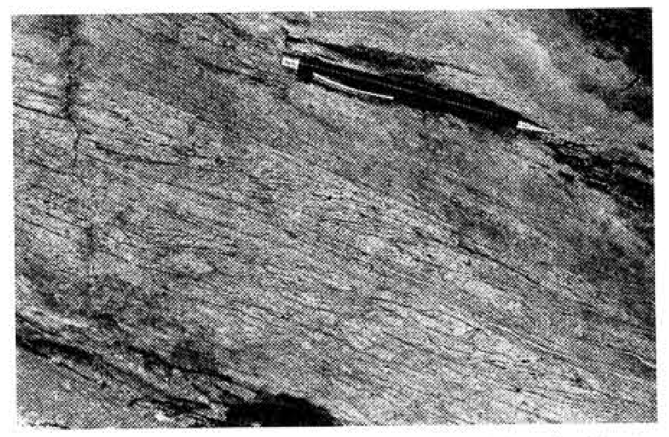


Figure 7. Intrafolial folds in metagreywacke showing incipient mylonitization (map loc. C, below). The mylonitic foliation is oriented approximately parallel to the pen (13.5 cm long) and truncates the earlier S1 schistosity.

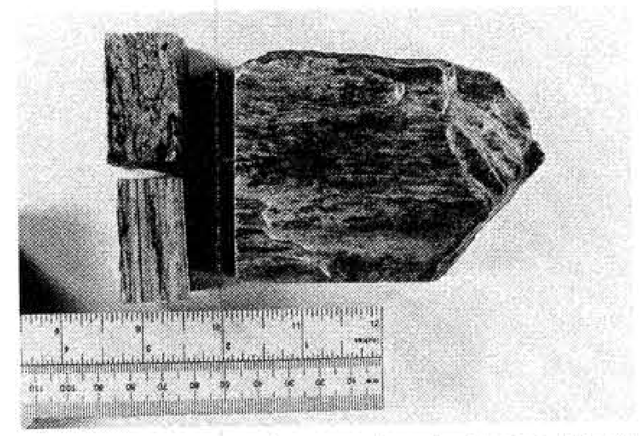


Figure 8. Metagreywacke showing pervasive mylonitization (map loc. C, below). Section at top right is oriented parallel to the mineral lineation and shows well-defined compositional layering. Section at bottom right is oriented perpendicular to the lineation and shows the well-developed intersecting (phacoidal) foliation. All sections are cut perpendicular to the foliation.

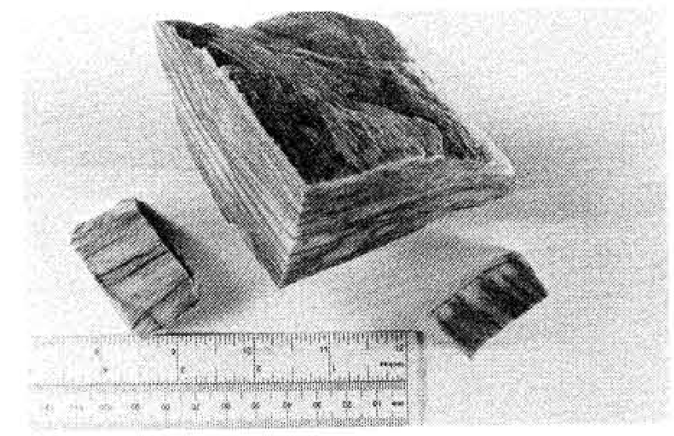


Figure 9. Quartz mylonite showing pervasive mineral lineation (map loc. C, below). Section at bottom right is oriented perpendicular to the lineation and is shown in figure 10. Section at bottom left is oriented parallel to the lineation and is shown in figure 11.

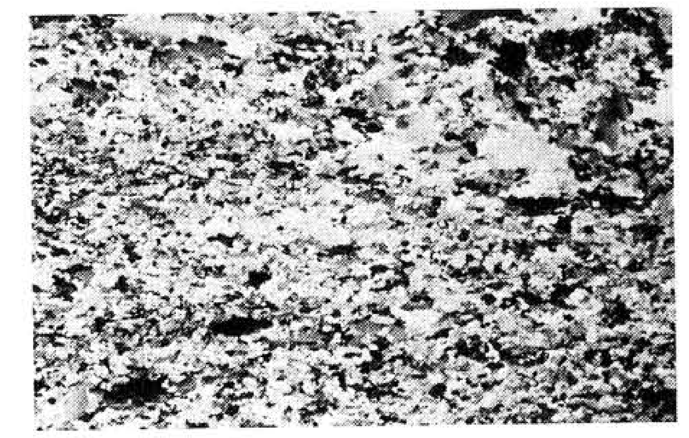


Figure 10. Photomicrograph of the quartz mylonite (fig. 9) oriented perpendicular to the mineral lineation. Note the equant grain shape and sutured grain boundaries. The mylonitic foliation is horizontal. The field of view is 1 cm wide and photographed under polarized light.

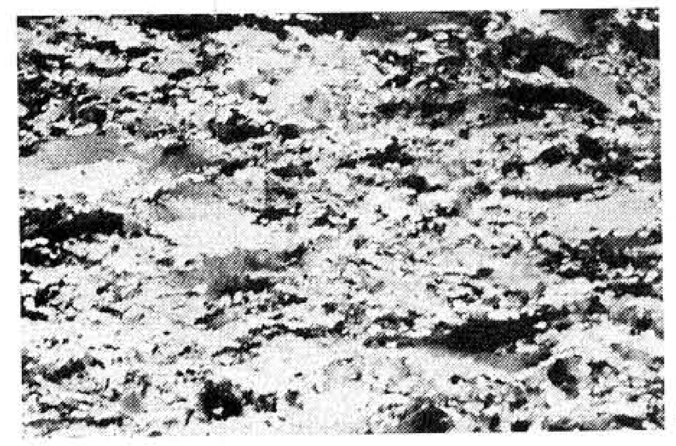


Figure 11. Photomicrograph of quartz mylonite (fig. 9) oriented parallel to the mineral lineation. Here the grains are more elongate compared to those in figure 10. The mylonitic foliation is horizontal. The field of view is approximately 1 cm wide and photographed under polarized light.

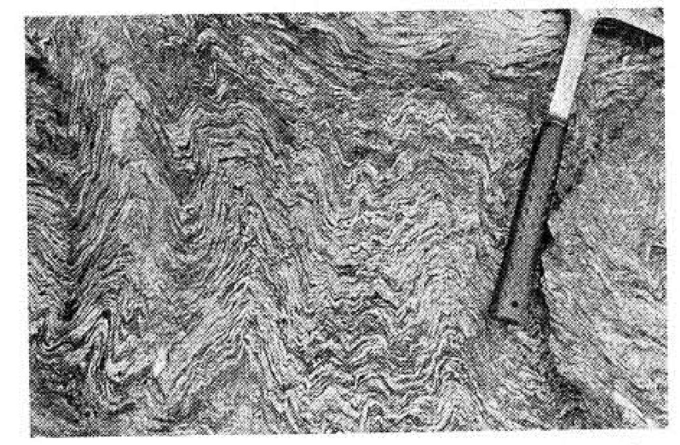


Figure 12. Typical outcrop of the quartz laminated schist (CZul). The quartz laminations are strongly folded by disharmonic F2 folds and broadly folded by F3. The outcrop is located west of map location B (pl. 2).

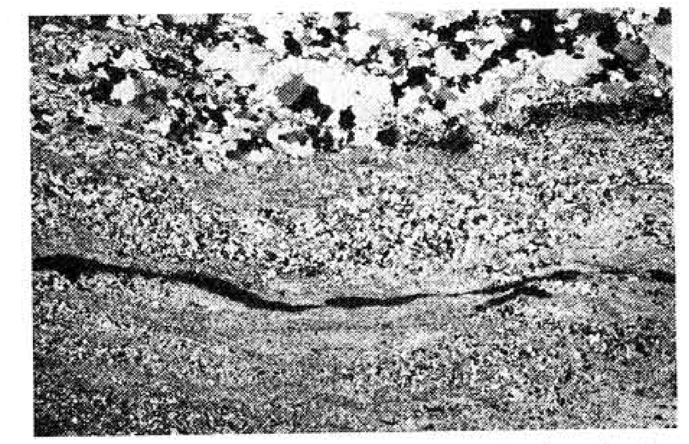
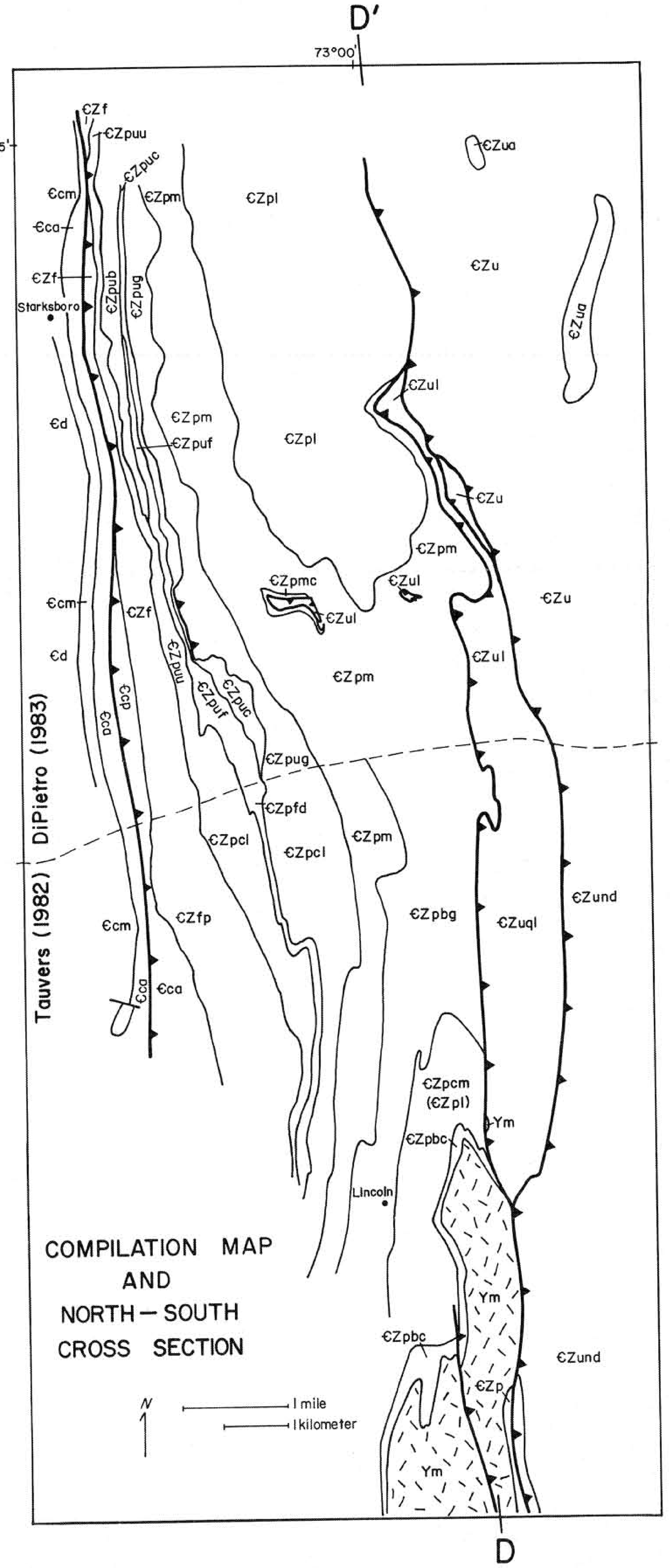


Figure 13. Photomicrograph of the quartz laminated schist oriented perpendicular to the mineral lineation (loc. P-8, pl. 1). A quartz vein at the top contains shear bands of fine-grained recrystallized quartz and grades into a quartz lamination at the left of the picture. Grain size in the quartz lamination varies from less than 50 microns to 250 microns. The micaceous layer at the bottom contains discontinuous lenses and stringers of quartz. The field of view is 2 cm and was photographed under polarized light.



COMPILATION MAP AND NORTH – SOUTH CROSS SECTION

1 mile
1 kilometer