Bedrock Geology of the Milton Quadrangle, Northwestern Vermont

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INTRODUCTION

The Milton Quadrangle is underlain by Late Precambrian to Lower Ordovician clastic and carbonate rocks that record depositional and deformational events ranging from Late Precambrian to Mesozoic age. These rocks are part of an extensive belt that extends along the western edge of the Appalachian Mountains, and consist of immature rift clastic deposits which are overlain by a stable Cambrian and Ordovician continental shelf sequence (Zen, 1972). This sequence is made up of alternating carbonate and siliciclastic deposits which grade northeastward into shales, turbidites, and slump breccias of a deeper marine basin.

The bedrock geology of the Milton Quadrangle is dominated by folds and thrusts of the Taconian age D1 deformation (Pl.1). To the west, along the eastern shore of Lake Champlain, the base of the Lower Cambrian Dunham Formation lies on top of Middle Ordovician shales along the Champlain thrust. East of there, the Hinesburg - St. Albans synclinorium extends through the central part of the Milton Quadrangle and is bound to the east by the Hinesburg thrust and the Georgia Mt. anticline. The eastern half of the Milton area consists of highly deformed Late Precambrian (Z) to Lower Ordovician rocks that mark the transition from the western imbricated foreland to the hinterland of higher grade eugeoclinal rocks.

PREVIOUS WORK

The geology of the Milton Quadrangle has been studied extensively over the past forty years. The eastern part was first mapped by Booth (1950), who traced rocks of the Oak Hill Succession in Quebec (Clark, 1934) from the international border southward to Hinesburg, Vermont. His study encompassed the stratigraphy of the Pinnacle through the Skeels Corners Formations, and delineated such major structural features as the Hinesburg and Arrowhead thrusts.

Stone and Dennis (1964) mapped the Milton Quadrangle at a scale of 1:62,500, and recognized a northeastward transition from clastic and carbonate deposits into shales and associated breccias in the Cambrian sequence. They substantially modified the location of the Hinesburg thrust compared to Booth's (1950) earlier work, and interpreted the Arrowhead thrust as a klippe of the Hinesburg thrust. Their interpretations are followed in the Vermont Bedrock Geologic Map (Doll and others, 1961).

Figure 1 shows the field areas mapped by the contributing authors and other workers, which provide a basis for our new structural interpretation. Recent sedimentologic studies by Rahmanian (1981), Gregory (1982), and Mehrtens and others (1983), have concentrated on rocks of the western shelf sequence in the Milton and adjacent areas. Myrow (1983) studied the Cheshire Formation in the Bristol area, Vermont, providing a useful framework for interpretation of the Cheshire in the Milton area.

STRATIGRAPHY

The rocks in the Milton Quadrangle have been divided into four conformable sequences according to lithologic association, inferred depositional environment, and paleogeography. They are: 1) rift clastic and transitional sequence, 2) eastern shelf sequence, 3) eastern basinal sequence, and 4) western shelf sequence (Fig.2).

The rift clastic and transitional sequence underlies the eastern part of the study area and consists of rocks belonging to the Late Precambrian Pinnacle and Fairfield Pond Formations. The eastern shelf sequence consists of eastern facies of the Cheshire and Dunham Formations, and represents the beginning of an ancient stable continental margin. The western shelf sequence contains alternating siliciclastic and carbonate deposits ranging from the Lower Cambrian Dunham Formation to the Lower Ordovician Cutting Formation. The eastern basinal sequence is a northeastern lateral equivalent of the western shelf sequence. It consists of interbedded shaley dolomitic quartzites, carbonate breccias, and conglomerates that occur within widespread shales of the Lower Cambrian to Lower Ordovician Skeels Corners Formation.

This study has concentrated on eastern facies of the Cheshire and Dunham Formations, as well as important lateral relationships between the western shelf and eastern basinal sequences (Fig.2). The following discussion will focus on these topics and their implications for an interpretation of the ancient depositional protolith.

Rift Clastic and Transitional Sequence

The rift clastic and transitional sequence consists of the Late Precambrian Pinnacle (CZp) and Fairfield Pond (CZfp) Formations. The Pinnacle, described by Carter (1979), is made up of immature boulder conglomerates, cross-bedded quartzites, the Tibbit Hill mafic volcanic rocks, and extensive phyllitic greywackes. These were deposited in active continental rift basins during initial separation of the proto-Atlantic sea (Tauvers, 1982). The Pinnacle occurs on the lower plate of the Hinesburg thrust in direct conformable contact with the overlying Cheshire Formation, and east of there on the upper plate where it is overlain by the Fairfield Pond phyllite.

The Fairfield Pond Formation (Agnew, 1977; Carter, 1979) is a fine grained, dark green, chloritic phyllite which is transitional between the Pinnacle rift clastics and the lower member of the Cheshire Formation. It is restricted to the upper plate of the Hinesburg thrust and is interpreted as an eastern distal equivalent of rocks at the Pinnacle - Cheshire transition to the west.

Eastern Shelf Sequence

Cheshire Formation. The Cheshire Formation occurs throughout the eastern part of the study area on both the upper and lower plates of the Hinesburg thrust. Recent work by Myrow (1983) in the Bristol area has shown the Cheshire to be a cyclic transgressive sequence, that grades from shaley tidal flat deposits of the lower member into massive subtidal sand bodies of the upper Cheshire. The Cheshire Formation in the Milton Quadrangle is divided into: 1) a lower thinly laminated argillaceous quartzite, and 2) an upper dolomitic member which shows considerable variation in composition and thickness.

Lower member, Cheshire Formation (Ꞓcl)

The lower Cheshire is in most areas heavily overprinted by the dominant S1 schistosity due to the abundance of shale and fine grained arenites. However, just north of Milton on Rt. 7 (Pl.2-North, 19-G) it is relatively undeformed, with many primary features still preserved. Here it occurs as thin (3 to 5cm) discontinuous rhythmic beds of white iron-stained quartzite that are interbedded with a highly bioturbated dark gray shaley matrix. Cross-beds are sporadically developed in the sandy units, and shale is found as isolated pockets within the matrix. Much of the lower Cheshire is highly feldspathic, suggesting that it is an immature sequence that was deposited in a near-shore environment.

Also present within the lower member are laterally extensive, massive, medium to coarse grained quartzite beds 1 to 3m thick. These beds have planar tops and bottoms, and probably represent high energy storm deposits. Due to the similarity of the lower Cheshire in the Milton area with that in Bristol (Myrow, 1983), it is believed to also represent cyclic tidal flat deposits in a restricted shallow marine basin.

The contact with the upper Cheshire is generally marked by the first appearance of dolomitic quartzite and coarse massive beds greater than 3m thick. At Bald Hill (Pl.2-South, 32-L) a 10 to 12m thick medium grained massive quartzite with minor amounts of dolomite is exposed between the lower and upper members. At Georgia Mt. and Milton (Pl.2-North, 15-K,L; 19-F) this transition occurs over a 15 to 20m interval of interbedded massive and shaley quartzites with minor amounts of dolomite cement.

The thickness of the lower Cheshire is difficult to determine because of repetiton by folding and volume loss to pressure solution. However, it is estimated on the west flank of Wagner Hill to be roughly 450m thick.

Upper member, Cheshire Formation (Ꞓcu)

Two important facies recognized within the upper member in the Milton area are: 1) an argillaceous dolomitic siltstone facies; and 2) a coarse massive dolomitic quartz arenite. The upper Cheshire has higher amounts of dolomite than was previously recognized, and shows large lateral variations in relative thickness and abundance of the two major facies.

The siltstone facies is commonly the lower of the two, and is well exposed at map locations 39-E and 31-L(Pl.2-South), and 16-O(Pl.2-North). It consists of a fine-to-medium grained, dark gray shaley dolomitic siltstone, with thin (3 to 8cm) beds containing less shale and dolomite cement. These thinner and more resistant beds tend to be lenticular and discontinuous, whereas the thicker beds (0.3 to 1m) are laterally more extensive. Beds of shale 0.3 to 0.6 m thick occur sporadically throughout the siltstone facies. Primary features are generally overprinted by the dominant regional schistosity, resulting in flattened quartz grains, abundant shear zones and pressure solution cleavage.

The quartz arenite facies is a massively bedded, light gray, medium-to-coarse grained arenite that commonly is feldspathic enough to make it a subarkose. Dolomite is generally present (up to 10 percent) as both primary detrital grains and diagenetic cement. This produces a diagnostic brown to maroon red friable weathered zone which is also typical of the siltstone facies.

At the Cheshire-Dunham contact the quartz arenite commonly displays ripple laminations and cross-bed sets indicating bipolar flow directions (Pl.2-South, 39-E and 31-L,M, and Pl.2-North, 21-F). This contact is in most places gradational through an interval of up to one meter, and is characterized by a rapid decrease in the detrital fraction. The total thickness of the upper Cheshire ranges from 150m in Milton to about 40m east of Indian Brook Reservoir (Pl.2-South, 40-J). It is interpreted as a distal equivalent of the subtidal sand bodies described in the Bristol, Vt. area by Myrow (1983).

Dunham Formation (Ꞓdu). The Dunham Formation crops out on both the western and eastern limbs of the Hinesburg - St. Albans synclinorium in the study area. Gregory (1982) documented a continuous transgressive sequence in the western Dunham from: 1) peritidal flat stromatolitic dolomicrospars; through 2) bioturbated subtidal/open shelf dolomicrospars; into 3) brecciated and channelled sandy dolomites of the shelf edge and slope. A complete section of the Dunham is exposed in Milton (Pl.2-North, 21-F,G) where it is divided into three members similar to those in the west.

The lower member consists of a finely crystalline dark gray dolomicrospar with abundant thin shale partings, planar stromatolites, and intermittent sandy dolospar beds. It has a thin buff-to-tan brown weathered rind which is characteristic of the middle and upper members as well. Along the base of the Dunham in the Bald Hill area there occurs a thin discontinuous deep red dolomicrospar which thickens rapidly at one place (Pl.2-South, 33-J) to about 25m.

The middle member of the Dunham is a massively bedded, highly bioturbated dolospar with colors ranging from light gray to cream and pink. Thin wispy chloritic partings are important in the Bald Hill area, but are rare in the Milton section. Horizontal and vertical burrows are present, with rare intraformational (rip-up) clasts.

The upper Dunham member is a dark gray, argillaceous dolomicrospar, including at the top a roughly 10m transitional package which grades directly into the Skeels Corners Formation (Milton Power Station, Pl.2-North, 21-F). This zone contains lenticular channelled dolomitic quartzites, polymictic dolomitic breccias, shaley dolomites, shale beds, and a thinly laminated dolomitic siltstone. The dolomitic breccias contain clasts of shale, dolomitic quartzite, and dolomite, all supported within a sandy dolomite matrix. The thinly laminated unit consists of alternating thin bands of light gray and black dolomitic siltstone, with sporadic graded beds indicative of down slope turbidity currents.

This transitional sequence is also exposed along the inverted Dunham - Skeels Corners contact at Cobble Hill (Pl.2-South, 28-D,E). It is believed to represent chaotic slump and channel features at the ancient shelf edge, and is correlated environmentally with similar but younger (Lower Ordovician) facies at the Clarendon Springs - Skeels Corners contact (Pl.2-South, 27,28-C). Thus, Gregory's (1982) interpretation of the Dunham, as a continuous transgressive sequence representing peritidal through shelf edge environments, is supported by the findings of this report.

Eastern Basinal Sequence

The eastern basinal sequence occupies a central, north-trending belt in the Milton Quadrangle, and includes rocks of the Parker (Cpa), Rugg Brook (Crb), and Skeels Corners (O?Csk) Formations. The Rock Ledge Formation of Stone and Dennis (1964) is a limestone conglomerate which is redefined here as a discontinuous member within the Skeels Corners Formation (Figs. 2,3).

The Parker and Rugg Brook Formations have been described by Howell (1939), Shaw (1958), and Stone and Dennis (1964). They occur at the base of the eastern basinal sequence, predominantly in the nothwestern part of the study area. The Parker and Rugg Brook are similar to and lateral equivalents of the base of the Skeels Corners Formation where it overlies the Dunham Formation (Figs.2,4).

The Skeels Corners Formation is a thick, shaley, transgressive unit that makes up most of the eastern basinal sequence in the Milton Quadrangle. It is composed largely of a black calcareous shale with thin limonitic and dolomitic sand beds that show sporadic grading. Other facies include locally abundant shaley dolomitic quartzites, lenticular beds of dolomite and limestone, sandy carbonate breccias (bs), and limestone conglomerates (bl) equivalent to and including the Rock Ledge member.

The sandy carbonate breccia shows considerable compositional and textural variations. At map location 33-H(Pl.2-South) it occurs as a dolomitic quartzite containing sporadic sandy clasts and shale laminations. At Cobble Hill (Pl.2-South, 28-D) it consists of angular dark gray micrite and scattered Epiphyton-rich micrite clasts floating in a light gray coarse sandy dolospar matrix (Mehrtens, 1983, personal communication).

The limestone conglomerate is recognized by Stone and Dennis (1964) as the Rock Ledge Formation, and is designated in this report as the Rock Ledge Member. It typically contains angular to rounded clasts composed primarily of fine grained, light gray weathering micrite, with rare sandy limestone and calcareous shale clasts. These occur in a coarse, light-to-dark gray sandy limestone matrix which grades laterally into the surrounding shales. At Cobble Hill (Pl.2-South, 28-D) the limestone conglomerate contains abundant clasts of Epiphyton-rich micrite along with scattered dolospar clasts in a fine grained dolomicrospar matrix (Mehrtens, 1983, personal communication).

The Skeels Corners Formation is reinterpreted in this report to range in age from Lower Cambrian to Lower Ordovician (Fig.3). This age revision is based on exposures of the base of the Skeels Corners Formation, which conformably overlies the Lower Cambrian Dunham to the Lower Ordovician Clarendon Springs Formation. The critical outcrops are exposed west of Cobble Hill (Pl.2-South, 27,28-C), where the Clarendon Springs grades upward through a normal depositional contact into the Skeels Corners Formation. This contact was previously mapped as the Muddy Brook thrust by Stone and Dennis (1964).

Western Shelf Sequence

The western shelf sequence occurs in a wide belt in the Milton Quadrangle between the Champlain thrust and the eastern basinal sequence. It is thickest in the south where the Lower Cambrian Dunham Formation is overlain by a thick clastic and carbonate succession, which is capped by the Lower Ordovician Cutting Formation. This sequence thins progressively northward to West Georgia where the Monkton, Winooski, Danby, and Clarendon Springs Formations grade laterally into the shaley and conglomeratic eastern basinal sequence. The map pattern indicates that the ancient shelf edge trends northwest through the study area, a trend which has been recognized by Rodgers (1969), Rahmanian (1981), and Mehrtens and others (1983).

Mehrtens and others (1983) have shown that the Cambrian continental shelf consists of a continuous and gradational sequence of alternating siliciclastic and carbonate deposits. This cyclic sedimentation is thought to result from local basin subsidence combined with changes in eustatic sea level and supply of clastic material to the area.

Interpretation

Figure 4 is a block diagram showing important spacial and temporal relationships for the stratigraphy of the Milton Quadrangle. The western shelf sequence is thickest in the southwest corner, and grades laterally both to the north and east into the eastern basinal sequence. Eastern facies of the Cheshire and Dunham Formations extend significantly farther to the east than younger shelf deposits.

The Late Precambrian rift clastics grade directly into the lower Cheshire Formation on the west flank of Wagner Hill. However, to the east the Fairfield Pond Phyllite occurs between the two as a distal fine grained transitional unit. In the west, at depth, the lower Cheshire is believed to directly overlie the Precambrian crystalline basement.

The stratigraphic succession in the study area records continuous deposition adjacent to the ancient North American continent which lasted from Late Precambrian to Lower Ordovician time. This began with early continental normal faulting and deposition of immature rift clastics belonging to the Late Precambrian Pinnacle Formation. These are overlain by stable shelf deposits which make up a sequence of alternating siliciclastic and carbonate units. Quiet shelf sedimentation was initiated with the deposition of the Lower Cambrian Cheshire Formation, and continued into the Lower Ordovician Cutting Formation.

North and east of the carbonate shelf, calcareous shales, carbonate breccias, and turbidites were deposited in a deep marine basin which persisted from Lower Cambrian to Lower Ordovician time. This is recorded by a thick shaley and conglomeratic sequence consisting primarily of the Skeels Corners Formation. The shelf edge appears to be a sharp declivity as proposed by Rodgers (1969), and is marked by a northeastward lateral transition from the western shelf sequence into the eastern basinal sequence.

STRUCTURE

Major structures in the Milton Quadrangle consist of: 1) the Hinesburg and Arrowhead thrust faults; 2) local "tectonic slides" (Fleuty, 1964) at Bald Hill; and 3) large scale folds including the Georgia Mt. anticline, the Dead Creek syncline, and a regional flat-lying recumbent nappe that is associated with emplacement of the Hinesburg thrust. These all formed during the D1 deformation, accompanied by metamorphism ranging from lower chlorite grade in the west above the Champlain thrust, to biotite grade in the east.

F2 folds are seen to deform earlier D1 fabrics, and become most intense in the Colchester Pond - Cobble Hill area (Pl.2-South). These may have formed in response to steps and imbrications along the Champlain thrust (Pl.1, cross-sections A-A', B-B'). Three cleavage surfaces have been identified in the study area, and have been superposed on bedding (S0). S1 and S2 are axial planar to F1 and F2 folds respectively. Sm falls chronologically between S1 and S2, but has not been correlated with any recognized folds in the area. All three cleavages are believed to have formed during the Middle Ordovician Taconic orogeny (Zen, 1972).

D1 Deformation

S1/F1. S1 cleavage forms the dominant regional schistosity in the Milton Quadrangle. It is associated with F1 folds that range in style from upright and open to flat-lying isoclinal folds, and shows a general increase in intensity from west to east. Throughout much of the lower argillite of the Cheshire Formation, S1 severely transposes bedding and forms a closely spaced penetrative schistosity which grades continuously into mylonites of the Hinesburg thrust zone. Figure 5 is a compilation of F1/S1 data from different parts of the study area.

Arrowhead thrust. The thrust at Arrowhead Mountain (Pl.2-North, 15-F) was previously interpreted by Stone and Dennis (1964) as a klippe or outlier of the Hinesburg thrust. Detailed mapping for this report, however, has shown that it represents the sheared-out lower limb of a major overturned anticline that can be traced southward into Milton (Pl.2-North, 20,21-F,G). Here, a continuous sequence occurs from the lower Cheshire member into the Skeels Corners Formation from east to west across the hinge of a flat-lying overturned anticline (Pl.2-North, cross-section D-D').

Outcrop data indicate that this structure becomes progressively sheared out to the north along its lower overturned limb, resulting in the juxtaposition of the lower Cheshire on top of the Skeels Corners Formation along the Arrowhead thrust (Pl.2-North, cross-section E-E'). Several slivers of the Dunham Formation are distributed along the thrust with size decreasing to the north. The fault is well defined by a zone consisting of cataclasites and planar slip surfaces, with slickensides indicating a transport direction of approximately N 70 W. Mylonitic quartzite occurs in a few places along this thrust surface.

Bald Hill. In the Bald Hill area (Pl.2-South, 30-K,L) similar fold-and-thrust systems occur within the Cheshire and Dunham Formations. Here, several thrust faults of limited displacement (up to 150m) are seen to nucleate along the western limbs of overturned isoclinal anticlines (Pl.2-South, cross-section C-C'). The dominant S1 schistosity is associated with these structures, flattens noticeably toward the fault surfaces, and is conformable with the thrusts in outcrop. Cataclasis or brittle-fault gouge have not been observed in exposures of these faults, indicating a more ductile style of deformation than that observed at Arrowhead Mountain.

This kind of fold related faulting is widely recognized in the British literature (Fleuty, 1964; Chadwick, 1968; Hutton, 1981). Fleuty (1964, p.452) defined a "tectonic slide" as "a fault formed in close connection with folding which is broadly conformable with a major geometric feature (either fold limb or axial plane) of the structure, and which is accompanied by thinning and/or excision of the rock succession". The structures at Bald Hill are geometrically and texturally distinct. They may be more typical of deformational styles where the ambient pressure and temperature are relatively high, representing deeper levels in the earth's crust. These are in contrast to near-surface deformation of the foreland, such as the Champlain and Arrowhead thrusts.

Hinesburg thrust. The Hinesburg thrust extends from the south-central to the northeastern part of the Milton Quadrangle (Pl.1), and has been traced through the area by Booth (1950), Stone and Dennis (1964), Agnew (1977), and Carter (1979). It is cut by the late St. George fault in the Colchester Pond area, and is folded by F2 folds from Colchester Pond to Cobble Hill (Pl.2-South). From Bald Hill northward the thrust truncates the eastern limb of the Dead Creek syncline, and is responsible for emplacement of undifferentiated Pinnacle and Fairfield Pond rocks on top of the Cheshire and Dunham Formations.

Detailed mapping for this report has shown that the Hinesburg thrust in the Colchester Pond - Cobble Hill area is genetically related to a large-scale, flat-lying recumbent nappe, with fault movement occurring on the lower limb during or after folding (Fig.6). Maximum displacement on the Hinesburg thrust is estimated to be 8 to 10 km (Pl.2-North, Pl,2-South).

The best evidence for the Hinesburg nappe is found in mappable sections of highly sheared, inverted stratigraphy along and near the fault trace. A good example of this occurs at Cobble Hill (Pl.2-South, 28-D,E) where the Dunham Formation grades conformably down structure, but up section, through a flat-lying depositional contact into the younger Skeels Corners Formation (Pl.2-South, cross-section C-C'). Just to the south (Pl.2-South, 30-D) another belt of Dunham overlies the Skeels Corners Formation along a fault contact. This is marked by rotated cleavage and missing stratigraphy in the Dunham. In the central part of this klippe the upper part of the Cheshire Formation overlies the Dunham along another inverted depositional contact.

Southeast of Cobble Hill near Colchester Pond several other sections of inverted stratigraphy occur within the Cheshire and Dunham Formations, in close proximity to the Hinesburg thrust (Pl.2-South, 36-E, 35-F). These are part of a complex thrust zone which is characterized by large amounts of distributed shear. Also common in these areas are flat-lying mylonites which grade into and are frequently indistinguishable from the dominant S1 schistosity. Prominent transport lineations are marked by elongate grains, grain clusters, and slickensides. Fault contacts are commonly "welded together", and show little or no sign of cataclasis.

The remaining lenticular fault blocks in the Colchester Pond area are regarded as sheared-out remnants of an original continuous stratigraphy along the overturned limb of the Hinesburg nappe (Pl.2-South, cross-section C-C'; Fig.6). They range in size from tens to hundreds of meters long, and consist of rocks belonging to the upper Cheshire and lower Dunham Formations. When both units are found together the Cheshire consistently overlies the younger Dunham.

Backlimb—Forelimb Geometry

One important aspect of the relationships observed along the Hinesburg thrust is the occurrence of a south-to-north transition from a backlimb to forelimb thrust geometry. The Dunham Formation, in synclines at Field Area C and Indian Brook Reservoir (Pl.2-South, 40,41-J) has been shown to conformably overlie the upper member of the Cheshire Formation. The Cheshire is in both cases truncated by the Hinesburg thrust a short distance below the normal contact with the Dunham Formation (Pl.2-South, cross-section A-A'). Across this latitude the Hinesburg thrust can be considered a backlimb thrust as defined by Dahlstrom (1970) and Butler (1982). This is the case in which a thrust fault cuts across a previously formed fold at a level which is structurally higher than the trace of the original overturned anticline.

A short distance (0.8km) north of these two synclines the Hinesburg thrust is characterized by the discontinuous inverted stratigraphy previously discussed (Pl.2-South, cross-section B-B'). This configuration is typical of a forelimb thrust, in which the fault surface occurs structurally below the axial plane of the related fold (Dahlstrom, 1970; Butler, 1982). Thus, a roughly east-west line can be drawn just north of the synclines at Field Area C and Indian Brook Reservoir (Pl.2-South), which marks a structural south-to-north transition in the Hinesburg thrust from a backlimb to forelimb thrust configuration (Pl.3, cross-sections G-G', H-H').

Sm

Sm is a discontinuous pressure solution cleavage which occurs sporadically throughout the Milton Quadrangle, and dips steeply to the east (Fig.7). Mappable folds associated with Sm have not been found. The cleavage is marked by insoluble clay residue 1 to 2 mm thick, and forms an irregular to dendritic pattern on most outcrops. Sm cuts across S1 but is in turn folded by F2 folds.

D2 Deformation

The second important deformation in the study area consists of F2 folds and S2 slip or widely spaced fracture cleavage. These structures are best developed in the Colchester Pond - Cobble Hill area (Pl.2-South), where F2 folds deform the flat-lying Hinesburg thrust and S1 cleavage. These folds are generally open and cylindrical in style, with F2 axes plunging gently to the north and south (Fig. 8).

S2 is commonly less intense and less penetrative than the dominant S1 schistosity. An exception to this occurs at Cobble Hill where S1 is severely overprinted and largely obscured by F2/S2. Here F2 fold axes have been rotated into the plane of S2 cleavage (Fig.8), probably due to differential strain during D2 deformation. In places F2/S2 looks like F1/S1, and one must be cautious when correlating minor folds from place to place in the Milton Quadrangle.

D2 folds and cleavage are locally restricted in the study area, and do not show a systematic eastward increase in intensity. They appear to occur in linear belts that vary in intensity across the region. Preliminary analysis suggests that D2 deformation may be associated with major steps and imbricated structures along the Champlain thrust. Although this interpretation is highly speculative, it was adapted in construction of cross-sections A-A', B-B' (Pl.1).

Champlain thrust

The Champlain thrust has long been recognized as a major structural discontinuity in northwestern Vermont which emplaces rocks of the Cambrian shelf sequence on top of Middle Ordovician shales of the Stony Point (Osp) and Iberville (Oi) Formations (Cady, 1945; Welby, 1961; Stone and Dennis, 1964; Coney and others, 1972; Stanley and Sarkisian, 1972).

Fault zone fabrics that occur along the Champlain thrust are typical of foreland thrusts which are found in many mountain belts. These include well-developed cataclasites, slivers of adjacent or exotic rocks, disharmonic drag folds, fault-zone cleavage, and a well-defined slip surface which is slickensided and grooved (Stanley and Morse, 1974). Pressure solution was an important process in cleavage development and rewelding of fault breccia and gouge. Deformation is restricted to a relatively narrow zone (1 to 10m) considering the magnitude of displacement involved.

The age of the thrust has been disputed. Cady (1969, p. 75) believes it developed during the Acadian orogeny although the youngest rocks exposed below the Champlain thrust are Middle Ordovician in age. Welby (1961, p. 221) believes the thrust developed in the Taconic orogeny of Middle to Upper Ordovician age. Thrusting predates the emplacement of the Mesozoic dikes which clearly cut the structures of the Champlain thrust.

Stanley and Sarkisian (1972) have suggested that major movement occurred during the Taconic orogeny, with minor reactivation occurring possibly during Acadian deformation. Regional analysis now suggests a late Taconic age for all the movement, and that the Champlain thrust is part of the major imbricated sialic slices of western New England (Stanley and Ratcliffe, 1982, in press). Recent seismic work in Quebec and New England suggest displacement in the order of 50 to 70km (Ando and others, 1983), which is substantially larger than earlier estimates of 8 to 10km (Doll and others, 1961).

Potassium-argon age dates along the western limb of the Green Mountain anticlinorium range from about 440 to 375 m.y. (Rickard, 1965; Harper, 1967; Cady, 1969), and are considered to represent cooling ages by Harper (1967). These data suggest a Taconian age for recrystallization of rocks in the Hinesburg and more westerly situated slices, although the effect of Acadian metamorphism cannot be ruled out. Recrystallization in the Champlain slice and in Middle Ordovician rocks to the west have not been radiometrically analyzed. However, the gradual reduction in cleavage intensity and its eventual absence in the Lower and Middle Ordovician sequence between the Champlain thrust and the Adirondack massif, suggests a Taconian age for the compressional deformation in the Milton area.

D3 Deformation

The third and final deformation documented in the Milton Quadrangle is recorded by the St. George fault (Pl.2-South) and a related system of fractures, minor kink folds, and bostonite dikes. These are correlated with similar structures to the south in the Monkton and Hinesburg area (Gillespie, 1975; Stanley, 1980). Elements of D3 were formed during late Mesozoic continental rifting, and cut across all earlier tectonic fabrics.

Regional Synthesis

Plate 1 shows the regional geologic map and cross-sections for the Milton Quadrangle. The western half of the map is taken primarily from that of Stone and Dennis (1964), whereas the eastern half is the result of the compilation work for this report (Fig. 1). The regional cross-sections (A-A', B-B', Pl.1) are based on data presented in this report, representative stratigraphic thicknesses for western Vermont, and regional seismic sections (SOQUIP and COCORP) reported by Ando and others (1983).

The development of regional structures in western Vermont is understood by evaluating the cross-sections in Plate 1. The vertical stacking sequence consists of three major thrusts with: 1) the Champlain thrust at the base; 2) the Arrowhead fold-and-thrust couple in the middle; and 3) the Hinesburg nappe which is floored by the Hinesburg thrust at the top. A comparison of fault zones and deformation styles shows a progressive increase in ductility from the Champlain to the Hinesburg thrusts.

The Champlain thrust is a classic foreland thrust containing brittle cataclasites and narrow fault zones. The Arrowhead thrust also has brittle fault zone fabrics, but it occurs on the western limb of a major overturned anticline which is accompanied by abundant cleavage, parasitic folds, and some mylonite zones. The Hinesburg thrust zone contains abundant mylonites that are distributed throughout the fragmented overturned limb of the Hinesburg nappe. The rocks on the upper plate have been metamorphosed to the biotite grade, and indicate that the Hinesburg nappe-and-thrust system developed at deeper levels in the crust compared to the Arrowhead and Champlain thrusts.

Perhaps more significant than the fault zone fabrics, is the change in structural style from the Champlain thrust to the fold-and-thrust couple at Arrowhead Mountain., to the tectonic slides of Bald Hill, and ultimately to the Hinesburg nappe and thrust. This sequence, with its progressive increase in ductility, appears to be typical of the transition from representative near-surface foreland thrust faults to deeper, ductile fold-and-thrust slices of the hinterland.

Palinspastic analysis of the Hinesburg thrust (Fig.6) indicates that it first developed as a fold that became severely overturned to the west, while the lower limb was coevally sheared out to form the Hinesburg thrust. During this time the lower plate became severely folded, forming tectonic slides in such zones of high strain as Bald Hill. As D1 deformation moved westward toward the earth's surface the Arrowhead fold-and-thrust couple developed, possibly as a result of drag on the overriding near-surface extension of the Hinesburg thrust. Subsequent movement on the Champlain thrust deformed the overlying thrust slices producing F2 folds, as the thrust stepped up section to the west.

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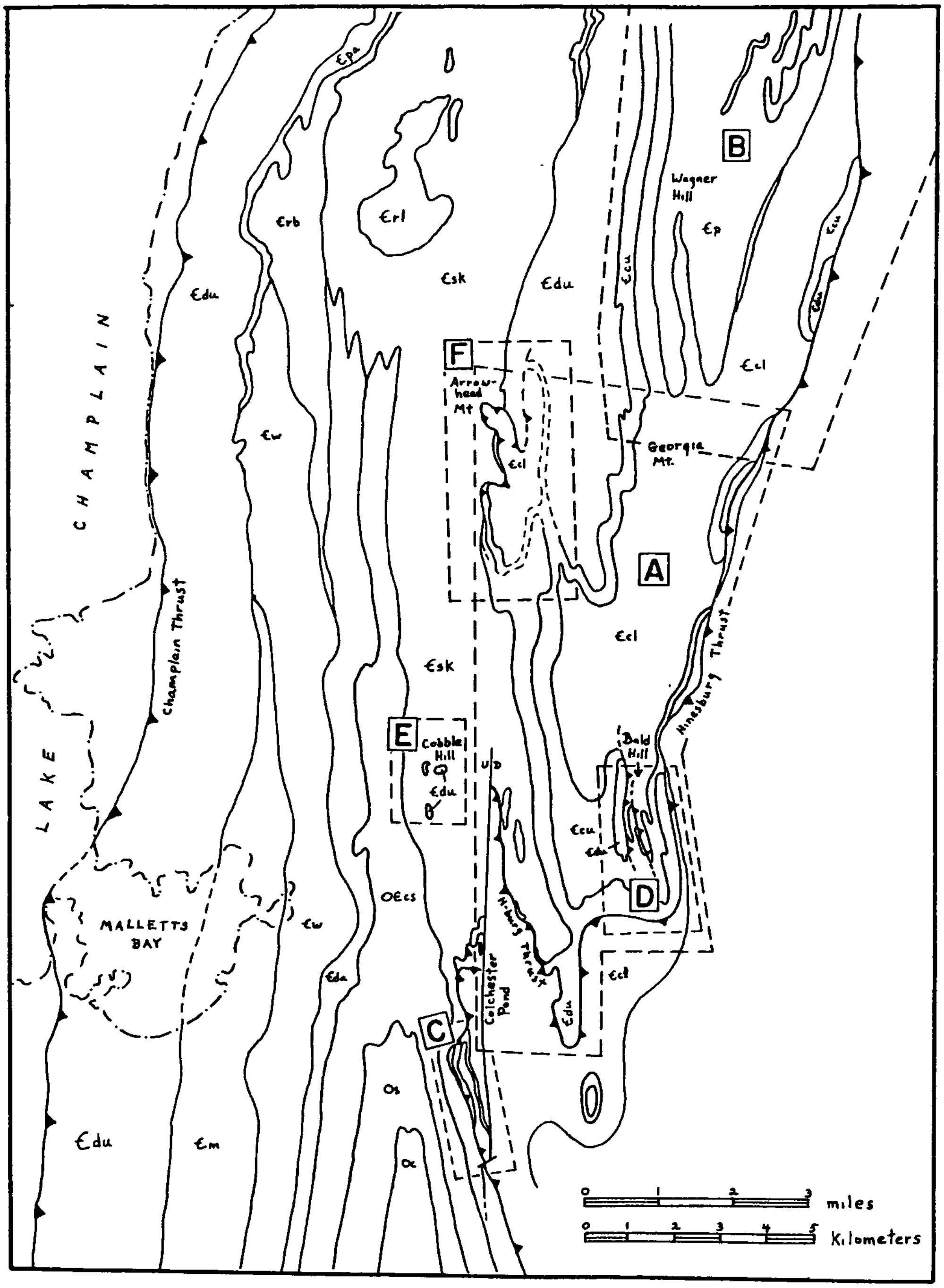


Figure 1. Location map showing bedrock geology of the Milton quadrangle and an index of recently mapped field areas: (A) Agnew (1977), scale 1:24,000; (B) Carter (1979), scale 1:24,000; (C,D) Dorsey (1983), scale 1:12,000; (E) Nyman (1983), scale 1:6,000; (F) Arrowhead fold-and-thrust couple, scale - all of the above. The area between field areas C,D and E has been throughly studied over the past five years, notably by Rosencrantz (1975) and University of Vermont students and Stanley. The geology in the western part of the study area is taken from Stone and Dennis (1964).

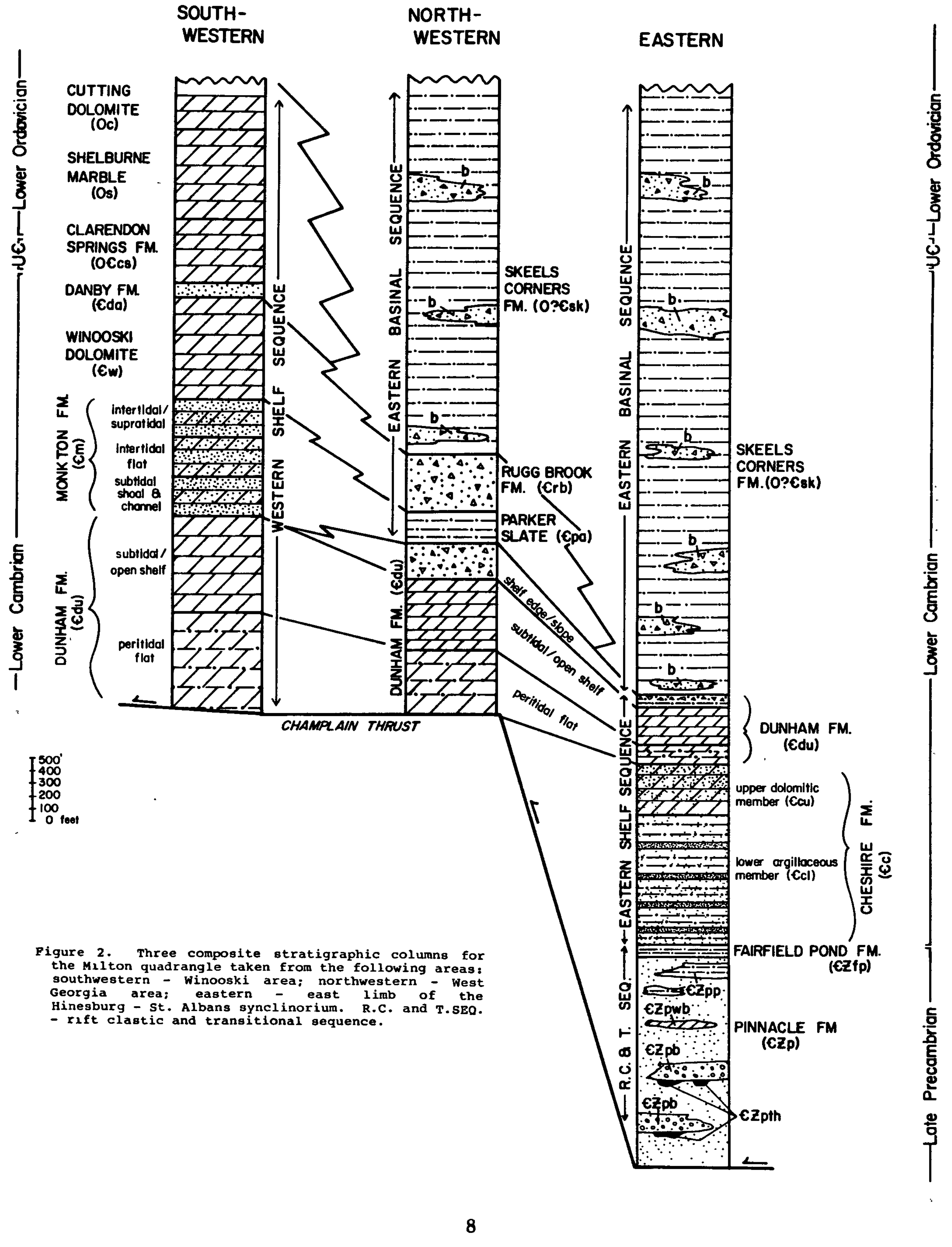


Figure 2. Three composite stratigraphic columns for the Milton quadrangle taken from the following areas: southwestern - Winooski area; northwestern - West Georgia area; eastern - east limb of the Hinesburg - St. Albans synclinorium. R.C. and T.SEQ. - rift clastic and transitional sequence.

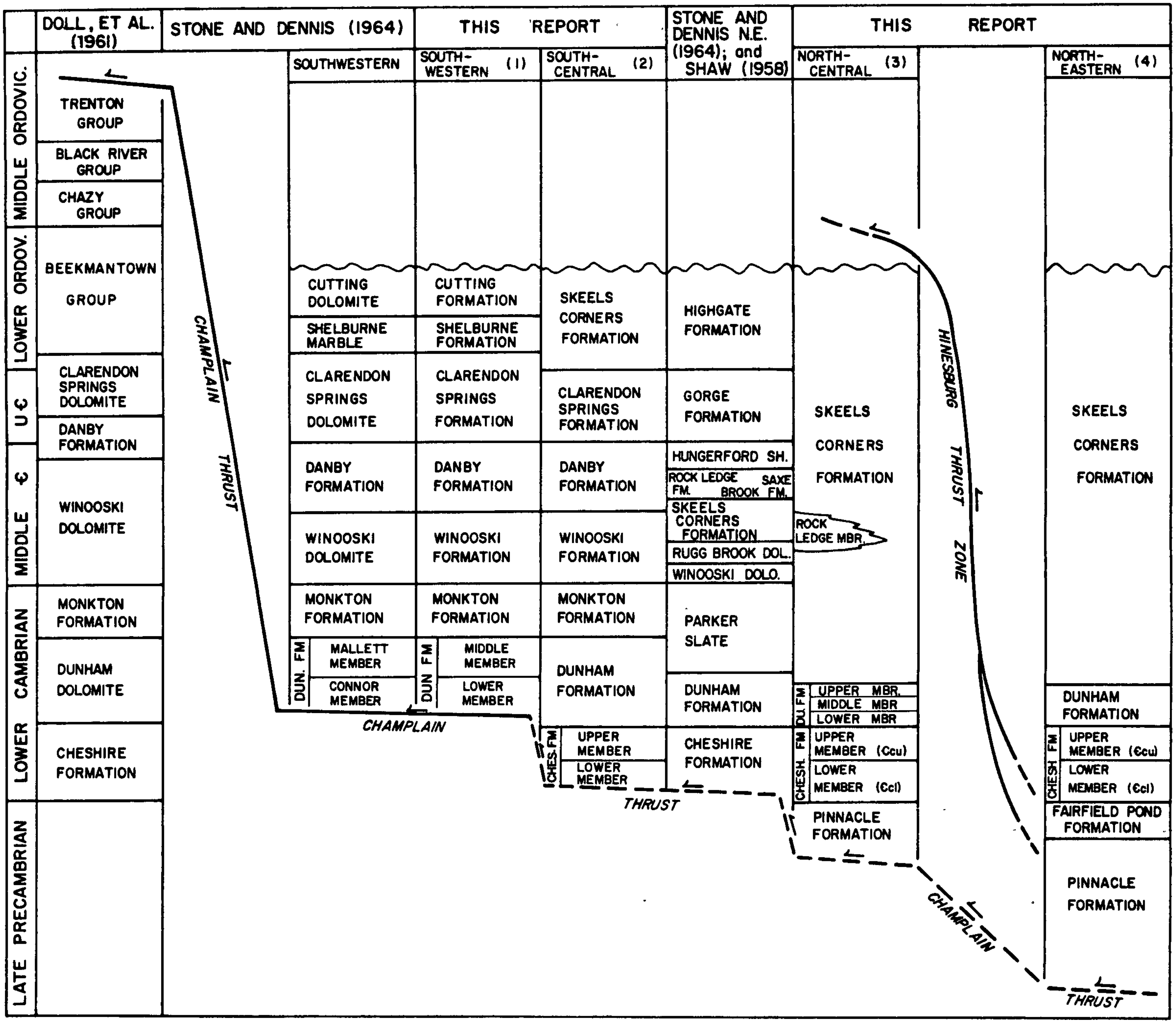


Figure 3. Correlation chart comparing findings of this report with previous interpretations of Shaw (1958), Doll and others (1961), and Stone and Dennis (1964).

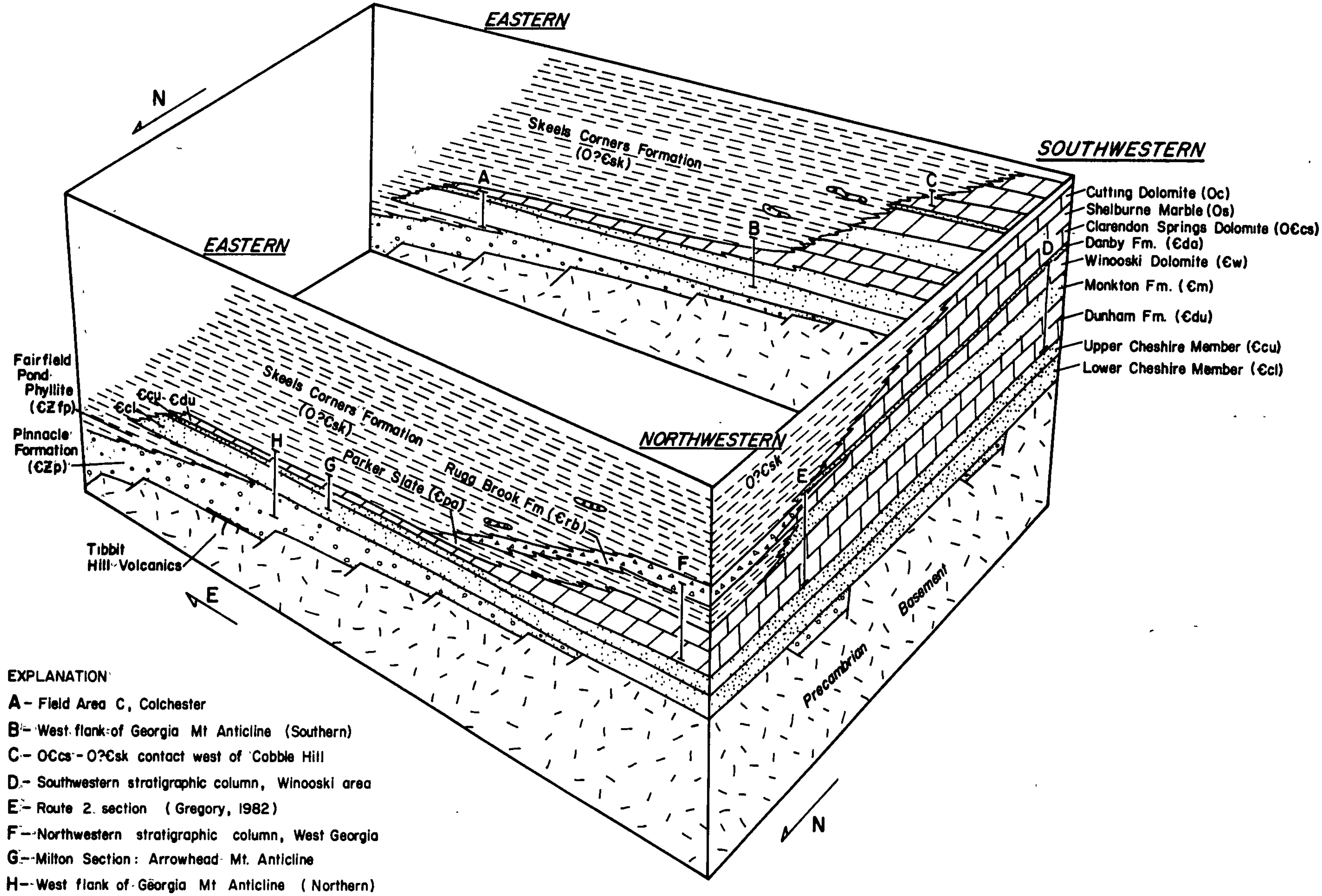


Figure 4. Diagrammatic representation of the original depositional protolith for the Milton quadrangle, reconstructed from stratigraphic information in the indicated areas.

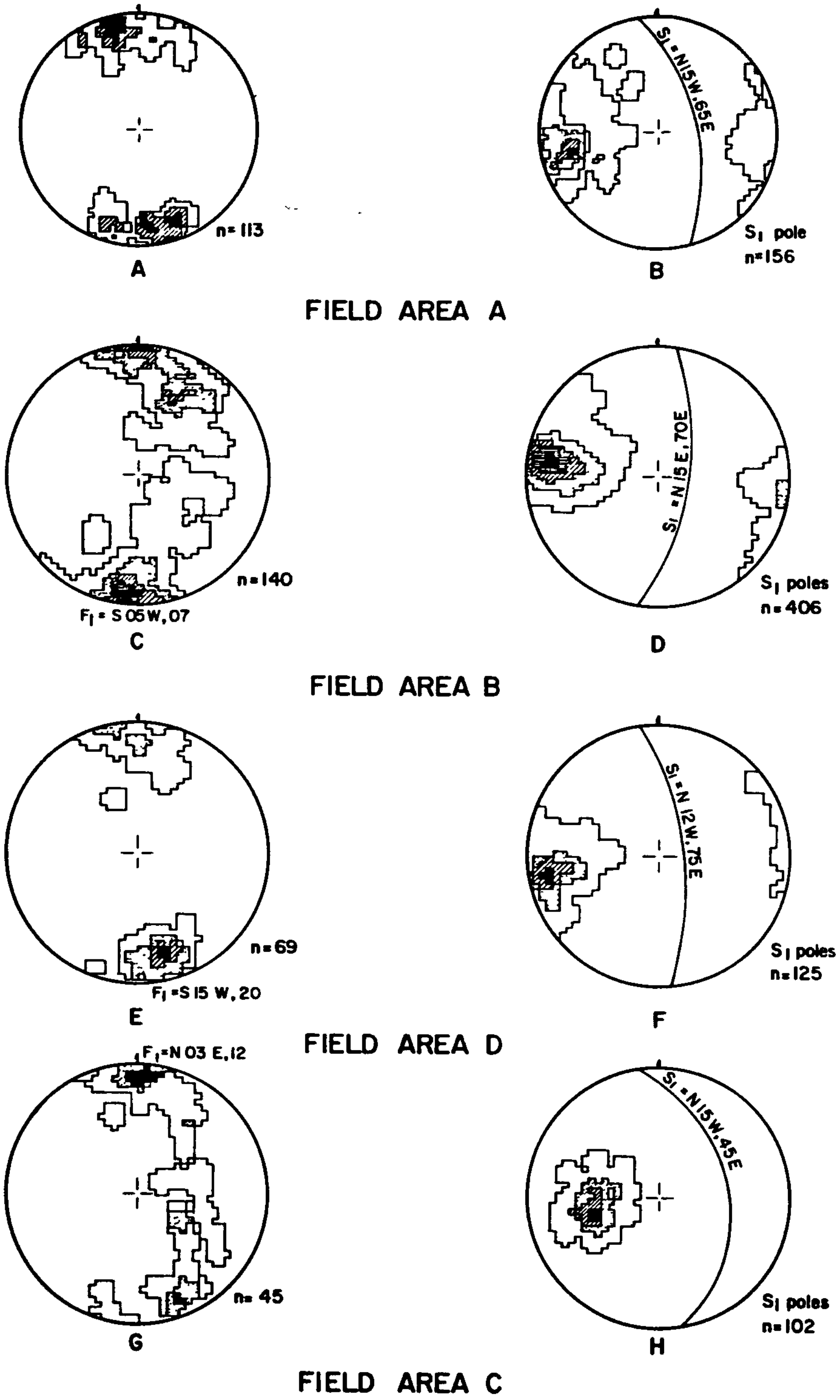


Figure 5. Lower hemisphere equal area net projections of F1 fold axes and poles to S1 cleavage. Plane of projection is horizontal; arrow points north. The orientation of F1 axes [A,C,E,G] and S1 cleavage [B,D,F,H] corresponding to each point maximum or average point maximum is shown beside each diagram. Locations of field areas are shown in Figure 1. (A) 113 F1 fold axes. Contour intervals are 0.9, 2.7, and 5.3 percent per one percent area. (B) 156 poles to S1 cleavage. Contour intervals are 0.6, 3.8, 7.7, 11.5 and 15.4 percent per one percent area. (C) 406 F1 fold axes. Contour intervals are 0.2, 1.2, 2.5, 3.7 and 4.9 percent per one percent area. (D) 140 poles to S1 cleavage. Contour intervals are 0.7, 2.1, 4.3, 6.4, 8.6 percent per one percent area. (E) 69 F1 fold axes. Contour intervals are 1.5, 7.2, 17.4 and 26.0 percent per one percent area. (F) 125 poles to S1 cleavage. Contour intervals are 0.8, 9.6, 17.6 and 26.4 percent per one percent area. (G) 45 F1 fold axes. Contour intervals are 2.2, 6.7 and 11.1 percent per one percent area. (H) 102 poles to S1 cleavage. Contour intervals are 1.0, 8.8, 14.7 and 21.6 percent per one percent area.

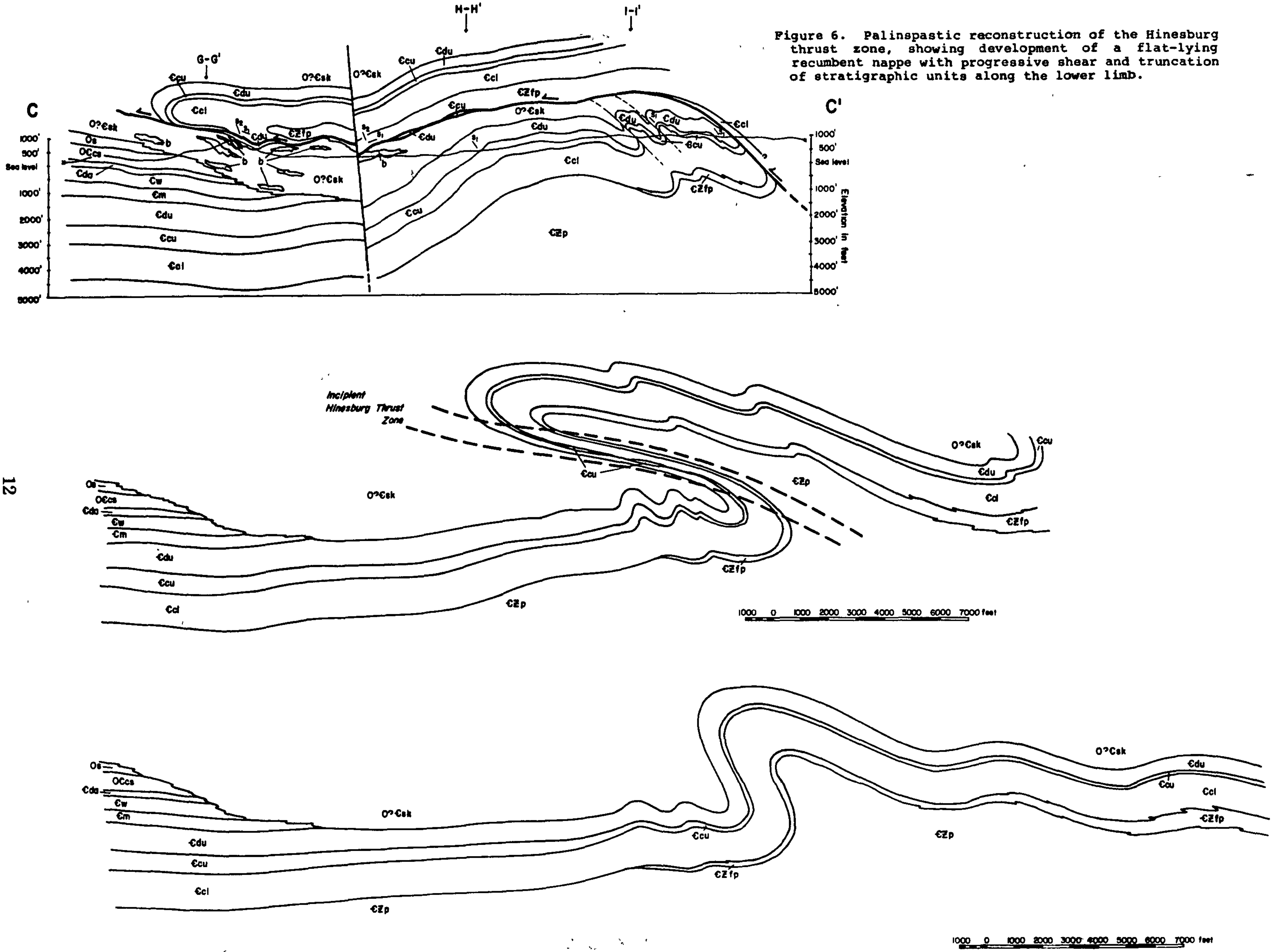


Figure 6. Palinspastic reconstruction of the Hinesburg thrust zone, showing development of a flat-lying recumbent nappe with progressive shear and truncation of stratigraphic units along the lower limb.

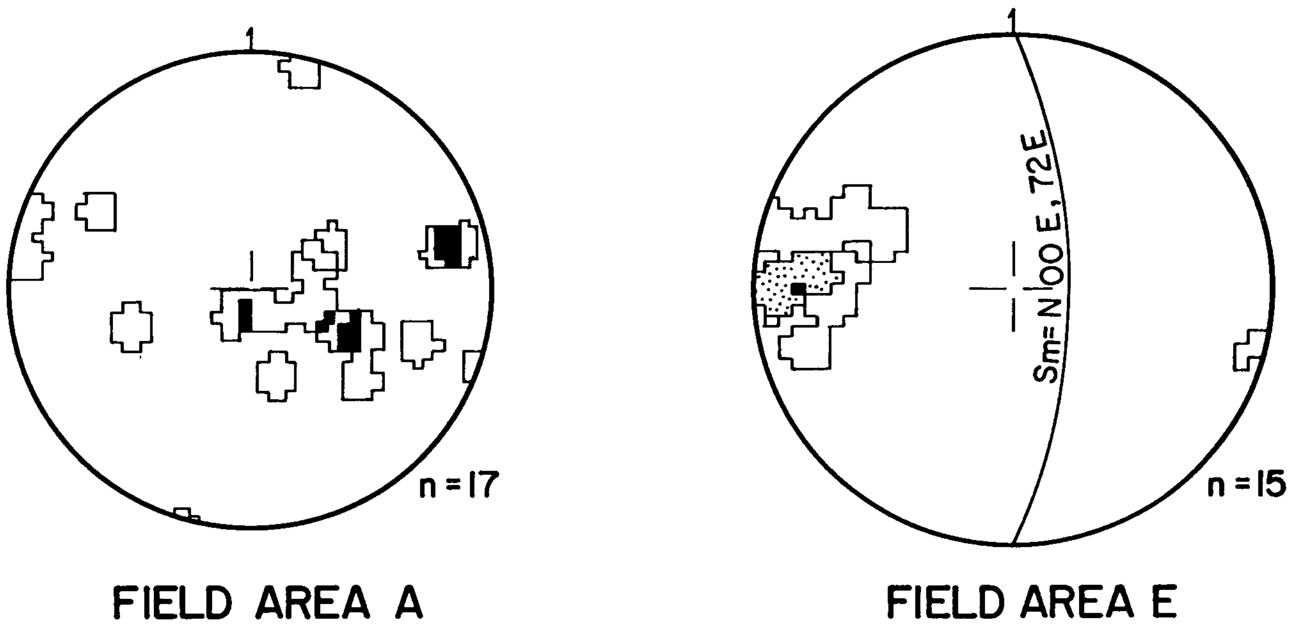


Figure 7. Lower hemisphere equal area net projections of poles to Sm cleavage. Plane of projection is horizontal; arrow points north. The orientation of Sm cleavage corresponding to the point maximum in (A) is shown beside the diagram. Locations of field areas are shown in Figure 1. (A) 17 poles to Sm cleavage. Contour intervals are 5.9 and 11.8 percent per one percent area. (B) 15 poles to Sm cleavage. Contour intervals are 6.6, 20.0 and 40.0 percent per one percent area.

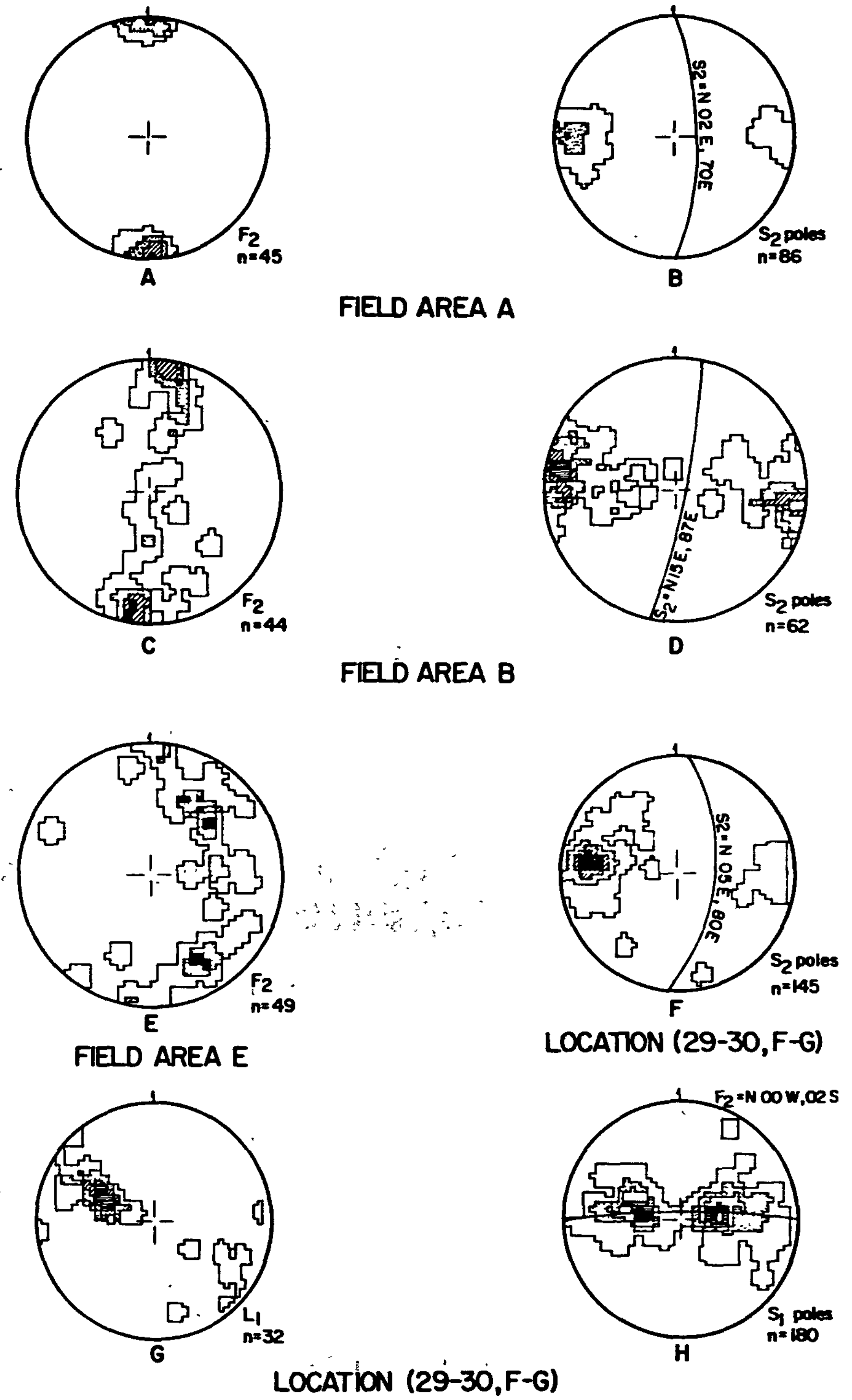
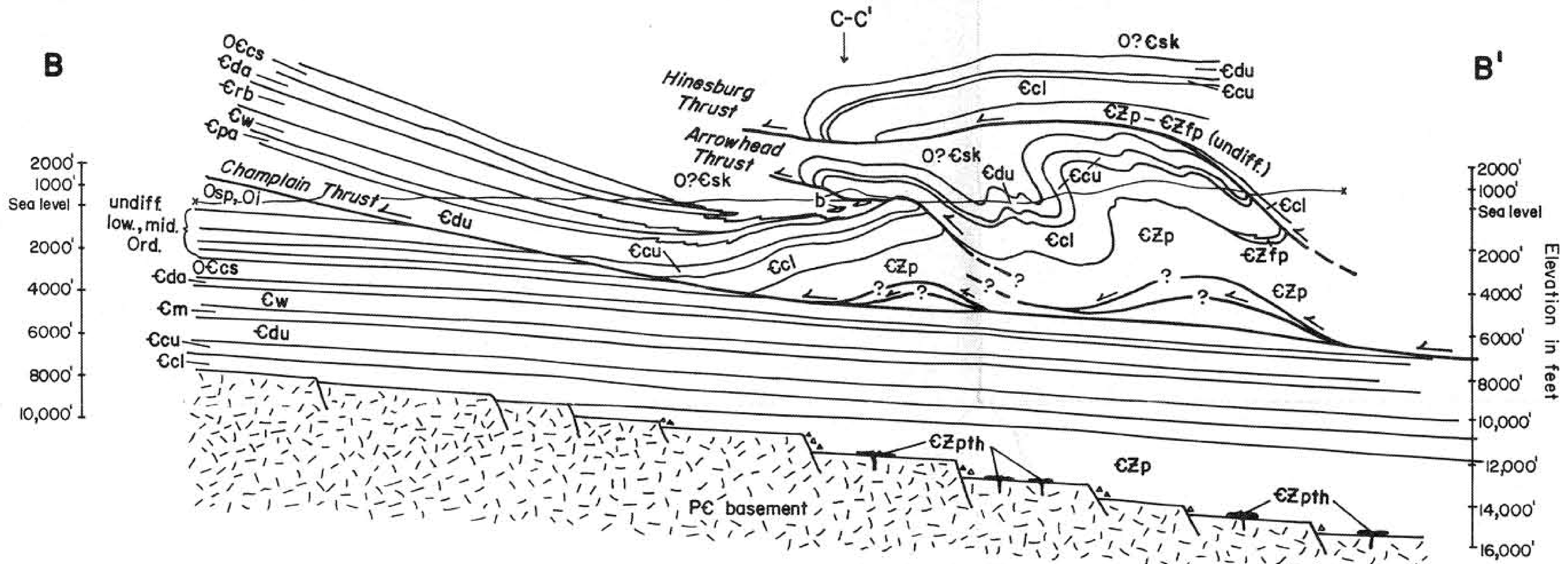


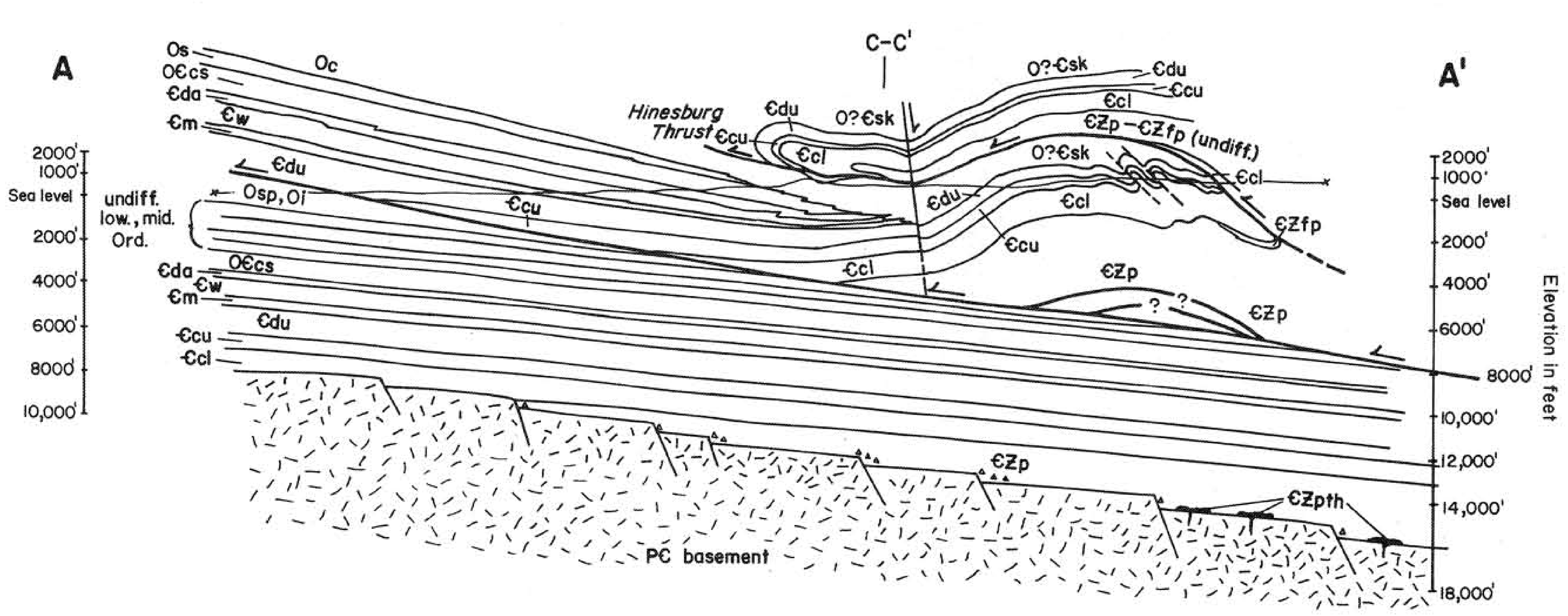
Figure 8. Lower hemisphere equal area net projections of F2 fold axes, poles to S2 cleavage, and rotated D1 elements. Plane of projection is horizontal; arrow points north. The orientation of F2 axes [A,C,E] and S2 cleavage [B,D,F] corresponding to each point maximum or average point maximum is shown beside each diagram. Locations of field areas A,B, and E are shown in Figure 1; remaining locations are shown on Plate 2-South. (A) 45 F1 fold axes. Contour intervals are 2.2, 13.3, 26.6 and 40.0 percent per one percent area. (B) 86 poles to S2 cleavage. Contour intervals are 1.1, 7.0, and 14.0 percent per one percent area. (C) 44 F2 fold axes. Contour intervals are 2.3, 11.4, 22.7 and 34.1 percent per one percent area. (D) 62 poles to S2 cleavage. Contour intervals are 1.6, 6.5, 11.3, 16.1 and 21.0 percent per one percent area. (E) 82 F2 fold axes. Contour intervals are 2.0, 6.1, and 10.2 percent per one percent area. (F) 145 poles to S2 cleavage. Contour intervals are 0.7, 6.9, 13.1, 19.3 and 25.5 percent per one percent area. (G) 32 L1 lithic lineations. Contour intervals are 3.1, 9.3, 15.5, 21.7 and 27.9 percent per one percent area. The orientation of the great circle defined by folded lineations is N 65 W, 85 S. (H) 180 poles to S1 cleavage. Contour intervals are 0.6, 3.3, 6.0 8.8, and 11.5 percent per one percent area.

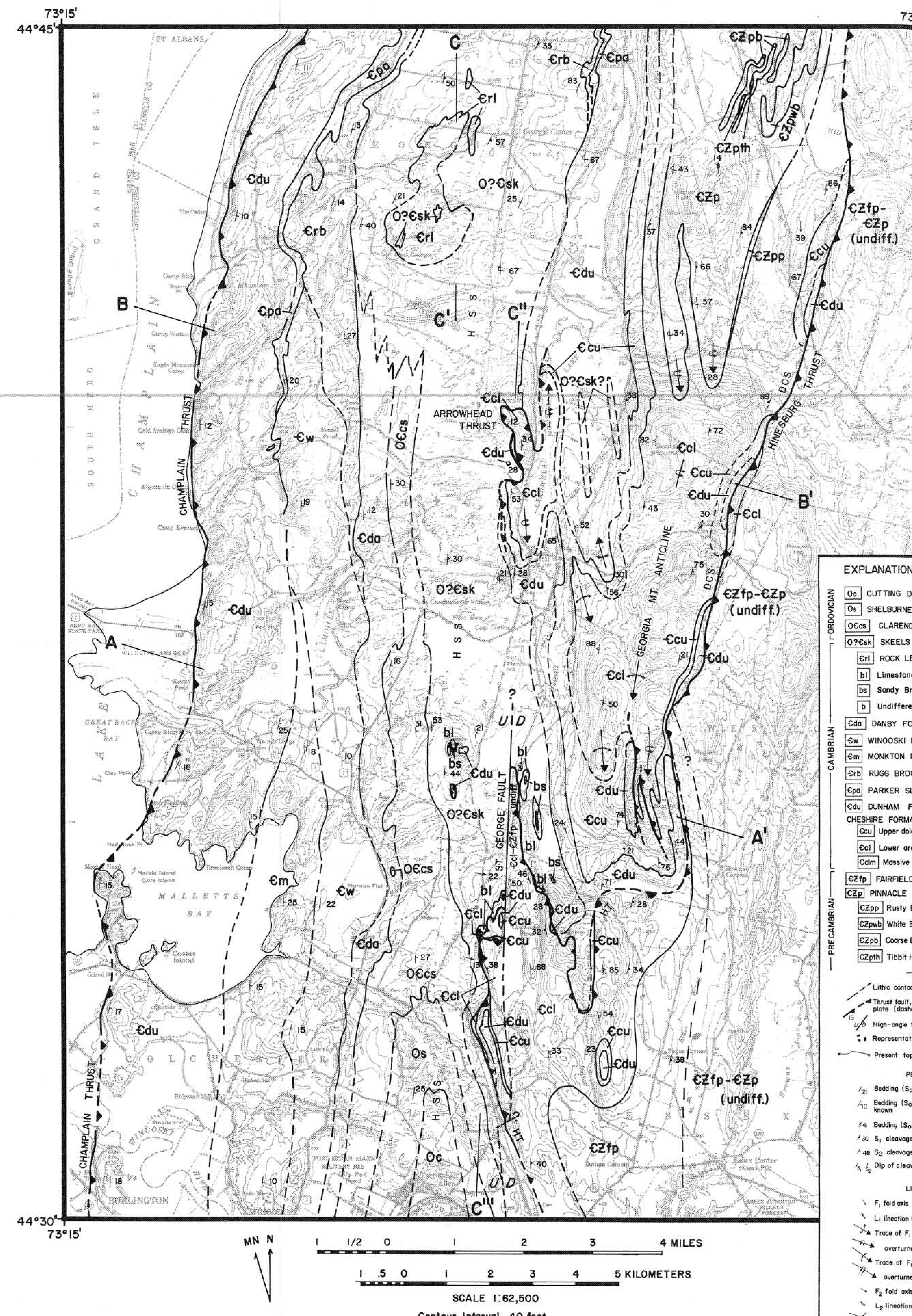
Bedrock Geology of the Milton Quadrangle Northwestern Vermont

PLATE 1

REBECCA J. DORSEY, PAUL C. AGNEW, CRAIG M. CARTER
ERIC J. ROSENCRANTZ, ROLFE S. STANLEY







EXPLANATION

ORDOVICIAN
- Oc — CUTTING DOLOMITE
- Os — SHELBURNE MARBLE
- O€cs — CLARENDON SPRINGS FM.
- O?€sk — SKEELS CORNERS FM.
  - €rl — ROCK LEDGE MEMBER
  - bl — Limestone Conglomerate
  - bs — Sandy Breccia
  - b — Undifferentiated bl & bs

CAMBRIAN
- €da — DANBY FORMATION
- €w — WINOOSKI FORMATION
- €m — MONKTON FORMATION
- €rb — RUGG BROOK FORMATION
- €pa — PARKER SLATE
- €du — DUNHAM FORMATION
- CHESHIRE FORMATION
  - €cu — Upper dolomitic member
  - €cl — Lower argillaceous mbr.
  - €clm — Massive unit

PRECAMBRIAN
- €Zfp — FAIRFIELD POND FM.
- €Zp — PINNACLE FORMATION
  - €Zpp — Rusty Black Phyllite
  - €Zpwb — White Brook Dolomite
  - €Zpb — Coarse Boulder Conglomerate
  - €Zpth — Tibbit Hill Volcanics

Lithic contact (dashed where infered)
Thrust fault, showing dip, teeth on upper plate (dashed where infered)
High-angle fault
Representative outcrop
Present topography

PLANAR FEATURES

Bedding (S_0)
Bedding (S_0), where tops of beds are known
Bedding (S_0), overturned
S_1 cleavage
S_2 cleavage
Dip of cleavage in cross section

LINEAR FEATURES

F_1 fold axis
L_1 lineation (intersection of S_0 and S_1)
Trace of F_1 anticline
overturned
Trace of F_1 syncline
overturned
F_2 fold axis
L_2 lineation (intersection of S_1 and S_2)
Trace of F_2 syncline

Mineral lineations
Slickensides

HSS - Hinesburg - St. Albans Synclinorium
DCS - Dead Creek Synclinorium
HT - Hinesburg Thrust

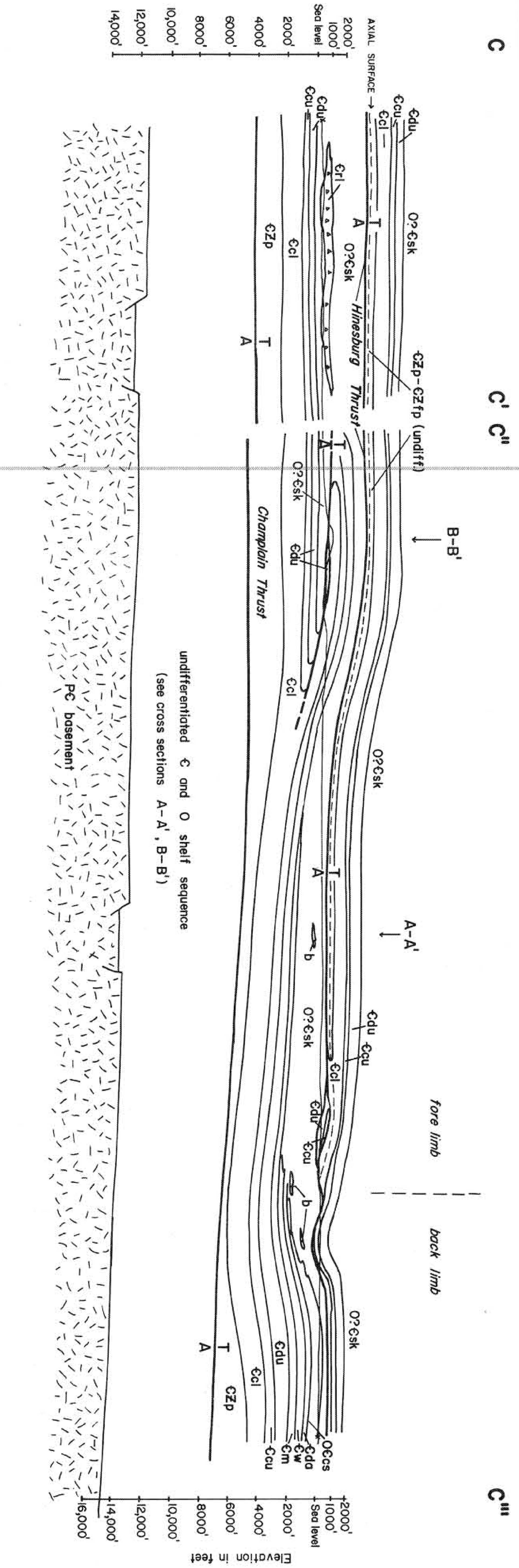


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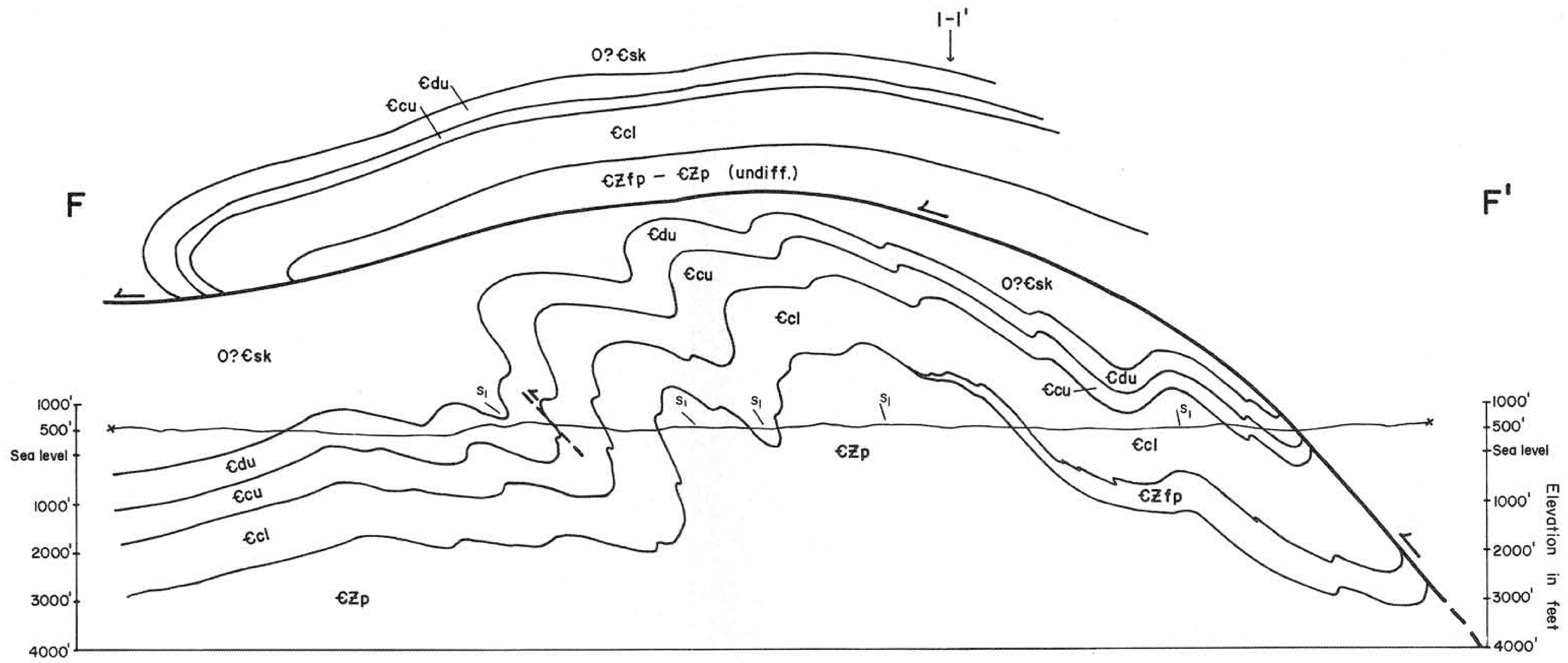
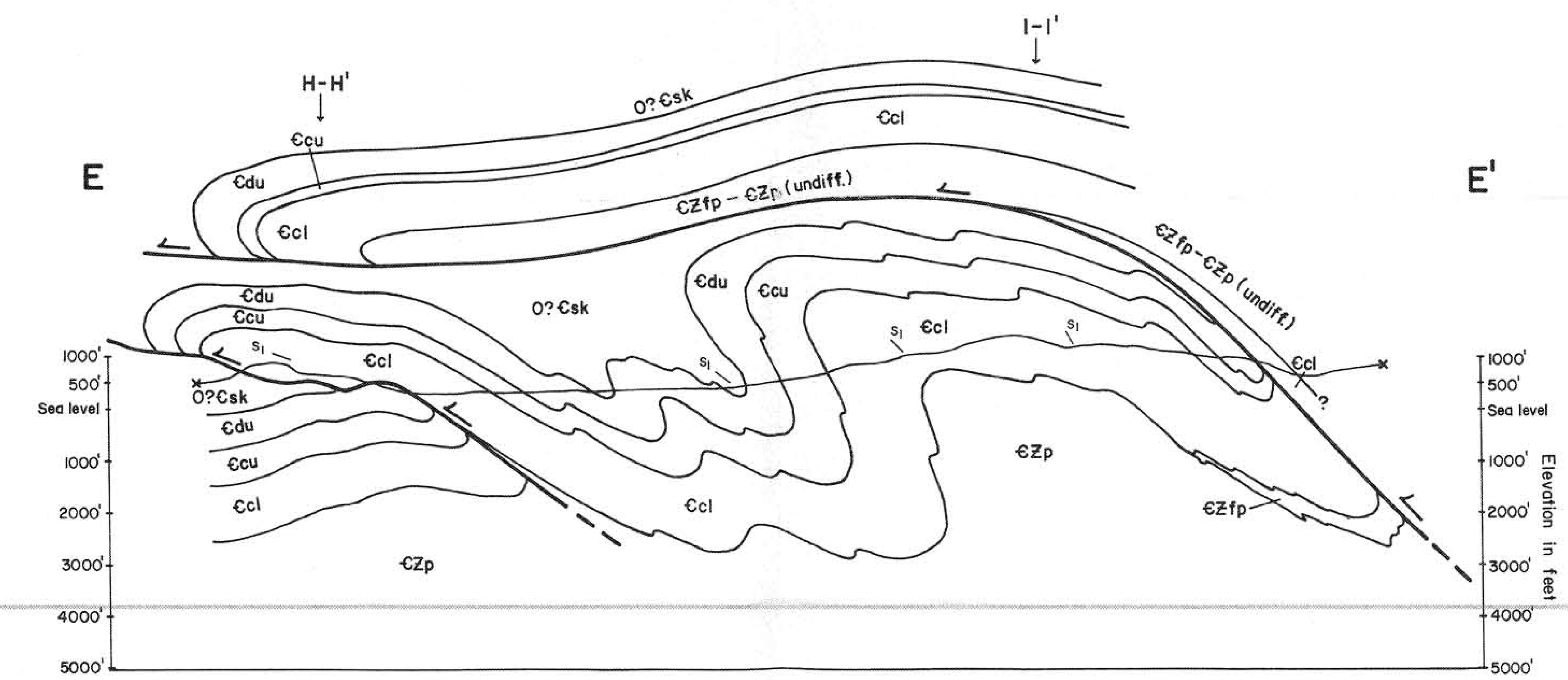
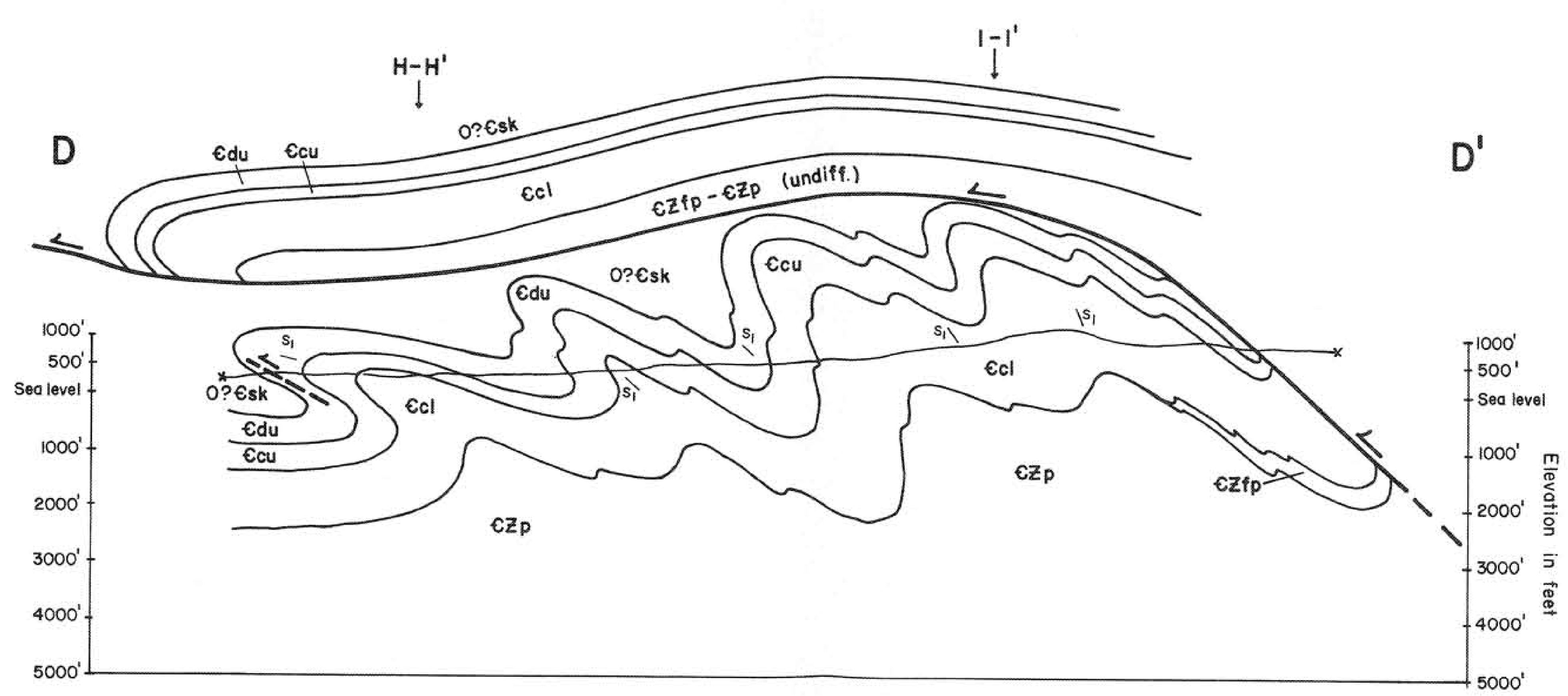
PLATE 2 - NORTH







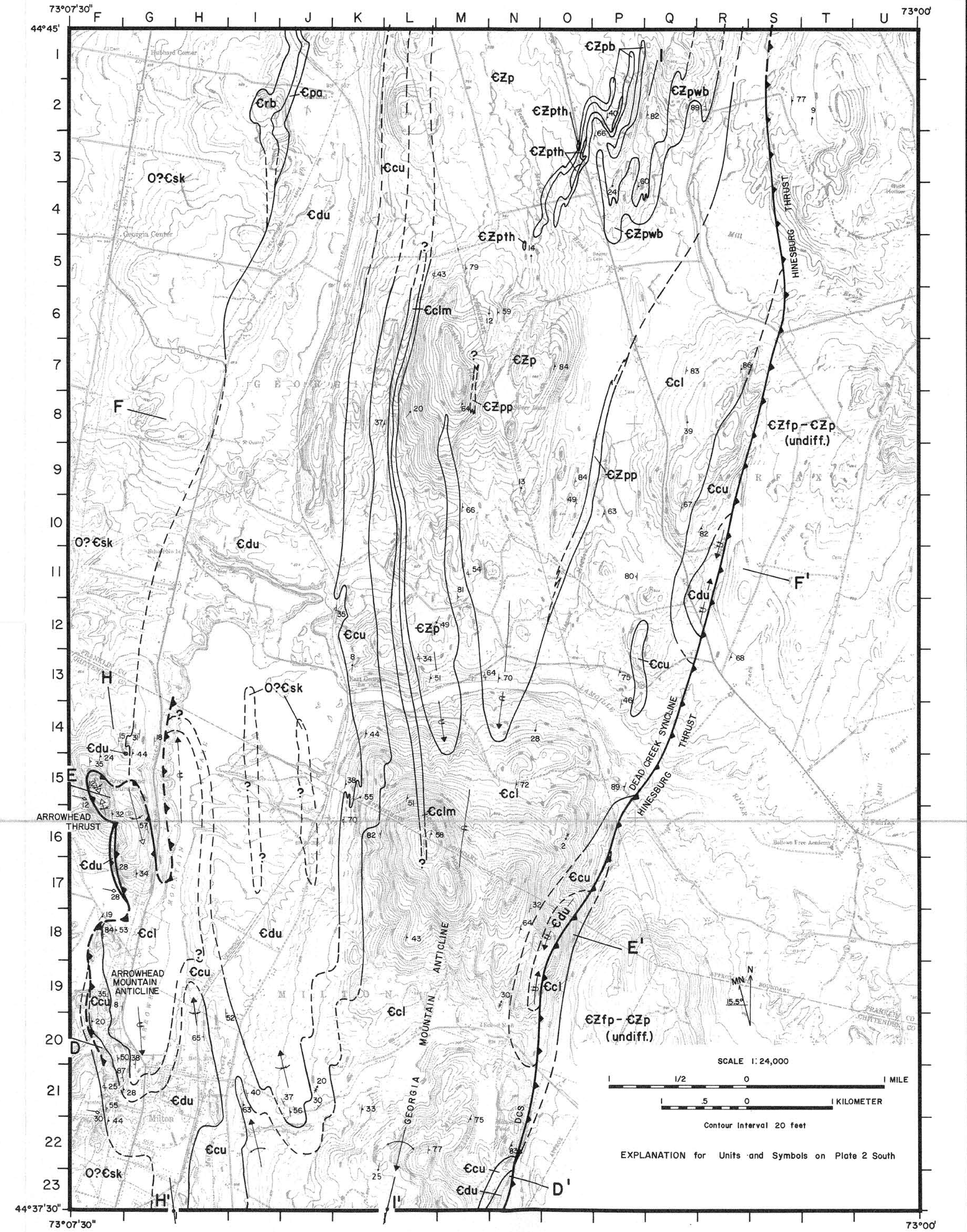


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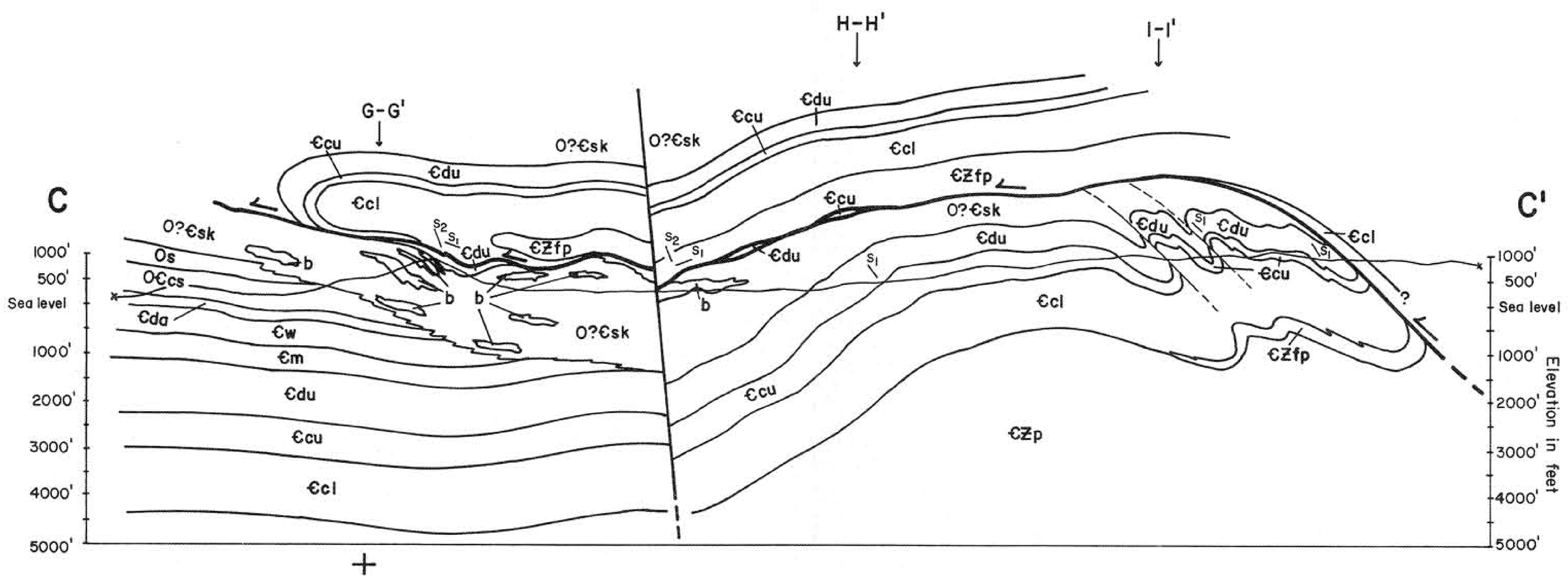
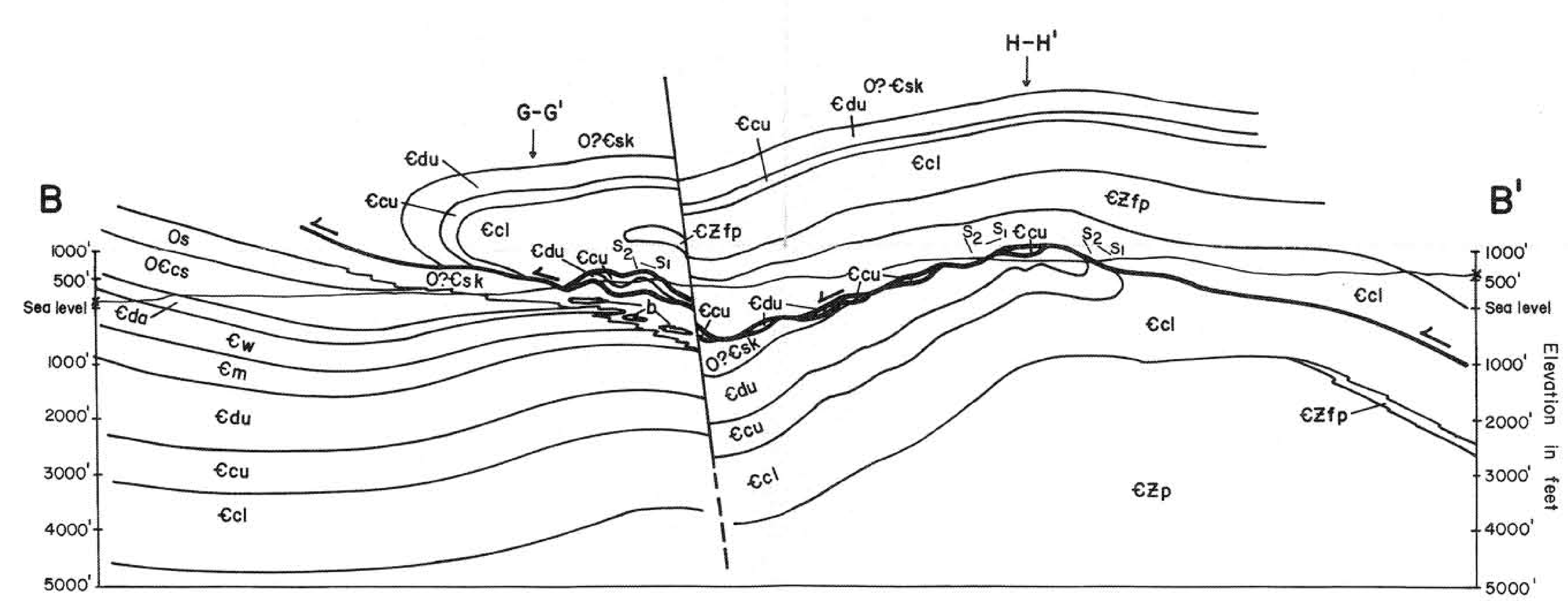
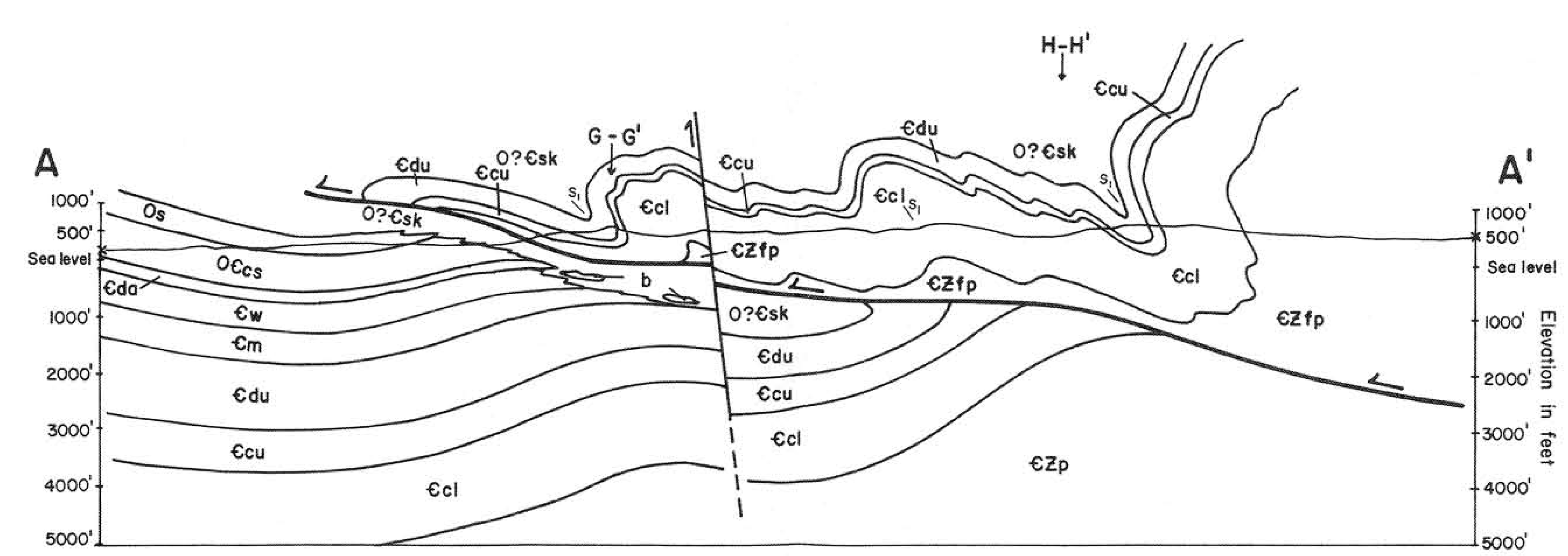
PLATE 2 - SOUTH







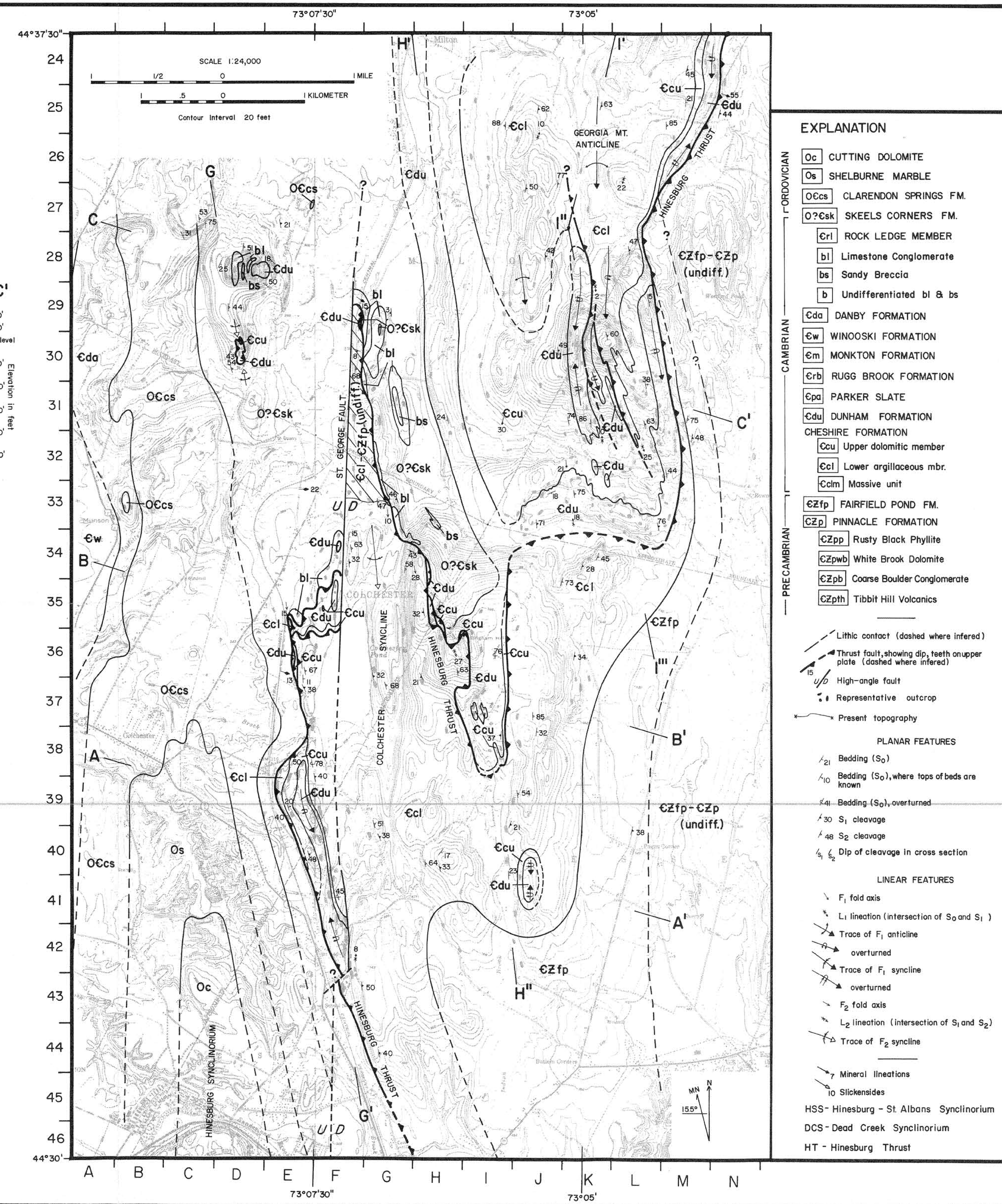


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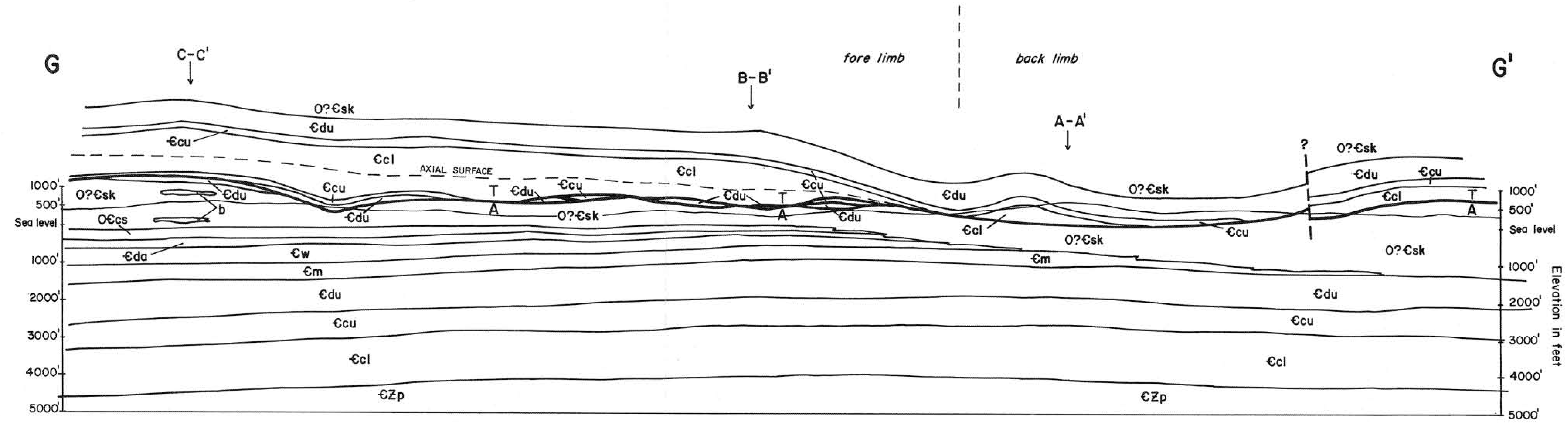
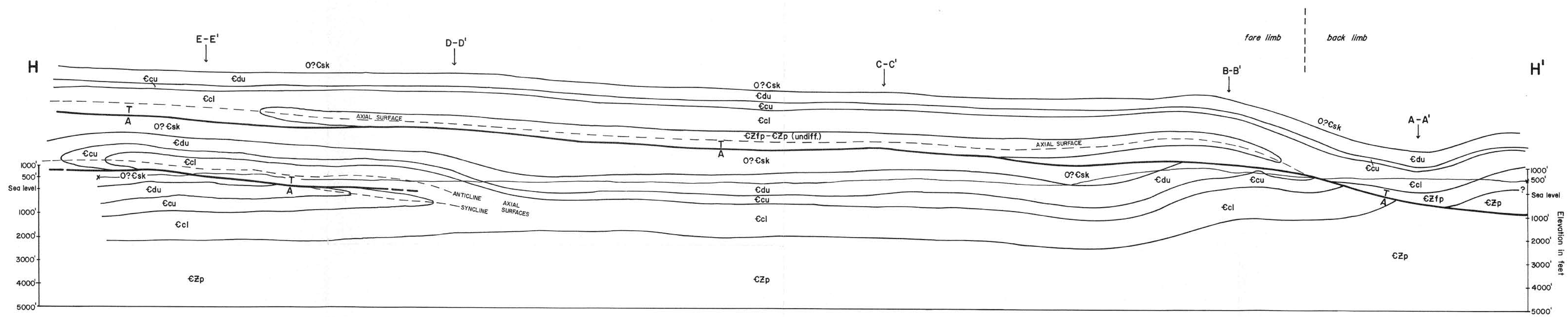
PLATE 3

AUTHOR'S NOTE: THE REGISTRY BETWEEN N-S AND E-W CROSS-SECTIONS IS NOT COMPLETELY ACCURATE. THE CRITICAL RELATIONSHIPS ARE CONTROLLED BEST NEAR THE TOPOGRAPHIC SURFACE AND BECOME MORE SCHEMATIC ABOVE AND BELOW. CONCEPTUALLY, HOWEVER, ALL SECTIONS ARE INTERNALLY CONSISTENT.





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