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Multiple Folding in South-Central Maine

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ABSTRACT

Field mapping in the Buckfield 7.5' quadrangle has revealed a complex deformational history. Silurian calcareous and pelitic metasediments of the Sangerville Formation (Pankiwskyj, 1979; Moench et al., 1982) display evidence of at least three distinct folding events. The oldest fold generation consists of reclined to recumbent folds with northwest to nearly east-west trends (F_1), believed to be parasitic to regional scale recumbent folds. These are postdated by upright, moderately open to isoclinal folds with a northeast trend (F_2). The youngest folds observed are small-scale, upright, asymmetric folds with a consistent northwest trend (F_3). The reclined to recumbent folds deform an early layer-parallel foliation (S_A).

Bedding trends in the Buckfield area are influenced by both F_1 and F_2 folds. Strata in the eastern half of the study area reflect F_2 folding with steep dips and northeast trends, whereas those in the southwestern portion display shallower dips and northwest trends, indicative of F_1 folding. A decrease in amplitude of the younger, upright folds from north to south may have produced this structural juxtaposition in south-central Maine. Field and map evidence suggest that the flat-lying F_1 folds predate Devonian and Carboniferous plutons and provide a favorable structural horizon for their later intrusion.

Regional correlations between unfossiliferous rocks of the Buckfield area and fossil-bearing units of the Waterville and central Maine regions are introduced to facilitate the proposed structural interpretation.

INTRODUCTION AND GEOLOGIC SETTING

A regional transition from largely vertical, northeast-trending structures to flat-lying, northwest-trending structures occupies a narrow region in Maine, roughly coincident with the sillimanite + K-feldspar metamorphic isograd (Fig. 1). This paper presents the results of a study of a small portion of this transition zone, in particular the relationships between small-scale structures in the Buckfield 7.5' quadrangle and adjacent areas.

The study area lies within the southeast limb of the Kearsarge-central Maine synclinorium (Lyons et al., 1982), near the northern terminus of the expansive New England metamorphic high (Guidotti, pers. commun., 1985). Stratified rocks of the study area are of Early to Middle Silurian age, and were derived from crystalline Taconian highlands to the west (Ludman, 1977). Sedimentologic features found in rocks correlative with the Sangerville Formation of the study area (formerly the Buckfield Group of Warner, 1967) suggest turbiditic deposition in an intermediate energy environment. Coarser-grained rocks to the west (Rangeley Formation) and thinner bedded, finer-grained rocks to the east (Sangerville and Waterville Formations) are

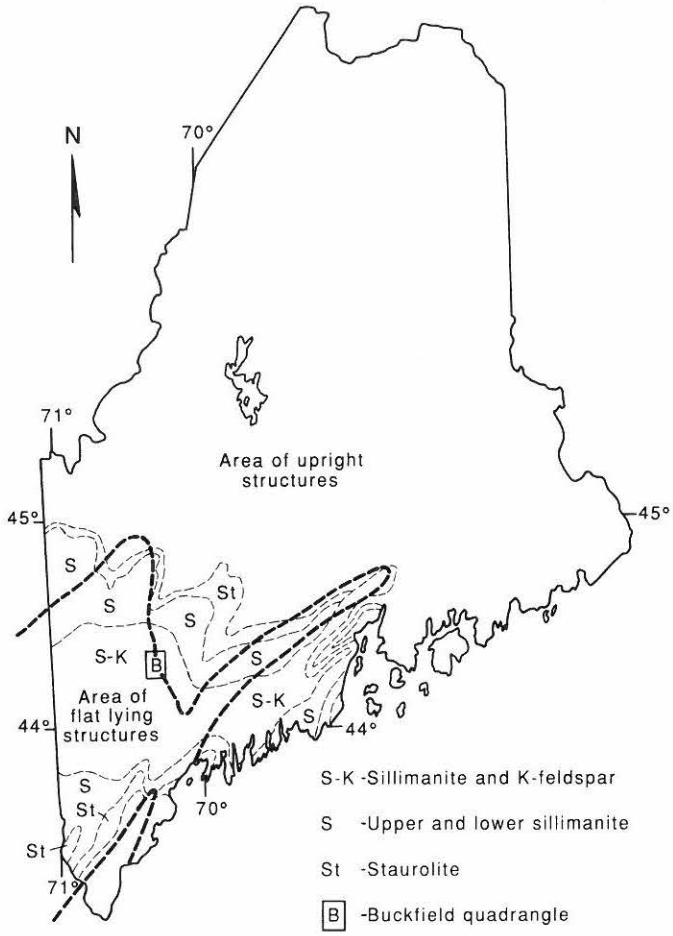


Figure 1. Location of regional transition from flat-lying to vertical structures (bold dashed line) and metamorphic isograds based on pelitic index minerals in southern Maine (modified from Osberg et al., 1985).

thought to represent proximal and distal depositional environments, respectively (Osberg et al., 1968; Ludman, 1977).

Recent isotopic and geophysical work has identified plutons of Ordovician, Devonian, Carboniferous, and Jurassic ages within the Kearsarge-central Maine synclinorium (Moench, 1984; Moench and Zartman, 1976; Lux and Guidotti, 1985; Hayward and Gaudette, 1984; Aleinikoff et al., 1985; Creasy et al., 1986). Many of these plutons have been modeled as 1 to 6 km thick sheets dipping gently to the northeast (Kane and Bromery, 1968; Nielson et al., 1976; Carnese et al., 1982; Hodge et al., 1982; Stewart et al., 1986). These findings have wide-ranging ramifications bearing upon regional tectonic mechanisms (De Yoreo et al., 1985; Moench and Zartman, 1976) and are relevant to the chronology of metamorphic and deformational events in south-central Maine.

Figure 2 illustrates a geologic column for rocks of the Buckfield area and proposed regional correlations across the Kearsarge-central Maine synclinorium in Maine. Observations of graded beds located adjacent to member contacts indicate that the order of younging within the Sangerville Formation differs from that reported by previous workers (Warner, 1967; Moench et al., 1982). In particular, graded sequences on the western slopes of Bear Mountain and Ricker Hill (in the northeast quadrant of the Buckfield quadrangle) suggest an inverted lithologic package. Moreover, inasmuch as Waterville/Sangerville Formation stratigraphic relationships are well demonstrated in the Waterville area (Osberg, 1979, 1980), the mapped structure of the correlative Buckfield area stratigraphy similarly indicates a downward-facing section.

STRUCTURE

Early Schistosity (S_A)

A layer-parallel foliation (S_A), ubiquitous in rocks of the study area, is defined by the alignment of micaceous minerals and/or elongation of fibrolite mats in pelites or parallelism of amphiboles in calc-silicate lithologies. This foliation is assumed to have been parallel to the axial surfaces of early isoclinal folds. However, folds of this generation have not been consistently observed, and their scale and original orientation are unknown; hence, no deformational event (e.g. F_1, F_2, etc.) has been associated with the S_A foliation as a result of this investigation. The existence of this fold set is predicated upon the observation of the S_A foliation wrapped around F_2 and F_3 fold hinges (Fig. 3b) in addition to the observation of folds which predate the F_1 and F_2 structures. An outcrop in Trap Corner (along Route 26 west of the study area) contains folds of three generations, including F_1 and F_2 events. The third set is demonstrably older than these, and may be coeval with the more widely observed S_A foliation.

Minor Folds and Cleavage

Nearly all folds described in the study area can be classified as small-scale, i.e. discernible in an outcrop; however, they are believed to mimic larger structural features detectable on map scale. Numerous outcrops, such as those depicted in Figure 3, display structures of two generations; crosscutting cleavages are particularly well preserved in the schistose lithologies.

Recumbent Folds (F_1)

Observations of primary stratigraphic relationships reveal that the oldest unit in the study area (the Anasagunticook Member) is located in the core of the large synform in Figure 4 (the Irish Hill syncline of Warner, 1967), which, therefore, faces downward. These way-up indicators, depicted in Figure 4, are comprised of graded bedding sequences located close to member contacts as described previously. This interpretation necessitates the existence of a recumbent (or strongly overturned) fold of regional scale. Several workers have postulated the presence of extensive fold-nappes in Maine to explain similar observa-

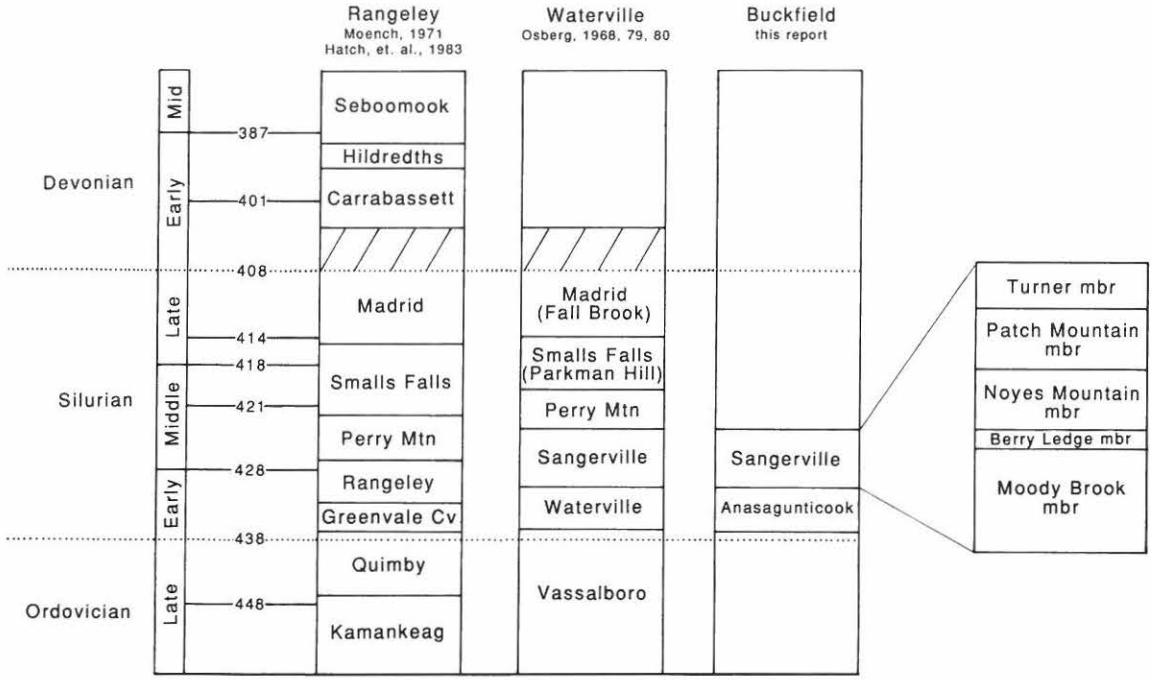


Figure 2. Comparative stratigraphic columns for the Buckfield, Rangeley, and Waterville areas (time scale after Palmer, 1983).

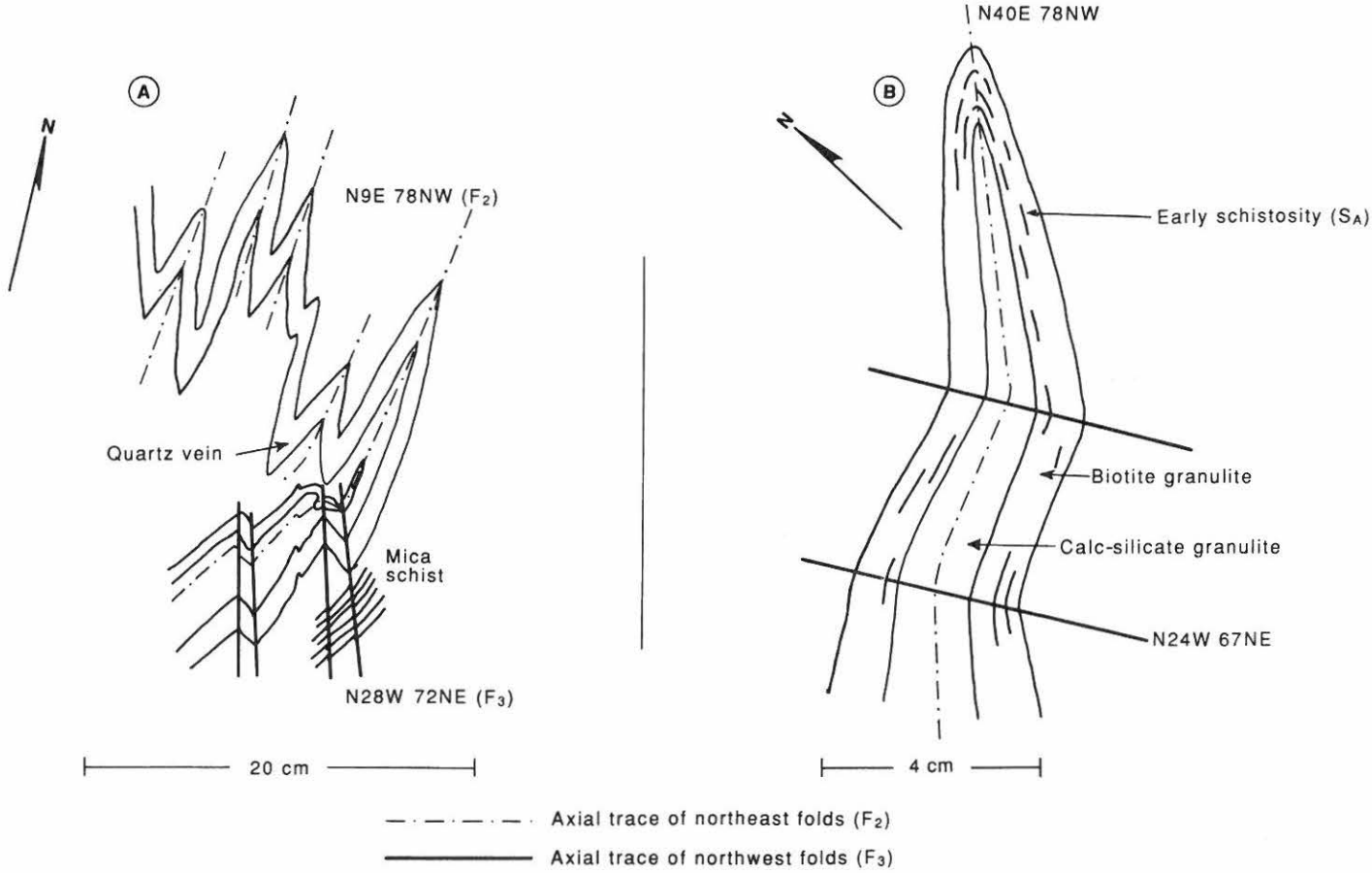


Figure 3. Sketches depicting crosscutting structures in the Buckfield area. (a) Map view of Turner Member on southeast flank of Bear Mountain. (b) Down-plunge view of Turner Member on eastern side of Ricker Hill.

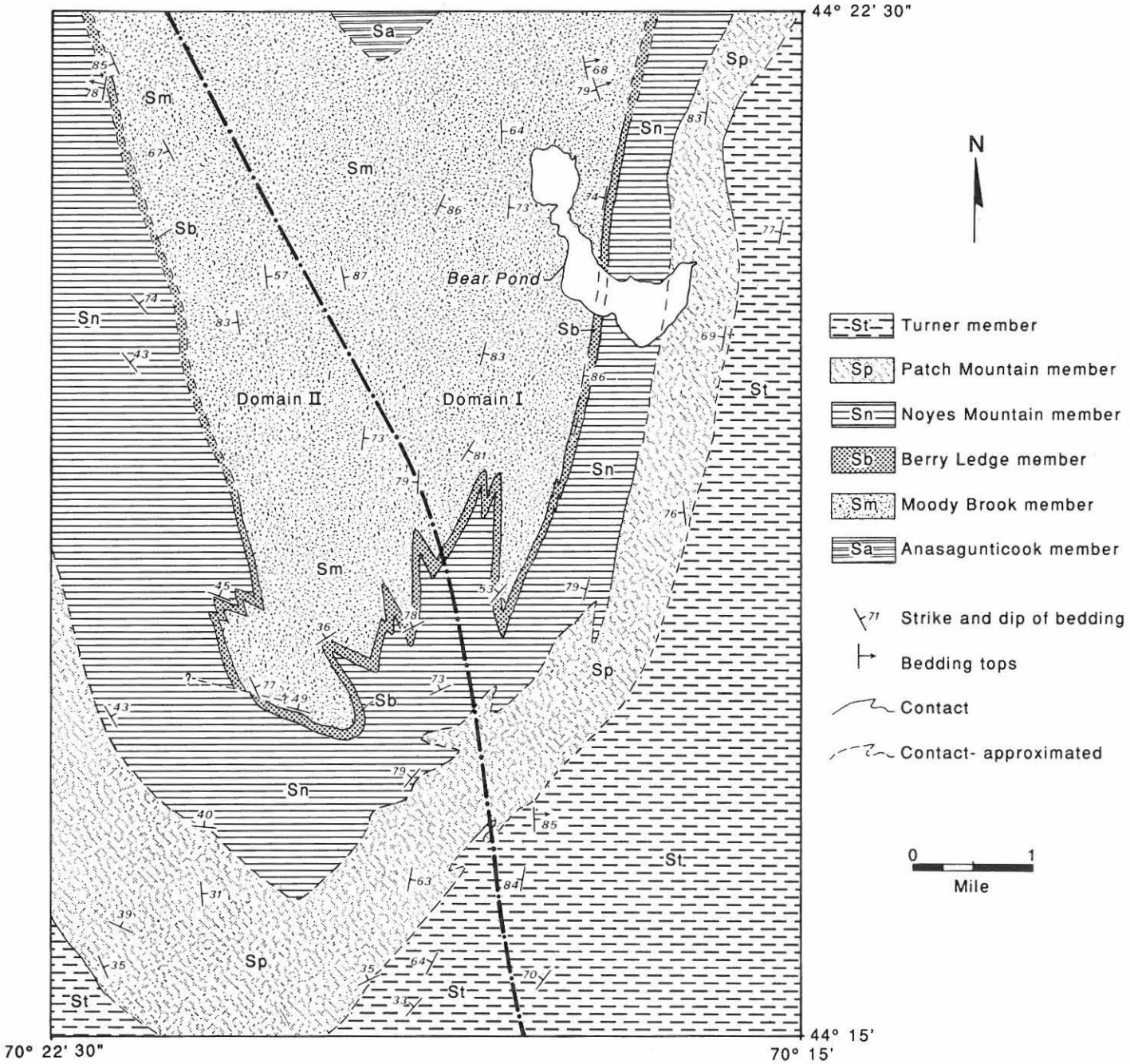


Figure 4. Geologic map of the Buckfield quadrangle. Domain I - area dominated by upright, northeast-trending folds (F_2). Domain II - area dominated by flat-lying, northwest-trending folds (F_1)

tions of inverted stratigraphic-sections (e.g. Osberg, 1979, 1980; Gates et al., 1984; Eusden et al., 1984, 1986; Wiley, 1986). In addition, Guidotti (1965), Creasy (1979), and Hussey (1983) have described gently inclined folds in regions devoid of primary stratigraphic indicators.

Small-scale recumbent folds mapped in the Buckfield quadrangle (F_1) are believed to be parasitic to larger folds of regional scale as tentatively suggested by Hussey (1983). Folds of this stage, along with co-genetic foliation and weakly developed cleavage (S_1), have been observed throughout the southern and western sectors of the study area.

Upright Northeast-Trending Folds (F_2)

The second fold set observed in the Buckfield area consists of moderately open to isoclinal, northeast-trending, upright,

symmetric folds (F_2). Generally, isoclinal structures persist in calc-silicate lithologies while granulites and schists display more open forms. These northeast-trending folds and associated axial planar cleavage (S_2) postdate F_1 recumbent folds. Evidence of this relationship was best found in the southwestern portion of the quadrangle where small-scale F_1 and F_2 folds are present (Fig. 5). This chronology is also suggested in Figure 6a where poles to flat-lying axial surfaces and foliation (S_1) define a tight girdle around northeast-trending isoclinal folds. The limited reorientation of F_1 fold limbs (denoted by dual maxima in Fig. 6a) is attributed to the isoclinal character of F_2 folds.

Regionally, F_2 folds show a wide variation in amplitude and wavelength, from millimeter-scale crenulations to quadrangle-scale outcrop flexures, yet folds of this generation display consistent orientations (Fig. 6b). These folds control the gross bedrock geometry of central Maine, yet their significance is negligible in areas south of the Buckfield quadrangle where flat-lying structures dominate. A decrease in the amplitude of the upright folds from north to south is believed to control the transition to flat-lying folds in south-central Maine. This structural juxtaposition is apparent in the anomalous outcrop geometry exhibited in the Buckfield quadrangle (Fig. 4) as well as other areas in southern Maine proximal to large plutons, suggesting a proclivity toward intrusion within the flat-lying strata and resistance to subsequent deformation (i.e. a "dampening out" of F_2 folds).

Asymmetric, Northwest-Trending Folds and Cleavage (F_3)

Upright, small-scale, northwest-trending, asymmetric folds (F_3) and associated crenulation cleavage (S_3) represent the youngest deformational episode in the Buckfield region. These structures display consistent style, small size, and orientation. The latter is illustrated by Figure 6c where poles to over 90% of F_3 axial surfaces and S_3 cleavage cluster within 3% of the equal area net. Closely-spaced crenulation cleavage axial planar to F_3 folds is well developed in schistose beds and clearly crosscuts older structures. It is conceivable that the F_3 folds and cleavage are a localized response to the intrusion of the Sebago batholith. Recent studies have substantiated the existence of similar areas of small-scale deformation adjacent to intrusive bodies (Thomson, 1985; Newberg, 1986). Nonetheless, west-to-northwest-trending minor folds and cleavage have been recognized throughout New England, many of which cannot be related to plutonic intrusions (Osberg, pers. commun., 1985).

LARGE-SCALE STRUCTURES

Folds producing map-scale deformation can be attributed to F_1 and F_2 fold generations. Prominent northwest-trending folds, including those mapped by Guidotti (1965), Creasy (1979), and Hussey (1983) south and west of the study area, display strongly overturned to recumbent axial surfaces and are here interpreted to be arch bends (Billings, 1972) parasitic to extensive fold-nappes. Downward-facing folds and overturned lithic units such as those presented herein are also indicative of nappe-stage deformation. Regional northeast-trending, upright, isoclinal folds have been mapped north of the study area (Osberg, 1968; Ludman, 1977; Pankiwskyj, 1978, 1979) and dominate the bedrock geometry of central and northern Maine.

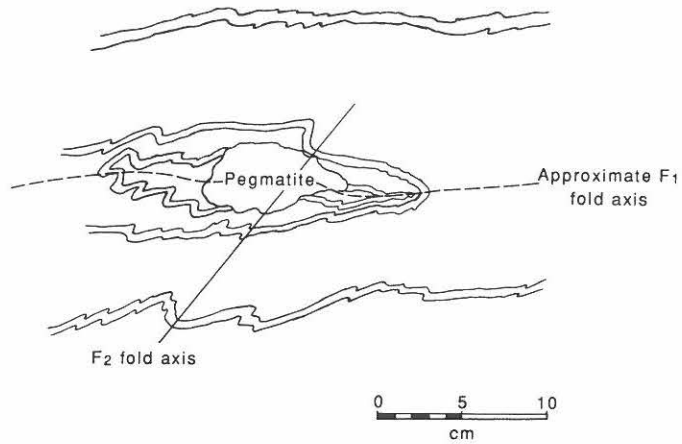
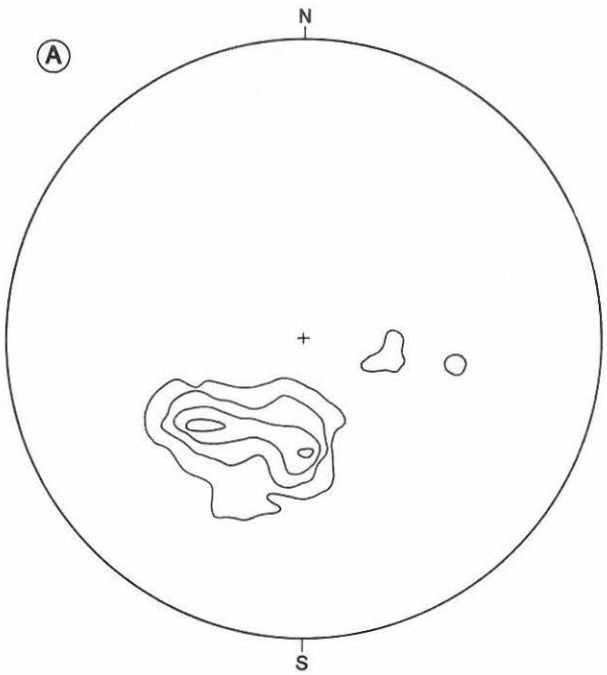


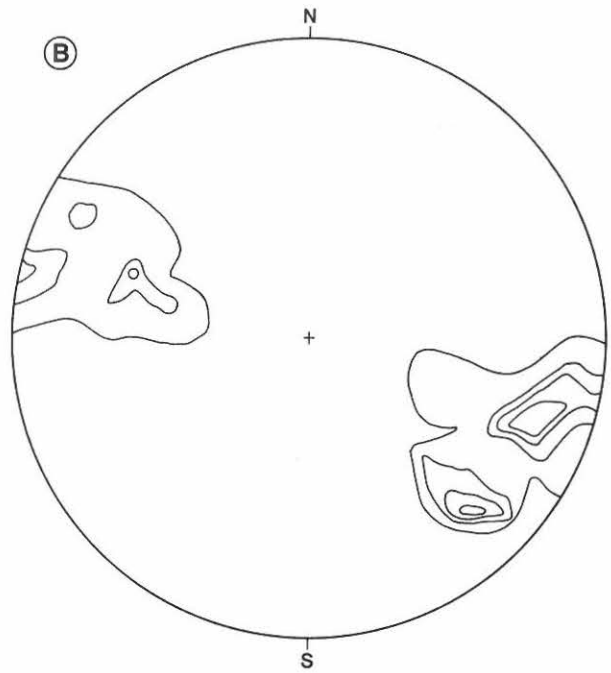
Figure 5. Down-plunge view of flat-lying fold (F_1) cut by smaller-scale, upright, northeast-trending fold and associated cleavage (F_2). Patch Mountain Member on southern flank of 704 foot hill near southwestern corner of Buckfield quadrangle.

Stratigraphic and structural data obtained in this study reveal that the large-scale structure mapped in the Buckfield quadrangle is a complex synform, consisting of recumbent to reclined northwest-trending folds on its western limb and upright, northeast-trending flexures on its eastern limb. Both fold types are present throughout the quadrangle, but their relative scales are such that the F_1 folds control outcrop geometries in the southwest and F_2 folds dictate map patterns in the northeast. Thus, the regional transition from flat-lying, northwest-trending to upright, northeast-trending structural domains can be located within the Buckfield 7.5' quadrangle (Fig. 4).

REGIONAL STRUCTURAL SYNTHESIS

Following the development of early, layer-parallel foliation (S_A), nappe-stage folding (F_1) affected the units of the Sangerville Formation and the underlying Anasagunticook Member of the Waterville Formation. Thereafter, gravity sliding or perhaps thrust faulting translated Devonian sediments of the Rumford allochthon over the autochthonous Silurian rocks (Fig. 7). Upright, northeast-trending, isoclinal folding (F_2) followed. This is apparent in the expression of the Winter Brook fault (Fig. 7), the eastern terminus of the allochthon, as well as in crosscutting folds observed in the study area. Finally, intrusion of the Sebago two mica-granite occurred, inundating the flat-lying structures and disrupting some areas of upright, northeast-trending structures. It is possible that this intrusion imparted a closely-spaced crenulate fabric (F_3, S_3) to the adjacent strata.





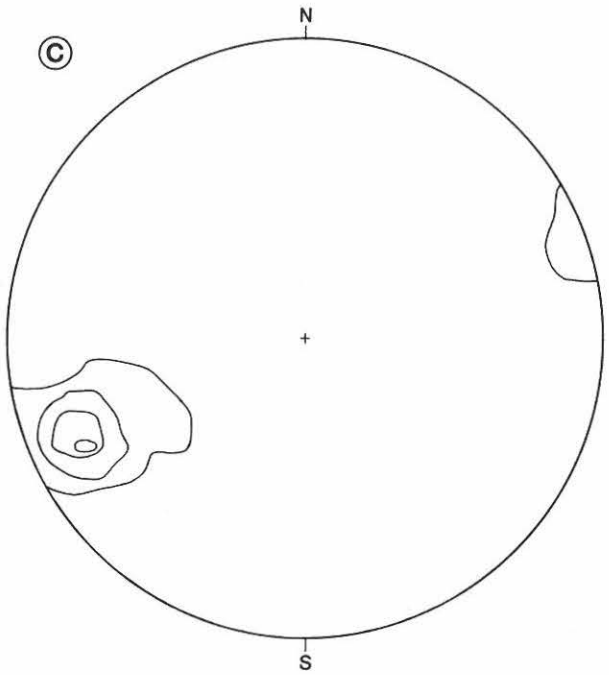


Figure 6. Equal area, lower hemisphere projections of poles to axial surfaces and cleavage for individual fold generations: (a) 61 S_1 poles, (b) 100 S_2 poles, (c) 138 S_3 poles.

Interpretive cross-sections A-A' and B-B' are presented in Figure 8 to illustrate the change in geometry of rock units as the transition zone juxtaposing upright and flat-lying structures is approached. These sections suggest an interaction of F_1 and F_2 folds which is compatible with regionally mapped facing directions and lithologic trends (Osberg et al., 1985; Osberg, pers. commun., 1986). It should be noted that the scale of F_3 deformation is too small to be suitably represented on these sections.

Numerous factors may contribute to the decrease toward southwestern Maine of the observed amplitude of F_2 folds. One interesting possibility involves the injection of igneous rocks into the flat-lying strata prior to upright F_2 folding. This may have locally diminished the effect of the F_2 folds. It is uncertain whether any plutons demonstrating such a relationship are presently exposed in Maine; however, the Cardigan, Bethlehem, and Winnipesaukee plutons of New Hampshire display appropriate age and structural relationships to warrant such a model.

CONCLUSION

Stratified rocks of the Buckfield region in south-central Maine have experienced at least three distinct deformational events as evidenced by folds, cleavages, and foliations observed to crosscut one another. Flat-lying, northwest-trending folds (F_1) and upright, northeast-trending folds (F_2) dominate the map pattern. An upright, asymmetric, northwest-trending fold generation (F_3) postdates these events, but does not appear to affect large-scale outcrop configurations. The unique map pattern in the study area has resulted from interference of F_1 and F_2 structures. Consequently, this area is located astride a regional transition between flat-lying and upright fold structures. Although equivocal, the field evidence suggests that a decrease in

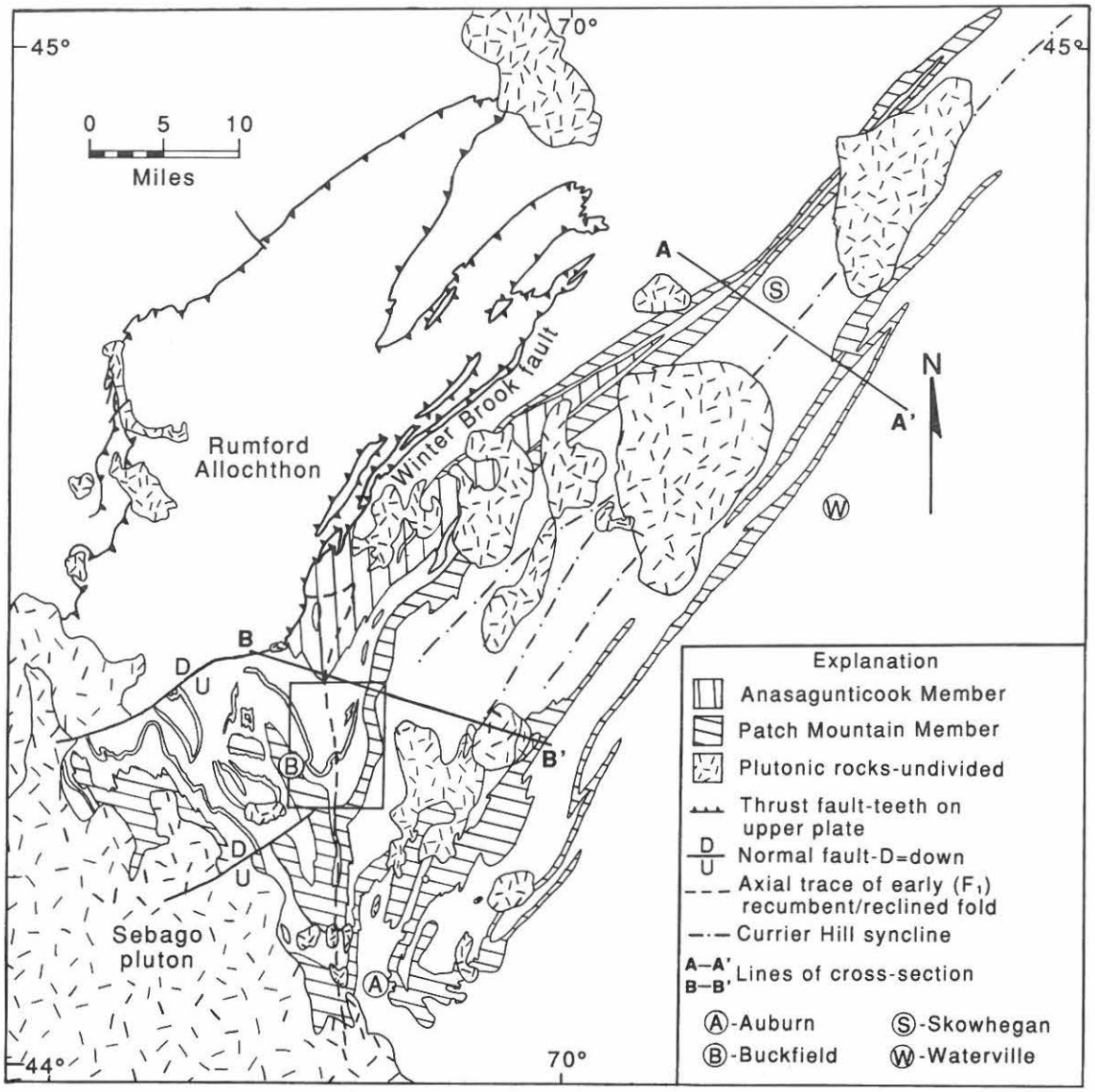


Figure 7. Regional geologic map of south-central Maine (after Osberg et al., 1985). Rectangle outlines the Buckfield quadrangle. Cross-sections for lines A-A', B-B' are presented in Figure 8.

the amplitude of F_2 folds towards southwestern Maine accounts for the exposure of this transition.

Regional correlation of fold sets F_1 and F_2 demonstrates that large-scale recumbent folding in south-central Maine (F_1) predated the Sebago intrusion and other widespread, tabular granitic plutons. Thus, it is apparent that these intrusions exploited rather than produced the flat-lying fold structures in the area not affected by large-scale F_2 deformation. This sequence of events is at odds with previously published interpretations (Guidotti, 1965; Warner, 1967; Moench and Zartman, 1976; Creasy, 1979), but is supported by many observations of crosscutting small-scale structures. Table 1 presents a chronologic outline of structural events postulated for south-central Maine.

TABLE 1. INFERRED STRUCTURAL HISTORY OF THE BUCKFIELD QUADRANGLE.

(1) Formation of early, layer-parallel foliation (S_A).
(2) Early Acadian thrust faulting, formation of large-scale nappes (F_1).
(3) Acadian regional, upright, NE-trending, symmetric, isoclinal folding (F_2).
(4) Late, small-scale, upright, NW-trending asymmetric folding (F_3) and crenulation cleavage (S_3). Possibly local Carboniferous deformation due to Sebago intrusion.
(5) Normal Faulting.

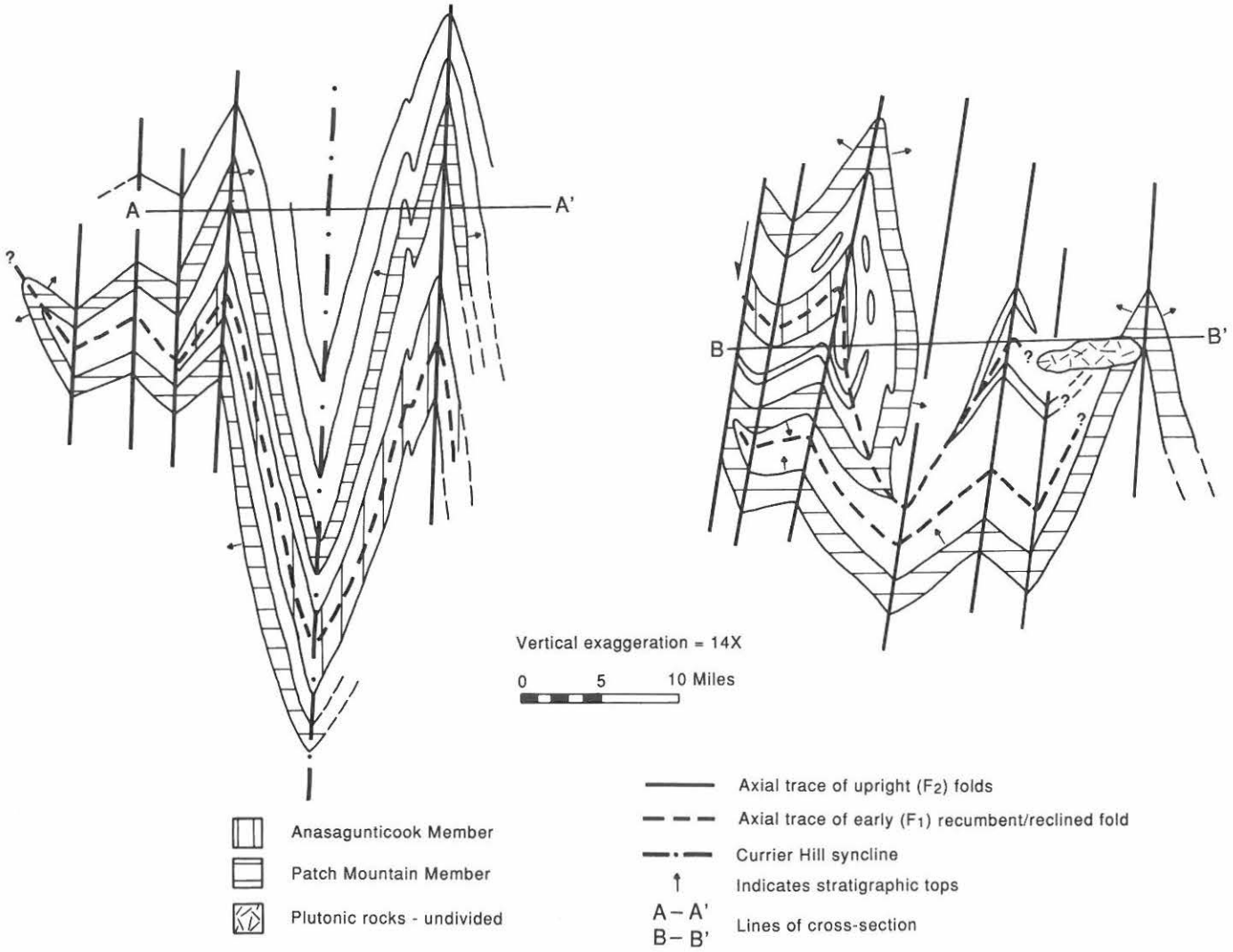


Figure 8. Interpretive cross-sections for profiles A-A' and B-B', south-central Maine (see Fig. 7).

Analysis of graded beds consistently shows that F_2 and F_3 folds face downward. This indicates that the Buckfield area rocks as presently exposed are situated on an overturned limb of a large-scale recumbent (or strongly overturned) F_1 fold. Correlation of the Buckfield area stratigraphy with that of the Waterville area supports this contention. Similarities in bedding style and lithology allow for such a correlation which is also consistent with the structural model presented.

ACKNOWLEDGMENTS

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