

Regional low-grade polygenetic metamorphism and inversion in the northern part of the Eastern Belt, Northern Sierra Nevada, California

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ABSTRACT

The Eastern belt of the Sierra Nevada comprises an Ordovician(?) to Devonian(?) succession of psammites and pelites belonging to the Shoo Fly Complex, and is overlain by three Paleozoic to Mesozoic arc volcanic sequences. The northern part of the belt, the subject of this chapter, is divided into a series of discrete blocks by steeply dipping faults, considered to be eastward-directed thrusts. The metamorphic history of this region has been little investigated previously. It has been argued that low-grade metamorphism of the Eastern belt is a Nevadan orogenic effect; in contrast, it has also been suggested that metamorphism of the arc volcanic rocks was a result of burial effects in the arc environment. In this study the metamorphic grade of the area has been established using mineral assemblages in metabasites and pelites, combined with illite crystallinity and b_0 data from pelitic rocks. The Shoo Fly Complex underwent epizonal metamorphism under Barrovian-type conditions prior to the earliest arc volcanism. Metamorphic grade in the overlying arc volcanic rocks ranges from pumpellyite-actinolite facies in the strongly foliated rocks of the (westernmost) Butt Valley and Hough blocks, through prehnite-pumpellyite facies in the Keddie Ridge and Genesee blocks, to low anchizone to diagenetic grade in Jurassic rocks of the (easternmost) Mt. Jura and Kettle Rock blocks. There is evidence for at least three discrete regional metamorphic events in these arc rocks; one is interpreted as being related to the burial of the arc volcanic rocks, which reached prehnite-pumpellyite facies; this event was followed by deformation and pumpellyite-actinolite facies metamorphism during the Nevadan orogeny; a final episode of static, low-grade metamorphism, possibly due to tectonic loading effects, probably also resulted in pumpellyite-actinolite facies. Subsequently, rocks exposed in the extreme east of the region were affected by contact metamorphism during the emplacement of Sierra Nevada batholith granitoids.

INTRODUCTION

The northern Sierra Nevada comprises four northwest-southeast-trending lithotectonic units of Paleozoic to Mesozoic age: the Western belt (comprising the Smartville Complex), the Central belt, the Feather River peridotite belt, and the Eastern

belt (Hannah and Moores, 1986; Day et al., 1988). In the work of Hardwood (1983, 1988, 1992) the Eastern belt is termed the northern Sierra terrane. The stratigraphic nomenclature and chronology adopted in this paper follows that used in the recent review by Harwood (1992). Rocks of these units have been affected in part by at least three orogenic events, the Devonian

Bevins, R. E., and Robinson, D., 1995. Regional low-grade polygenetic metamorphism and inversion in the northern part of the Eastern Belt, Northern Sierra Nevada, California, in Schiffman, P., and Day, H. W., eds., Low-Grade Metamorphism of Mafic Rocks: Boulder, Colorado, Geological Society of America Special Paper 296.

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Antler, the Permian-Triassic Sonoran, and the Jurassic Nevadan orogenies (Dickinson, 1981), and have been intruded by Late Jurassic to Cretaceous granitoids of the Sierra Nevada batholith. The effects of the Nevadan orogeny are critical to this study. Although the orogeny is typically considered to be of Late Jurassic age, there is now evidence of protracted deformation, possibly back to 179 Ma (i.e., about late Early Jurassic time) (Harwood, 1988).

The Eastern belt (Fig. 1), the subject of this chapter, is bordered to the west by the Feather River peridotite belt (Day et al., 1985) and to the east by the Sierra Nevada batholith (McMath, 1966). A series of major northwest-trending faults, the Taylorsville, Ward Creek, Hull, and Grizzly Mountain faults, which were originally thrust faults but are now in places of near vertical orientation (Day et al., 1985; Harwood, 1992), divide the area into a number of blocks; from east to west, these are the Kettle Rock, Genesee, Mt. Jura, Keddie Ridge, Grizzly, Hough, and Butt Valley blocks. The Butt Valley block is used in this chapter in relation to rocks between the Shoo Fly Complex and the Feather River peridotite belt in the area north of the North Fork of the Feather River, and comprises both the Butt Valley and Soda Ravine blocks of Jayko (1988). In places these various faults are responsible for local and regional inversion and repetition of stratigraphy.

The succession comprises an Ordovician(?) to Devonian(?) thrust-slice sequence of predominantly psammitic and rarer pelitic rocks belonging to the Shoo Fly Complex (Schweickert, 1981), and is overlain unconformably by volcanic and associated rocks belonging to three Paleozoic to Mesozoic arc-related magmatic episodes (Hannah and Moores, 1986; Day et al., 1988; Harwood, 1992). The earliest of these comprises mid-Paleozoic (Devonian to Early Mississippian) extrusive, intrusive, and sedimentary rocks of the Grizzly, Sierra Buttes, and Taylor formations and the lower member of the Peale Formation. Following an interval of pelagic sedimentation (represented by cherts of the Early Mississippian to Middle Pennsylvanian upper member of the Peale Formation), volcanic activity was renewed in mid-Permian time, as evidenced by lavas and volcanoclastic rocks of the Arlington, Goodhue, Reeve, and Robinson formations. The most recent activity is represented by volcanic, volcanoclastic, and sedimentary rocks of Early to Middle Jurassic age. The various pre-Jurassic volcanic successions probably represent volcanic arc products formed marginal to and accreted onto the western margin of North America during Mesozoic time.

In recent years there have been a number of investigations into the metamorphic evolution of the northern Sierra Nevada. Day et al. (1988), in reviewing earlier work, reported five different episodes of regional metamorphism in the area, including in particular prehnite-pumpellyite facies burial metamorphism of the Paleozoic and Mesozoic volcanic arc rocks, overprinted in part by Late Jurassic Nevadan greenschist facies dynamothermal metamorphism. Complex metamorphic histories have been revealed in a number of areas in the Sierra Nevada; e.g., in the

Smartville Complex, pre-Nevadan burial, contact, and hydrothermal events have been proposed, events thought to relate to metamorphism during construction of a volcanic arc (Beiersdorfer and Day, 1991; Springer et al., 1992; Beiersdorfer, 1993). In addition, mapped prehnite and pumpellyite zones with undeformed, nonfoliated rocks relating to these earlier events have been crosscut by later syntectonic shear zones of Nevadan age. These shear zones contain strongly foliated rocks with greenschist facies assemblages. Similar relations have been reported from the central Sierra Nevada, where deformed and foliated Middle or Upper Jurassic metamorphosed volcanic rocks contain pre-tectonic amygdules filled with prehnite, pumpellyite, epidote, or quartz (Zhai, 1991; Zhai and Day, 1992). The deformation and foliation are thought to be Nevadan, the pre-tectonic minerals relating to burial metamorphism in the arc environment.

Currently, however, little is known about the metamorphic history of the Eastern belt. Harwood (1988) reported the presence of quartz + muscovite + chlorite + albite along with rare biotite in metasedimentary rocks of the Shoo Fly Complex, and the succession reached greenschist facies. Day et al. (1988) described prehnite-pumpellyite to lowermost greenschist facies assemblages in the little deformed Devonian to Mississippian volcanic arc rocks in the area, for example, on Keddie Ridge. The presence of prehnite and pumpellyite in this area was noted originally by Hannah (1980), who also reported an increase in intensity of deformation and grade of metamorphism to the west across the Grizzly Mountain fault. In more strongly foliated rocks, in contrast, greenschist facies assemblages have been recorded. Harwood (1988) considered metamorphism in the Eastern belt to relate to Late Jurassic Nevadan orogenic effects. Day et al. (1988) suggested that the Jurassic volcanic arc rocks exposed in the east of the area may have been metamorphosed at a lower grade than the earlier arc rocks. As for the Western and Central belts, the suggestion of Day et al. (1988) was that the metamorphic patterns in the Eastern belt relate to a pre-Nevadan episode of burial metamorphism developed during construction of the volcanic arcs, which was locally superimposed by Nevadan dynamic metamorphism at greenschist grade.

In order to provide a more comprehensive account of the metamorphic character of rocks of the Eastern belt and to test the hypothesis of Day et al. (1988) outlined above, samples were collected from the various Paleozoic and Mesozoic arc volcanic and related sedimentary rocks in the northern part of the Eastern belt, as well as from the underlying metasedimentary Paleozoic Shoo Fly Complex. This region is critical to gaining an understanding of the metamorphic evolution of the Sierra Nevada in view of the fact that the Late Jurassic to Early Cretaceous age granites are some distance to the east. Farther south, for example, around Clio, Mills Peak, and Gold Lake, the intrusions are in close proximity to the volcanic sequence and contact metamorphic effects have obliterated evidence of any earlier metamorphic assemblages.

All samples described in this chapter were collected from

an area bounded to the north by Keddie Ridge, to the south by the Middle Fork of the Feather River, to the west by the Feather River peridotite belt, and to the east by the Sierra Nevada batholith, as well as Quaternary and Tertiary cover rocks (Fig. 1).

Petrographic examinations and mineral chemical determinations were undertaken on the arc volcanic rocks, and pelitic rocks from the metasedimentary successions were investigated utilizing the illite crystallinity technique, along with determi-

nations of b_0 values. The findings of this study are in broad agreement with the earlier suggestions of Day et al. (1988) concerning metamorphic grade. First, the Shoo Fly Complex was metamorphosed to greenschist facies prior to development of the earliest arc volcanic episode (of Devonian age). These arc volcanic rocks were initially affected by burial metamorphism prior to the development of a foliation and associated metamorphic assemblages, which are attributed to the Nevadan orogeny, and finally postdeformation metamorphism occurred.

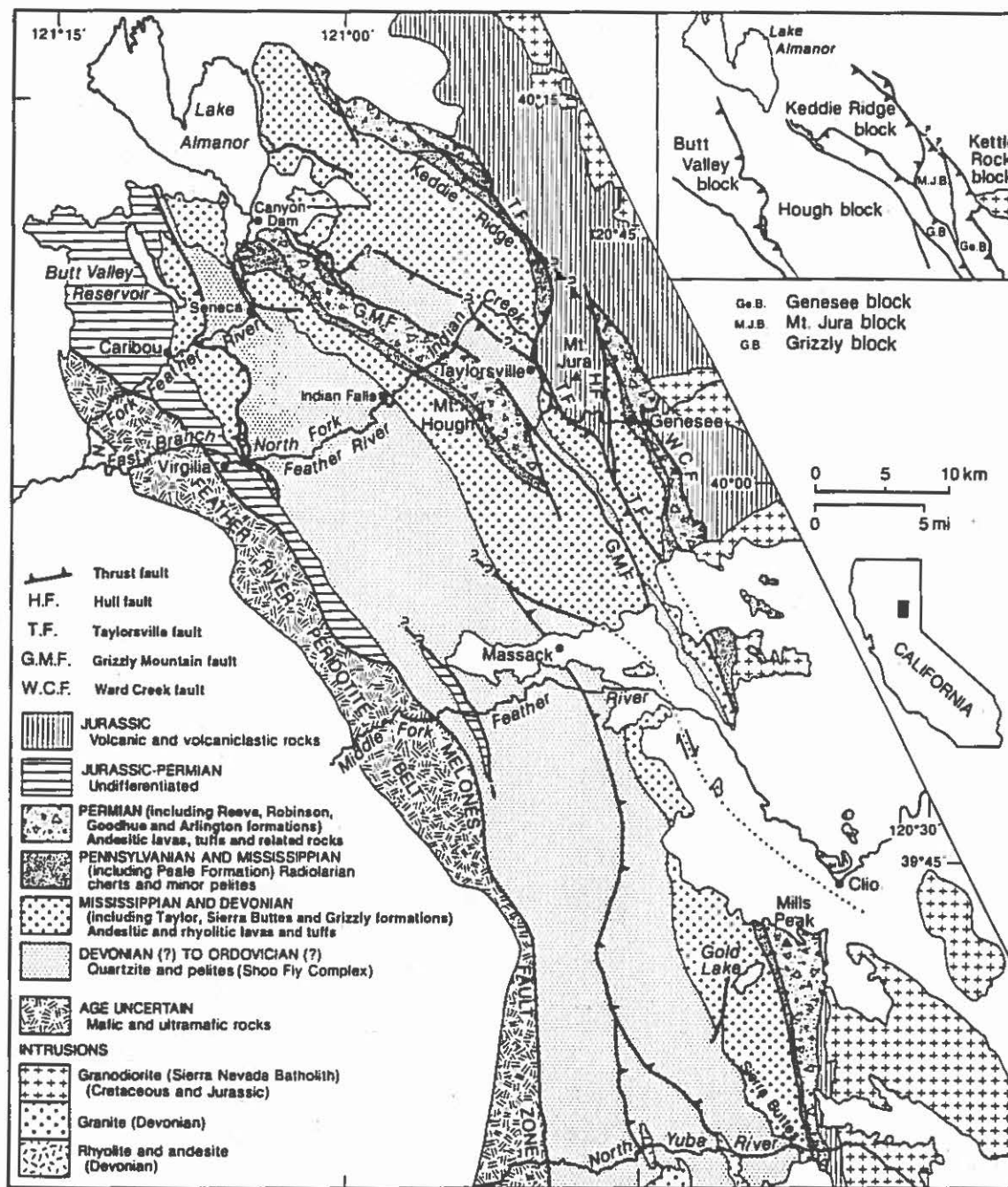


Figure 1. Simplified geologic map of the Eastern belt, based on Hannah and Moores (1986) and Harwood (1988, 1992). Tertiary and Quaternary volcanic and sedimentary cover are unpatterned.

TABLE 1. DETAILS OF SAMPLES USED IN THIS CHAPTER

Sample	Locality	Block*	Lithology	Horizon	Quadrangle 7.5' sheet	UTMN†	UTME†
1661	1A	BVB	Pelite	Unnamed Triassic and Permian	Twain	4,432,280	660,060
1662	1B	BVB	Pelite	Unnamed Triassic and Permian	Twain	4,432,510	660,210
1663	2A	BVB	Pelite	Unnamed Triassic and Permian	Twain	4,431,225	662,530
1666	3	HB	Pelite	Shoo Fly Complex	Twain	4,431,280	663,525
1667	4	BVB	Andesite	Sierra Buttes Formation	Twain	4,430,960	663,250
1668	5A	HB	Volcaniclastite	Shoo Fly Complex	Twain	4,431,915	660,075
1669	5B	HB	Pelite	Shoo Fly Complex	Twain	4,431,985	665,170
1670	6	HB	Pelite	Shoo Fly Complex	Twain	4,431,600	667,500
1671	7	HB	Pelite	Shoo Fly Complex	Twain	4,431,655	668,130
1672	8	HB	Pelite	Shoo Fly Complex	Twain	4,432,975	669,600
1674	9A	HB	Pelite	Shoo Fly Complex	Crescent Mills	4,433,950	671,100
1677	9C	HB	Pelite	Shoo Fly Complex	Crescent Mills	4,433,975	670,900
1679	10	HB	Pelite	Shoo Fly Complex	Crescent Mills	4,433,850	672,340
1680	11	HB	Pelite	Shoo Fly Complex	Crescent Mills	4,434,110	672,740
1681	12	HB	Pelite	Shoo Fly Complex	Crescent Mills	4,435,740	673,350
1683	13A	HB	Metabasite	Taylor Formation	Crescent Mills	4,436,560	674,125
1684	13B	HB	Metabasite	Taylor Formation	Crescent Mills	4,436,510	674,040
1685	13C	HB	Metabasite	Taylor Formation	Crescent Mills	4,436,500	673,925
1686	14	HB	Metabasite	Taylor Formation	Crescent Mills	4,436,990	674,750
1687	15	HB	Metabasite	Taylor Formation	Crescent Mills	4,437,450	675,075
1688	16A	HB	Volcaniclastite	Arlington Formation	Crescent Mills	4,438,250	676,140
1689	16B	HB	Volcaniclastite	Arlington Formation	Crescent Mills	4,438,190	676,100
1690	17	HB	Volcaniclastite	Arlington Formation	Crescent Mills	4,438,975	677,100
1691	18A	HB	Metabasite	Arlington Formation	Crescent Mills	4,439,490	677,820
1692	18B	HB	Metabasite	Arlington Formation	Crescent Mills	4,439,425	677,790
1693	19	GB	Diorite	Intrusive	Crescent Mills	4,440,780	678,310
1695	21	HB	Pelite	Peale Formation	Canyondam	4,446,720	662,920
1696	22A	HB	Metabasite	Taylor Formation	Canyondam	4,443,390	662,925
1697	22B	HB	Metabasite	Taylor Formation	Canyondam	4,443,325	663,000
1699	24	BVB	Pelite	Unnamed Triassic and Permian	Caribou	4,436,400	654,575
1700	25	BVB	Pelite	Unnamed Triassic and Permian	Caribou	4,436,700	655,340
1746	26	BVB	Pelite	Unnamed Triassic and Permian	Caribou	4,437,190	655,800
1747	27	BVB	Metabasite	Taylor Formation	Caribou	4,439,375	657,700
1748	28	HB	Pelite	Shoo Fly Complex	Twain	4,441,580	660,425
1749	29	HB	Pelite	Shoo Fly Complex	Twain	4,441,175	662,425
1750	30	HB	Pelite	Shoo Fly Complex	Twain	4,442,025	663,550
1751	31	BVB	Pelite	Unnamed Jurassic-Triassic	Almanor	4,446,210	655,645
1752	32	BVB	Pelite	Unnamed Jurassic-Triassic	Almanor	4,448,825	654,390
1753	33	KRB	Pelite	Shoo Fly Complex	Canyondam	4,453,445	664,325
1754	34	HB	Pelite	Shoo Fly Complex	Crescent Mills	4,443,600	673,675
1755	35	HB	Pelite	Shoo Fly Complex	Crescent Mills	4,430,330	673,975
1756	36	HB	Pelite	Shoo Fly Complex	Quincy	4,426,225	679,540
1757	37	HB	Metabasite	Arlington Formation	Taylorsville	4,434,175	682,240
1758	38	HB	Metabasite	Arlington Formation	Taylorsville	4,434,325	682,160
1759	39	HB	Metabasite	Arlington Formation	Taylorsville	4,434,350	682,030
1760	40	MJB	Volcaniclastite	Jurassic	Taylorsville	4,436,975	685,600
1761	41	MJB	Andesite	Jurassic	Taylorsville	4,435,300	686,200
1762	42	MJB	Ignimbrite	Jurassic	Taylorsville	4,435,990	686,340
1763	43	GEB	Metabasite	Taylor Formation	Taylorsville	4,434,775	690,260
1764	44	GEB	Metabasite	Taylor Formation	Taylorsville	4,434,630	690,400
1765	45	GEB	Pelite	Peale Formation	Genesee Valley	4,434,700	692,200
1766	46A	GEB	Andesite	Reeve Formation	Genesee Valley	4,435,225	693,500
1767	46B	GEB	Andesite	Intrusive	Genesee Valley	4,435,230	693,550
1768	47	MJB	Pelite	Jurassic	Taylorsville	4,441,600	685,990
1769	48	MJB	Pelite	Jurassic	Taylorsville	4,442,080	687,200
1770	49	MJB	Pelite	Jurassic	Taylorsville	4,441,690	689,000
1771	51	KB	Pelite	Jurassic	Moonlight Peak	4,444,500	687,630
1772	50	MJB	Pelite	Jurassic	Taylorsville	4,441,450	689,180

TABLE 1. DETAILS OF SAMPLES USED IN THIS CHAPTER (continued)

Sample	Locality	Block*	Lithology	Horizon	Quadrangle 7.5' sheet	UTMN†	UTME†
1773	52	KB	Dacite	Jurassic	Moonlight Peak	4,445,050	687,480
1774	53	KRB	Volcaniclastite	Peale Formation	Taylorville	4,441,440	685,200
1776	55	HB	Metabasite	Taylor Formation	Spring Garden	4,421,725	687,075
1777	56	HB	Metabasite	Intrusive	Spring Garden	4,421,750	689,025
1778	58	HB	Pelite	Shoo Fly Complex	Spring Garden	4,420,825	688,340
1779	57	HB	Metabasite	Intrusive	Spring Garden	4,422,250	688,920
1780	59	HB	Pelite	Shoo Fly Complex	Spring Garden	4,419,825	683,880
1782	61	HB	Pelite	Shoo Fly Complex	Spring Garden	4,418,260	682,475
1783	62	HB	Pelite	Shoo Fly Complex	Spring Garden	4,415,950	682,660
1788	66	HB	Pelite	Shoo Fly Complex	Quincy	4,423,150	672,920
1790	68	?GEB	Metabasite	Reeve Formation	Clio	4,403,575	709,400
1791	69	?GEB	Metabasite	Reeve Formation	Clio	4,402,140	709,040
1792	70	?GEB	Metabasite	Reeve Formation	Clio	4,402,270	707,600
1793	71A	?GEB	Metabasite	Reeve Formation	Clio	4,402,340	706,820
1794	71B	?GEB	Metabasite	Reeve Formation	Clio	4,402,300	706,850
1795	71C	?GEB	Metabasite	Reeve Formation	Clio	4,402,250	706,975
1799	74A	?GEB	Metabasite	Goodhue Formation	Blairsdon	4,403,250	706,325
2300	74B	?GEB	Metabasite	Goodhue Formation	Blairsdon	4,403,200	706,330
2301	74C	?GEB	Metabasite	Goodhue Formation	Blairsdon	4,403,175	706,340
2302	75	?GEB	Metabasite	Goodhue Formation	Blairsdon	4,403,030	706,380
2303	76	?GEB	Metabasite	Intrusive	Blairsdon	4,402,675	706,600
2304	77	?GEB	Metabasite	Intrusive	Blairsdon	4,402,800	706,510
2305	78	GEB	Metabasite	Goodhue Formation	Mt. Ingalls	4,426,430	696,100
2306	79	GEB	Metabasite	Goodhue Formation	Mt. Ingalls	4,426,820	695,790
2307	80	GEB	Metabasite	Goodhue Formation	Mt. Ingalls	4,428,020	695,450
2308	81	GEB	Metabasite	Goodhue Formation	Mt. Ingalls	4,428,290	695,300
2309	82	GEB	Pelite	Peale Formation	Mt. Ingalls	4,429,590	694,650
2310	83	GEB	Metabasite	Taylor Formation	Mt. Ingalls	4,429,575	693,690
2311	84	GEB	Metabasite	Intrusive	Mt. Ingalls	4,431,600	691,970
2312	85	GEB	Metabasite	Taylor Formation	Taylorville	4,432,790	690,500
2313	86	GEB	Metabasite	Taylor Formation	Taylorville	4,433,300	690,350
2314	87	KRB	Metabasite	Intrusive	Greenville	4,451,380	672,370
2315	88	KRB	Metabasite	Taylor Formation	Greenville	4,451,700	673,070
2316	89	KRB	Metabasite	Taylor Formation	Greenville	4,451,775	673,390
2317	90	KRB	Metabasite	Taylor Formation	Greenville	4,451,060	673,850
2318	91	KRB	Metabasite	Taylor Formation	Greenville	4,451,450	674,275
2319	92	KRB	Metabasite	Taylor Formation	Greenville	4,451,440	674,640
2320	93	KRB	Metabasite	Intrusive	Greenville	4,451,490	674,940
2321	94	KRB	Metabasite	Reeve Formation	Greenville	4,454,400	675,200
2322	95	KRB	Metabasite	Intrusive	Greenville	4,453,720	674,850
2323	96	KRB	Metabasite	Intrusive	Greenville	4,453,880	674,450
2324	97	KRB	Metabasite	Intrusive	Greenville	4,455,320	675,720
2325	97	KRB	Metabasite	Reeve Formation	Greenville	4,455,320	675,720

*BVB = Butt Valley block; HB = Hough block; GEB = Genesee block; KB = Kettle Rock block; GB = Grizzly block; KRB = Keddle Ridge block; MJB = Mt. Jura block.

†UTMN and UTME are universal transmercator coordinates.

Subsequently, these effects were themselves overprinted in places as a result of emplacement of the Sierra Nevada batholith and its related contact metamorphism. The current disposition of metamorphic grades relates to the Middle to Late Jurassic stacking of imbricate thrust slices, which inverted the stratigraphic and metamorphic succession.

METAMORPHIC ALTERATION OF EASTERN BELT ROCKS

Methodology

The degree of metamorphism in rocks of the Eastern belt was investigated using a variety of techniques, including stan-

dard optical microscopy, electron microprobe analysis of critical secondary minerals, and the determination of clay mineralogy in pelitic rocks by X-ray diffraction. In total 101 specimens were utilized in this investigation. Sample details, along with UTM coordinates of sampling sites, are presented in Table 1; the sites are plotted in Figure 2.

Electron microprobe analyses were determined using a Jeol JXA-8600 Superprobe at the University of Bristol. A wavelength dispersive system was used for analysis, with an accelerating voltage of 15 kV, a nominal beam current of 15 nA and a beam size of either 1 or 5 μm . All standards were silicates or oxides. Full analyses are presented in Table 2, a-c. Recalculations for chlorite, actinolite, and pumpellyite were

on the basis of 28, 23, and 24.5 oxygens, respectively. X-ray diffraction (XRD) investigations of 47 pelitic rocks were undertaken at the University of Bristol. Clay fractions ($<2 \mu\text{m}$) were separated from each of these samples, which were then analyzed by XRD for general mineralogical composition, illite crystallinity (IC), and b_0 values (Table 3). All determinations followed the general routine outlined by Robinson et al. (1990), but we used a Philips PW1800 instrument running at 50 kV and 40 mA. The b_0 determinations (Sassi and Scolari, 1974) were measured from scans over the range 59° – 63° 2θ at $1/4^\circ$ 2θ min, using quartz (1.541 Å) as an internal standard. In this study, the b_0 parameter has been measured on only 15 samples. When using this parameter the number of samples of

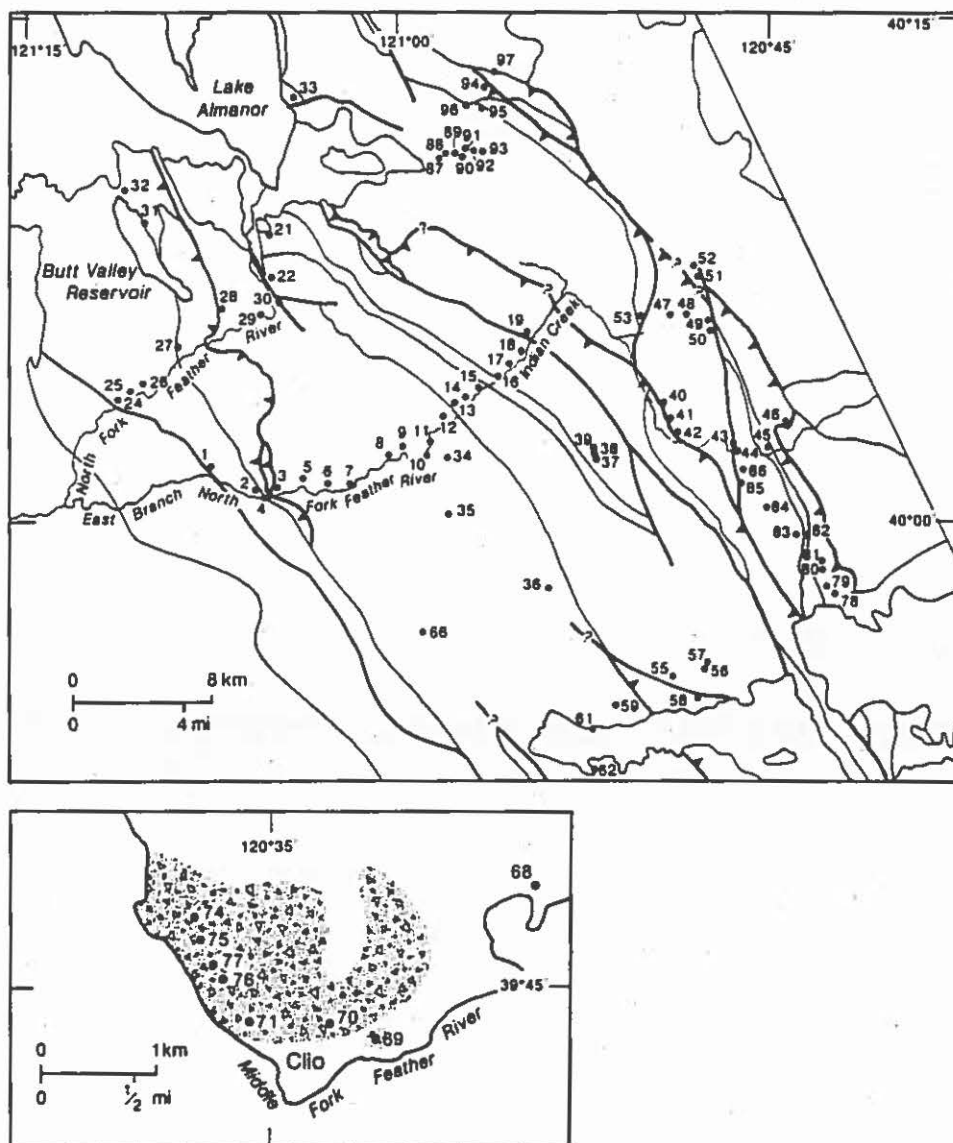


Figure 2. The location of samples collected during this study. Geologic boundaries from Figure 1. The inset shows localities in the Clio area (see Fig. 1), and the ornament shows the approximate distribution of Permian volcanic rocks.

TABLE 2a. CHLORITE ANALYSES FROM EASTERN BELT METABASITES

Sample	1683	1683	1683	1683	1683	1683	Mean (6)	Standard deviation	1776	1776	1776	1776	1776	1776	1776	1776	1776	1776	Mean (9)	Standard deviation
SiO ₂	25.58	26.37	26.01	26.41	26.43	26.39	26.20	0.34	26.87	27.60	26.36	26.70	27.06	26.94	26.97	26.98	27.26	26.97	0.34	
TiO ₂	n.d.	n.d.	n.d.	n.d.	0.08	0.04	0.02	0.03	n.d.	0.06	n.d.	n.d.	n.d.	0.20	n.d.	n.d.	n.d.	0.03	0.07	
Al ₂ O ₃	20.11	19.91	20.09	19.09	20.66	19.68	19.92	0.52	19.24	19.24	19.71	19.95	19.38	18.54	18.19	19.30	19.04	19.18	0.54	
FeO	26.98	26.34	26.99	26.69	27.01	26.63	26.77	0.27	25.27	26.14	25.15	25.77	26.05	25.34	24.86	25.60	26.39	25.62	0.51	
MnO	0.28	0.43	0.42	0.14	0.31	0.32	0.32	0.11	0.39	0.45	0.41	0.44	0.41	0.66	0.48	0.30	0.35	0.43	0.10	
MgO	12.96	13.23	13.17	12.09	13.22	13.28	12.99	0.46	13.76	13.97	13.45	14.02	13.87	14.92	14.49	13.54	14.28	14.03	0.47	
CaO	0.09	0.12	0.10	0.13	0.08	0.07	0.10	0.02	0.32	0.42	0.28	0.04	0.19	0.20	0.17	0.27	0.12	0.22	0.11	
Na ₂ O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	0.00	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	0.00	
K ₂ O	n.d.	n.d.	n.d.	0.04	0.03	0.02	0.02	0.02	0.02	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.04	n.d.	0.01	0.01	
Total	86.00	86.40	86.78	84.55	87.79	86.41	86.34	1.06	85.85	87.88	85.36	86.92	86.96	86.80	85.16	85.99	87.44	86.49	0.94	
Cations per 28 oxygens																				
Si	5.56	5.67	5.59	5.81	5.60	5.68	5.65	0.09	5.78	5.82	5.71	5.68	5.77	5.75	5.85	5.80	5.78	5.77	0.05	
Ti	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.01	0.01	
Al ^{iv}	2.44	2.33	2.41	2.19	2.40	2.32	2.35	0.09	2.22	2.18	2.29	2.32	2.23	2.25	2.15	2.20	2.22	2.23	0.05	
Al ^{vi}	2.70	2.72	2.69	2.77	2.76	2.68	2.72	0.04	2.67	2.60	2.74	2.69	2.63	2.42	2.50	2.69	2.55	2.61	0.10	
Fe ²⁺	4.90	4.74	4.85	4.91	4.79	4.79	4.83	0.07	4.55	4.61	4.55	4.59	4.64	4.52	4.51	4.60	4.68	4.59	0.06	
Mn	0.05	0.08	0.08	0.03	0.06	0.06	0.06	0.02	0.07	0.08	0.08	0.08	0.07	0.12	0.09	0.05	0.06	0.08	0.02	
Mg	4.19	4.24	4.22	3.97	4.17	4.26	4.18	0.11	4.41	4.39	4.34	4.45	4.40	4.75	4.68	4.34	4.52	4.48	0.15	
Ca	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.01	0.07	0.09	0.06	0.01	0.04	0.05	0.04	0.06	0.03	0.05	0.03	
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
K	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
AF*	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.01	0.21	0.20	0.22	0.22	0.21	0.20	0.20	0.21	0.20	0.21	0.01	
Mg†	0.46	0.47	0.47	0.45	0.47	0.47	0.46	0.01	0.49	0.49	0.49	0.49	0.49	0.51	0.51	0.49	0.49	0.49	0.01	

*AF = $100(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2) / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2 + \text{FeO} + \text{MgO})$.†Mg = $\text{MgO} / (\text{MgO} + \text{FeO})$.

n.d. = not detected.

TABLE 2a. CHLORITE ANALYSES FROM EASTERN BELT METABASITES (continued)

Sample	1696	1696	Mean (2)	1747	1747	1747	1747	1747	1747	1747	Mean (7)	Standard deviation	2318	2318	2318	2318	Mean (4)	Standard deviation
SiO ₂	26.63	26.24	26.44	27.16	26.97	28.08	28.75	28.23	29.64	28.50	28.19	0.80	28.18	28.87	29.36	28.59	28.75	0.33
TiO ₂	n.d.	n.d.	n.d.	n.d.	0.02	0.61	n.d.	n.d.	n.d.	n.d.	0.09	0.23	0.02	n.d.	n.d.	n.d.	0.01	0.00
Al ₂ O ₃	18.88	18.99	18.94	19.91	19.55	18.74	20.34	20.51	20.17	20.37	19.94	0.62	17.24	15.61	16.76	15.01	16.16	0.75
FeO	29.03	29.84	29.44	20.39	20.11	19.42	19.94	20.82	19.80	19.99	20.07	0.42	30.94	29.69	29.01	29.00	29.66	0.39
MnO	0.39	0.56	0.48	0.24	0.28	0.17	0.31	0.30	0.29	0.25	0.26	0.05	0.53	0.42	0.46	0.46	0.47	0.02
MgO	11.94	12.27	12.11	19.36	19.58	18.81	19.12	19.15	19.12	19.06	19.17	0.23	12.80	14.47	14.34	14.18	13.95	0.23
CaO	0.25	0.13	0.19	0.15	0.07	0.78	0.09	0.05	0.15	0.11	0.20	0.26	0.14	0.19	0.22	0.13	0.17	0.04
Na ₂ O	n.d.	0.08	0.08	n.d.	n.d.	n.d.	n.d.	n.d.	0.03	n.d.	n.d.	0.01	0.05	0.04	n.d.	0.03	0.03	0.02
K ₂ O	0.04	0.02	0.03	0.02	n.d.	0.04	n.d.	n.d.	n.d.	n.d.	0.01	0.02	n.d.	n.d.	n.d.	n.d.	n.d.	0.00
Total	87.12	88.11	87.66	87.21	86.58	86.61	88.55	89.06	89.20	88.28	87.93	1.07	90.23	89.29	90.15	87.40	89.19	1.15
Cations per 28 oxygens																		
Si	5.76	5.65	5.71	5.60	5.60	5.80	5.79	5.69	5.91	5.76	5.74	0.10	5.96	6.11	6.11	6.17	6.09	0.04
Ti	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Al ^{IV}	2.24	2.35	2.29	2.40	2.40	2.20	2.21	2.31	2.09	2.24	2.26	0.10	2.04	1.89	1.89	1.83	1.91	0.04
Al ^{VI}	2.58	2.47	2.53	2.44	2.39	2.37	2.62	2.56	2.65	2.62	2.52	0.12	2.25	2.00	2.22	1.99	2.12	0.11
Fe ²⁺	5.26	5.37	5.31	3.52	3.49	3.36	3.36	3.51	3.30	3.38	3.42	0.08	5.47	5.25	5.05	5.24	5.25	0.10
Mn	0.07	0.10	0.09	0.04	0.05	0.03	0.05	0.05	0.05	0.04	0.05	0.01	0.09	0.08	0.08	0.08	0.08	0.00
Mg	3.85	3.94	3.89	5.95	6.06	5.79	5.74	5.75	5.68	5.74	5.82	0.12	4.03	4.56	4.45	4.56	4.40	0.08
Ca	0.06	0.03	0.04	0.03	0.02	0.17	0.02	0.01	0.03	0.02	0.04	0.06	0.03	0.04	0.05	0.03	0.04	0.01
Na	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.02	0.00	0.01	0.01	0.01
K	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AF*	0.21	0.20	0.20	0.20	0.20	0.19	0.21	0.21	0.21	0.21	0.20	0.01	0.18	0.16	0.18	0.16	0.17	0.01
Mg [†]	0.42	0.42	0.42	0.63	0.63	0.63	0.63	0.62	0.63	0.63	0.63	0.01	0.42	0.46	0.47	0.47	0.46	0.01

*AF = $100(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2) / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2 + \text{FeO} + \text{MgO})$.†Mg = $\text{MgO} / (\text{MgO} + \text{FeO})$.

n.d. = not detected.

TABLE 2b. ACTINOLITE ANALYSES FROM EASTERN BELT METABASITES

Sample	1683	1683	1683	1683	Mean (4)	Standard deviation	1776	1776	1776	1776	1776	Mean (5)	Standard deviation	1696	1696	Mean (2)
SiO ₂	51.57	53.03	54.06	53.82	53.12	1.12	54.95	54.25	55.17	55.26	55.06	54.94	0.40	52.20	52.60	52.40
TiO ₂	n.d.	n.d.	n.d.	n.d.	0.00	0.00	0.06	0.04	n.d.	n.d.	0.12	0.04	0.05	0.03	0.05	0.04
Al ₂ O ₃	3.11	1.68	1.16	1.76	1.93	0.83	0.89	1.36	1.23	0.69	2.19	1.27	0.58	1.89	1.07	1.48
FeO	17.28	16.26	16.03	16.62	16.55	0.55	15.48	14.63	15.17	13.90	14.62	14.76	0.61	17.15	17.10	17.13
MnO	0.32	0.21	0.24	0.27	0.26	0.05	0.21	0.29	0.20	0.33	0.25	0.26	0.06	0.31	0.32	0.32
MgO	13.92	13.89	13.93	14.15	13.97	0.12	13.52	14.00	15.02	14.68	13.52	14.15	0.68	12.59	13.02	12.81
CaO	11.44	12.37	12.93	12.59	12.33	0.64	12.72	12.70	12.55	13.40	12.55	12.78	0.35	12.54	12.74	12.64
Na ₂ O	0.11	0.10	0.07	0.10	0.10	0.02	0.08	0.12	n.d.	0.05	0.45	0.14	0.18	0.22	0.10	0.16
K ₂ O	0.06	0.04	0.03	0.06	0.05	0.02	0.03	0.02	n.d.	0.06	0.08	0.04	0.03	0.07	0.04	0.06
Total	97.75	97.54	98.42	99.31	98.31	0.80	97.91	97.39	99.34	98.31	98.76	98.38	0.75	96.93	97.00	97.04
Cations per 23 oxygens																
Si	7.578	7.774	7.846	7.758	7.739	0.114	7.971	7.895	7.871	7.945	7.881	7.912	0.043	7.753	7.809	7.781
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.004	0.000	0.000	0.013	0.005	0.005	0.003	0.006	0.004
Al	0.539	0.290	0.198	0.299	0.331	0.145	0.152	0.233	0.207	0.117	0.370	0.216	0.097	0.331	0.187	0.259
Fe ²⁺	2.124	1.994	1.946	2.003	2.016	0.076	1.878	1.781	1.810	1.671	1.750	1.778	0.076	2.130	2.123	2.127
Mn	0.040	0.026	0.030	0.033	0.032	0.006	0.026	0.036	0.024	0.040	0.030	0.031	0.007	0.039	0.040	0.040
Mg	3.049	3.035	3.013	3.039	3.034	0.015	2.923	3.036	3.194	3.146	2.884	3.037	0.135	2.787	2.881	2.834
Ca	1.801	1.943	2.015	1.944	1.925	0.088	1.977	1.981	1.919	2.065	1.925	1.973	0.059	1.996	2.027	2.011
Na	0.031	0.028	0.020	0.028	0.027	0.005	0.022	0.034	0.000	0.014	0.125	0.039	0.050	0.063	0.029	0.046
K	0.011	0.007	0.006	0.011	0.009	0.003	0.006	0.004	0.000	0.011	0.015	0.007	0.006	0.013	0.008	0.010
AF*	-0.27	-0.36	-0.40	-0.36	-0.34	0.06	-0.42	-0.40	-0.36	-0.45	-0.40	-0.41	0.03	-0.38	-0.40	-0.39
Mg [†]	0.59	0.60	0.61	0.60	0.60	0.01	0.61	0.63	0.64	0.65	0.62	0.63	0.02	0.57	0.58	0.57

*AF = $100(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2) / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2 + \text{FeO} + \text{MgO})$.†Mg = $\text{MgO} / (\text{MgO} + \text{FeO})$.

n.d. = not detected.

TABLE 2b. ACTINOLITE ANALYSES FROM EASTERN BELT METABASITES (continued)

Sample	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	Mean (10)	Standard deviation
SiO ₂	54.92	55.07	56.35	54.39	56.86	57.04	57.43	56.54	57.47	56.51	56.26	1.09
TiO ₂	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.10	n.d.	0.19	0.03	0.06
Al ₂ O ₃	0.67	0.90	0.57	1.04	1.03	1.12	0.65	1.51	1.00	0.81	0.93	0.28
FeO	10.38	10.20	10.31	10.79	10.82	9.68	10.91	11.17	10.32	10.16	10.47	0.44
MnO	0.12	0.18	0.21	0.21	0.15	0.23	0.15	0.24	0.16	0.14	0.18	0.04
MgO	17.41	17.35	17.03	17.28	17.19	17.61	17.50	16.75	17.13	17.43	17.27	0.25
CaO	13.03	13.02	12.61	12.88	13.13	13.28	13.27	12.95	12.97	13.42	13.06	0.23
Na ₂ O	0.12	0.13	0.13	0.17	0.26	0.13	0.05	0.16	0.16	0.13	0.14	0.05
K ₂ O	0.04	0.04	0.02	0.04	0.04	0.02	n.d.	0.06	n.d.	0.02	0.03	0.02
Total	96.65	96.85	97.21	96.76	99.44	99.09	99.96	99.42	99.21	98.79	98.36	1.30
Cations per 23 oxygens												
Si	7.902	7.898	8.023	7.840	7.941	7.953	7.976	7.906	8.008	7.933	7.938	0.055
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.000	0.020	0.003	0.007
Al	0.114	0.152	0.096	0.177	0.170	0.184	0.106	0.249	0.164	0.134	0.155	0.045
Fe ²⁺	1.249	1.223	1.228	1.301	1.264	1.129	1.267	1.306	1.203	1.193	1.236	0.054
Mn	0.015	0.022	0.025	0.026	0.018	0.027	0.018	0.028	0.019	0.017	0.021	0.005
Mg	3.733	3.708	3.614	3.712	3.578	3.659	3.622	3.491	3.557	3.646	3.631	0.076
Ca	2.009	2.001	1.924	1.989	1.965	1.984	1.974	1.940	1.937	2.019	1.974	0.032
Na	0.033	0.036	0.036	0.048	0.070	0.035	0.013	0.043	0.043	0.035	0.039	0.014
K	0.007	0.007	0.004	0.007	0.007	0.004	0.000	0.011	0.000	0.004	0.005	0.003
AF*	-0.42	-0.41	-0.41	-0.40	-0.42	-0.42	-0.42	-0.39	-0.41	-0.43	-0.41	0.01
Mg [†]	0.75	0.75	0.75	0.74	0.74	0.76	0.74	0.73	0.75	0.75	0.75	0.01

*AF = 100(Al₂O₃+Fe₂O₃-0.75CaO-Na₂O+0.75TiO₂)/Al₂O₃+Fe₂O₃-0.75CaO-Na₂O+0.75TiO₂+FeO+MgO.

†Mg = MgO/(MgO+FeO).

n.d. = not detected.

TABLE 2c. PUMPELLYITE ANALYSES FROM EASTERN BELT METABASITES

Sample	1683	1683	1683	1683	1683	Mean (5)	Standard deviation	1776	1776	1776	1776	1776	1776	1776	1776	1776	1776	1776	Mean (11)
SiO ₂	37.10	36.90	37.01	38.96	36.60	37.31	0.94	37.22	37.23	37.74	37.18	37.08	37.26	37.35	37.53	37.04	37.77	37.36	37.34
TiO ₂	0.08	0.09	0.09	0.11	0.06	0.09	0.02	0.05	n.d.	0.05	0.05	0.11	n.d.	0.06	0.08	n.d.	n.d.	0.10	0.05
Al ₂ O ₃	21.35	22.09	22.12	23.20	22.81	22.31	0.72	22.54	22.97	23.06	23.30	23.22	22.62	23.08	22.84	23.13	23.61	23.36	23.07
FeO	8.42	8.09	8.41	6.03	7.60	7.71	1.00	7.11	6.53	7.05	6.81	6.84	7.25	7.29	7.79	6.69	6.55	6.60	6.96
MnO	0.08	0.09	0.09	0.08	0.12	0.09	0.02	0.13	n.d.	0.14	n.d.	0.23	n.d.	0.13	0.09	0.15	0.16	0.28	0.12
MgO	2.12	2.13	2.16	2.08	1.92	2.08	1.00	2.23	2.40	2.21	2.22	2.24	2.24	2.21	2.16	2.37	2.50	2.42	2.29
CaO	22.59	22.39	22.03	21.53	22.66	22.24	0.47	22.77	22.70	22.65	22.77	22.61	22.72	22.34	22.80	22.21	22.59	22.74	22.63
Na ₂ O	n.d.	n.d.	0.07	0.54	0.08	0.14	0.23	n.d.	n.d.	0.08	n.d.	0.04	n.d.	n.d.	n.d.	n.d.	0.05	n.d.	0.02
K ₂ O	n.d.	0.02	n.d.	0.02	n.d.	0.01	0.01	n.d.	n.d.	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00
Total	91.74	91.80	91.98	92.55	91.85	91.98	0.33	92.05	91.83	93.01	92.33	92.37	92.09	92.46	93.29	91.59	93.23	92.86	92.46
Cations per 24.5 oxygens																			
Si	6.202	6.149	6.157	6.324	6.087	6.185	0.088	6.155	6.145	6.164	6.112	6.101	6.157	6.140	6.138	6.130	6.133	6.106	6.134
Ti	0.010	0.011	0.011	0.013	0.008	0.011	0.002	0.006	0.000	0.006	0.006	0.014	0.000	0.007	0.010	0.000	0.000	0.012	0.006
Al	4.208	4.340	4.338	4.440	4.473	4.360	0.104	4.394	4.470	4.440	4.515	4.504	4.407	4.473	4.404	4.513	4.520	4.501	4.467
Fe ²⁺	1.177	1.127	1.170	0.819	1.057	1.069	0.148	0.983	0.901	0.963	0.936	0.941	1.002	1.002	1.065	0.926	0.889	0.902	0.956
Mn	0.011	0.013	0.013	0.011	0.017	0.013	0.002	0.018	0.000	0.019	0.000	0.032	0.000	0.018	0.012	0.021	0.022	0.039	0.017
Mg	0.528	0.529	0.536	0.503	0.476	0.514	0.025	0.550	0.590	0.538	0.544	0.549	0.552	0.541	0.526	0.585	0.605	0.589	0.561
Ca	4.047	3.998	3.927	3.745	4.038	3.950	0.125	4.035	4.015	3.964	4.011	3.986	4.023	3.935	3.995	3.939	3.930	3.982	3.983
Na	0.000	0.000	0.023	0.170	0.026	0.044	0.072	0.000	0.000	0.025	0.000	0.013	0.000	0.000	0.000	0.000	0.016	0.000	0.005
K	0.000	0.004	0.000	0.004	0.000	0.002	0.002	0.000	0.000	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AF*	-1.20	-1.00	-0.86	-1.04	-1.11	-1.03	0.13	-1.18	-1.08	-1.04	-1.03	-1.00	-1.10	-0.86	-1.00	-0.86	-0.87	-0.97	-0.99
Mg [†]	0.31	0.32	0.31	0.38	0.31	0.32	0.03	0.36	0.40	0.36	0.37	0.37	0.36	0.35	0.33	0.39	0.40	0.40	0.37

*AF = $100(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2) / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2 + \text{FeO} + \text{MgO})$.

[†]Mg = $\text{MgO} / (\text{MgO} + \text{FeO})$.

[‡]1696 and 1747 = analyses for relatively Mg/Al-rich pumpellyites.

n.d. = not detected.

TABLE 2c. PUMPELLYITE ANALYSES FROM EASTERN BELT METABASITES (continued)

Sample	Standard deviation	1696 [§]	1696 [§]	1696 [§]	1696 [§]	Mean (4)	Standard deviation	1696	1696	Mean (2)	1747	1747	1747	1747	1747	1747	1747	1747	1747
SiO ₂	0.24	37.27	36.92	37.64	37.47	37.32	0.31	36.75	37.50	37.13	35.64	35.85	39.02	35.56	37.50	37.86	37.66	38.54	37.69
TiO ₂	0.04	n.d.	0.07	n.d.	n.d.	0.02	0.04	n.d.	n.d.	0.00	0.05	n.d.	0.03	0.04	0.04	n.d.	0.04	0.03	0.06
Al ₂ O ₃	0.26	25.00	24.69	24.92	25.02	24.91	0.15	23.30	24.50	23.90	19.75	19.00	19.08	20.77	22.68	22.11	22.54	22.86	18.36
FeO	0.39	5.56	5.34	5.30	4.34	5.14	0.54	7.89	6.31	7.10	10.15	11.69	9.90	8.46	6.98	8.26	6.58	6.76	12.09
MnO	0.09	0.14	0.19	0.25	0.27	0.21	0.06	0.12	0.15	0.13	0.15	0.11	0.13	0.12	n.d.	0.08	0.09	0.12	0.18
MgO	0.11	2.05	2.54	2.34	2.54	2.37	0.23	1.79	1.77	1.78	2.90	2.74	2.83	2.60	2.81	2.55	2.76	2.98	2.35
CaO	0.18	22.98	22.68	23.15	22.81	22.91	0.20	22.68	22.71	22.69	21.53	21.20	20.06	22.23	22.75	22.55	23.11	22.21	21.95
Na ₂ O	0.03	0.05	0.02	n.d.	0.02	0.02	0.02	n.d.	0.04	0.02	0.02	0.06	n.d.	0.04	0.08	0.03	0.04	0.05	0.04
K ₂ O	0.01	n.d.	n.d.	n.d.	n.d.	0.00	0.00	n.d.	n.d.	0.00	n.d.	0.04	0.03	0.07	0.13	n.d.	0.05	0.05	0.03
Total	0.55	93.05	92.45	93.60	92.47	92.89	0.55	92.53	92.98	92.75	90.19	89.89	91.08	89.89	92.97	93.44	92.87	93.60	92.75
Cations per 24.5 oxygens																			
Si	0.020	6.037	6.017	6.056	6.068	6.044	0.022	6.068	6.095	6.082	6.136	6.183	6.550	6.098	6.136	6.193	6.161	6.227	6.356
Ti	0.005	0.000	0.009	0.000	0.000	0.002	0.004	0.000	0.000	0.000	0.006	0.000	0.004	0.005	0.005	0.000	0.005	0.004	0.008
Al	0.042	4.774	4.744	4.727	4.777	4.755	0.024	4.536	4.695	4.616	4.009	3.863	3.776	4.199	4.375	4.264	4.347	4.355	3.650
Fe ²⁺	0.053	0.753	0.728	0.713	0.588	0.695	0.074	1.090	0.858	0.974	1.462	1.686	1.390	1.213	0.955	1.130	0.900	0.914	1.705
Mn	0.013	0.019	0.026	0.034	0.037	0.029	0.008	0.017	0.021	0.019	0.022	0.016	0.018	0.017	0.000	0.011	0.012	0.016	0.026
Mg	0.026	0.495	0.617	0.561	0.613	0.571	0.057	0.440	0.429	0.435	0.744	0.704	0.708	0.665	0.685	0.622	0.673	0.718	0.591
Ca	0.033	3.989	3.960	3.991	3.958	3.974	0.018	4.013	3.955	3.984	3.972	3.918	3.608	4.085	3.989	3.952	4.051	3.845	3.966
Na	0.009	0.016	0.006	0.000	0.006	0.007	0.006	0.000	0.013	0.006	0.000	0.020	0.000	0.013	0.025	0.010	0.013	0.016	0.013
K	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.009	0.006	0.015	0.027	0.000	0.010	0.010	0.006
AF*	0.09	-0.96	-0.81	-0.98	-0.94	-0.92	0.08	-0.94	-0.95	-0.95	-0.79	-0.74	-0.64	-1.07	-0.99	-0.92	-1.24	-0.78	-1.01
Mg†	0.02	0.40	0.46	0.44	0.51	0.45	0.05	0.29	0.33	0.31	0.34	0.29	0.34	0.35	0.42	0.35	0.43	0.44	0.26

*AF = $100(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2) / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2 + \text{FeO} + \text{MgO})$.†Mg = $\text{MgO} / (\text{MgO} + \text{FeO})$.

§1696 and 1747 = analyses for relatively Mg/Al-rich pumpellyites.

n.d. = not detected.

TABLE 2c. PUMPELLYITE ANALYSES FROM EASTERN BELT METABASITES (continued)

Sample	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	Mean (21)	Standard deviation	1747 [§]	1747 [§]	1747 [§]	1747 [§]	Mean (4)
SiO ₂	37.59	37.02	37.91	37.39	37.79	36.87	38.19	37.90	37.94	37.76	37.95	37.25	37.47	0.78	38.81	38.61	38.87	39.51	38.95
TiO ₂	n.d.	0.05	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.06	n.d.	0.02	0.02	0.02	n.d.	0.07	n.d.	0.03	0.03
Al ₂ O ₃	21.76	19.10	22.66	19.88	22.96	20.73	23.29	22.21	22.39	21.67	19.23	21.59	21.17	1.55	25.65	25.31	26.15	24.50	25.40
FeO	9.18	11.66	6.96	9.72	7.17	11.64	6.28	8.21	7.77	9.75	12.16	8.66	9.05	1.95	2.97	2.56	2.33	2.97	2.71
MnO	0.09	0.14	0.08	0.11	0.14	0.19	0.13	0.08	0.17	0.13	0.15	0.08	0.12	0.04	0.17	0.30	0.17	0.22	0.22
MgO	2.66	2.50	2.61	2.68	3.78	3.47	2.83	2.88	2.80	2.55	2.07	2.86	2.77	0.35	3.34	3.53	3.47	3.99	3.58
CaO	22.49	22.14	22.90	22.46	21.69	20.90	22.97	22.31	21.71	22.69	21.93	22.48	22.11	0.73	22.59	22.33	22.42	22.17	22.38
Na ₂ O	0.05	0.09	0.06	0.06	0.06	0.07	0.02	n.d.	n.d.	0.07	n.d.	n.d.	0.04	0.03	n.d.	n.d.	n.d.	0.05	0.01
K ₂ O	0.03	0.03	0.02	0.02	0.07	0.02	0.02	n.d.	n.d.	n.d.	0.03	n.d.	0.03	0.03	n.d.	0.02	n.d.	n.d.	0.01
Total	93.85	92.73	93.20	92.32	93.66	93.89	93.73	93.59	92.78	94.68	93.52	92.94	92.78	1.13	93.53	92.73	93.41	93.44	93.28
Cations per 24.5 oxygens																			
Si	6.158	6.241	6.180	6.262	6.120	6.106	6.164	6.182	6.215	6.152	6.333	6.151	6.205	0.10	6.143	6.155	6.133	6.253	6.171
Ti	0.000	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.002	0.002	0.000	0.000	0.008	0.000	0.004	0.003
Al	4.203	3.796	4.355	3.925	4.384	4.047	4.432	4.271	4.324	4.162	3.783	4.203	4.133	0.24	4.786	4.757	4.864	4.571	4.745
Fe ²⁺	1.258	1.644	0.949	1.361	0.971	1.612	0.848	1.120	1.065	1.329	1.697	1.196	1.253	0.29	0.393	0.341	0.307	0.393	0.359
Mn	0.012	0.020	0.011	0.016	0.019	0.027	0.018	0.011	0.024	0.018	0.021	0.011	0.016	0.01	0.023	0.041	0.023	0.029	0.029
Mg	0.649	0.628	0.634	0.669	0.912	0.856	0.681	0.700	0.684	0.619	0.515	0.704	0.684	0.08	0.788	0.839	0.816	0.941	0.846
Ca	3.948	4.000	4.000	4.030	3.764	3.709	3.973	3.899	3.811	3.961	3.922	3.978	3.923	0.12	3.831	3.814	3.791	3.759	3.799
Na	0.016	0.029	0.019	0.019	0.019	0.022	0.006	0.000	0.000	0.022	0.000	0.000	0.013	0.01	0.000	0.000	0.000	0.015	0.004
K	0.006	0.006	0.004	0.004	0.014	0.004	0.004	0.000	0.000	0.000	0.006	0.000	0.007	0.01	0.000	0.004	0.000	0.000	0.001
AF*	-0.83	-0.97	-1.11	-1.11	-0.52	-0.45	-1.01	-0.77	-0.66	-0.86	-0.90	-0.87	-0.84	0.20	-0.69	-0.69	-0.58	-0.68	-0.66
Mg [†]	0.34	0.28	0.40	0.33	0.48	0.35	0.45	0.38	0.39	0.32	0.23	0.37	0.35	0.06	0.67	0.71	0.73	0.71	0.70

*AF = $100(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2) / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2 + \text{FeO} + \text{MgO})$.†Mg = $\text{MgO} / (\text{MgO} + \text{FeO})$.

§1696 and 1747 = analyses for relatively Mg/Al-rich pumpellyites.

n.d. = not detected.

TABLE 2c. PUMPELLYITE ANALYSES FROM EASTERN BELT METABASITES (continued)

Sample	Standard deviation	2318	2318	Mean (2)
SiO ₂	0.38	39.90	37.32	38.61
TiO ₂	0.03	n.d.	n.d.	0.00
Al ₂ O ₃	0.67	21.80	22.55	22.18
FeO	0.27	8.47	9.04	8.76
MnO	0.05	0.11	0.10	0.11
MgO	0.24	1.47	1.73	1.60
CaO	0.11	20.73	22.36	21.55
Na ₂ O	0.02	0.42	0.13	0.28
K ₂ O	0.01	n.d.	n.d.	0.00
Total	0.33	92.90	93.23	93.07
Cations per 24.5 oxygens				
Si	0.05	6.502	6.144	6.324
Ti	0.000	0.000	0.000	0.000
Al	0.12	4.188	4.376	4.282
Fe ²⁺	0.04	1.154	1.245	1.199
Mn	0.01	0.015	0.014	0.015
Mg	0.06	0.357	0.424	0.391
Ca	0.02	3.620	3.944	3.781
Na	0.01	0.133	0.041	0.087
K	0.000	0.000	0.000	0.000
AF*	0.05	-0.83	-0.90	-0.87
Mg†	0.01	0.24	0.25	0.25

*AF = $100(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2) / \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - 0.75\text{CaO} - \text{Na}_2\text{O} + 0.75\text{TiO}_2 + \text{FeO} + \text{MgO}$.
†Mg = $\text{MgO} / (\text{MgO} + \text{FeO})$.
‡1696 and 1747 = analyses for relatively Mg/Al-rich pumpellyites.
n.d. = not detected.

Al-rich pelites should typically be large, in order to accommodate the "statistical" approach to use of this method (Sassi and Scolari, 1974; Guidotti and Sassi, 1976). The geobarometric application of the b_0 parameter is only valid when other factors (e.g., grade, $a_{\text{H}_2\text{O}}$, composition) are equal. However, although the samples are small in number, they have similar IC values (i.e., grade), were typical pelites, and, from the general mineralogical scans, were judged to have high phyllosilicate content and to be free of carbonate and K-feldspar. This suggests that the samples are of similar compositions and represent the most suitable pelitic material on which such analysis should be undertaken.

Results

Results of the current investigation are presented below for the various samples studied. The data are described in relation to the tectonic block from which the samples were collected, from the highest to the lowest structural level (i.e., from west to east).

Butt Valley block. Ten samples were investigated from the Butt Valley block. The oldest rocks in this block are Devo-

TABLE 3. ILLITE CRYSTALLINITY (IC) AND b_0 VALUES FOR PELITIC SAMPLES FROM THE EASTERN BELT

Sample	IC Value ($\Delta^*2\theta$)	b_0 Value (Å)
BUTT VALLEY BLOCK		
Unnamed Triassic and Permian (of Harwood, 1992)		
1661	0.187	9.041
1662	0.185	9.045
1663	0.186	9.039
1699	0.205	9.048
1700	0.211	9.039
1746	0.194	9.022
Unnamed Jurassic and Triassic (of Harwood, 1992)		
1751	0.230	9.038
1752	0.236	9.034
HOUGH BLOCK		
Shoo Fly Complex		
1666	0.226	
1669	0.150	
1670	0.212	
1671	0.206	9.027
1672	0.208	
1674	0.190	
1679	0.188	
1680	0.203	9.031
1681	0.174	
1748	0.195	
1749	0.192	9.010
1750	0.180	
1754	0.184	9.027
1755	0.176	
1756	0.198	
1778	0.183	9.013
1780	0.214	9.049
1782	0.172	
1783	0.200	
1788	0.173	
Peale Formation		
1695	0.189	
Arlington Formation		
1690	0.199	9.042
KEDDIE RIDGE BLOCK		
Shoo Fly Complex		
1753	0.195	
MT. JURA BLOCK		
Unnamed Jurassic volcanic and volcanoclastics (of Harwood, 1992)		
1768	0.186	
1769	0.260	
1770	0.294	
1772	0.460	
KETTLE ROCK BLOCK		
Unnamed Jurassic volcanic and volcanoclastics (of Harwood, 1992)		
1771	0.390	
GENESEE BLOCK		
Peale Formation		
1765	0.219	
2309	0.236	

nian to Early Mississippian arc volcanics belonging to the Sierra Buttes and Taylor formations. Diagnostic calc-silicate minerals and actinolite are generally absent from volcanic rocks of the Sierra Buttes Formation in the northern part of the Eastern belt, chiefly because of their silicic nature, although prehnite, pumpellyite, and actinolite have all been reported from the Gold Lake area farther south (Brooks, 1992). In this study, however, actinolite was recorded in andesitic rocks of the Sierra Buttes Formation exposed on the East Branch of the North Fork of the Feather River, east of Virgilia (Fig. 1). In addition, actinolite has been identified in a metabasite sample from the Taylor Formation exposed near Caribou, on the North Fork of the Feather River. This sample (1747) has a strong penetrative foliation, defined by actinolite and chlorite (Fig. 3A), that strikes approximately northwest-southeast (i.e., Nevadan in orientation). In the same sample pumpellyite is present in three forms: (1) it forms circular to ovate spongy aggregates up to 0.3 mm across (Fig. 3B), around which the foliation wraps, that show complex variations in Fe and Al contents (see Fig. 4), although the rims are typically Al-rich; (2) pumpellyite occurs forming rare "s" shaped aggregates (Fig. 3C) that show elongation along the foliation; and (3) Mg/Al-rich pumpellyite occurs as radially oriented needles (Figs. 3, D and E, and 5) rimming relatively Fe-rich cores, and also discrete Mg/Al-rich crystals that are oriented at a slightly oblique angle (25° in Fig. 5) to the foliation. These textural relations are interpreted as reflecting the growth of pumpellyite prior to the development of the foliation defined by actinolite and chlorite, its continued growth during the development of the foliation, and finally the crystallization of pumpellyite after the foliation minerals had developed.

Southwest of Lake Almanor, a sequence of limestones, graywackes, slates, metabasites, and conglomerates of Permian to Jurassic age (Jayko, 1988, 1990; Harwood, 1992), exposed in two tectonic slivers (one of Late Triassic age, and the other of Late Triassic [?] to Early Jurassic age), has been correlated previously with the Arlington Formation (D'Allura et al., 1977). However, a revision of the age of the Arlington Formation as Early Permian (see Harwood, 1992) means that the original correlation is not tenable. Six pelitic samples from the Late Triassic age sliver have epizone IC values in the range 0.185–0.211 $\Delta^\circ 2\theta$, with a mean value of 0.195 ($1\sigma = 0.011$), and two samples from the second sliver, of Late Triassic(?) to Early Jurassic age, have slightly higher values of 0.230 and 0.236 $\Delta^\circ 2\theta$, equating broadly with metamorphic conditions close to the anchizone-epizone boundary. Values for b_0 are indistinguishable from the two slivers; the mean is 9.038 Å ($1\sigma = 0.009$) for eight samples.

Hough block. We investigated 41 samples from the various stratigraphic units exposed in the Hough block.

The oldest rocks in this block are pelites and psammites of the Shoo Fly Complex. About 20 pelite samples were investigated for illite crystallinity and b_0 (see Table 3). IC values show little variation and no regional pattern in crystallinity has

been detected. All values are of epizone grade, with a mean $\Delta^\circ 2\theta = 0.191$ ($1\sigma = 0.018$). Epizone crystallinities equate broadly with greenschist facies assemblages in metabasites. All epizone pelites in this area are dominated by quartz, illite, and chlorite, along with variable but minor amounts of feldspar, calcite, and rutile. No other minerals of the kind often reported in low-grade pelites, such as paragonite, paragonite-muscovite, and pyrophyllite, as in studies from the Welsh basin (Merriman and Roberts, 1985; Robinson and Bevins, 1986), were found in any of the Eastern belt pelitic rocks. A mean b_0 for six samples from the Shoo Fly Complex (Table 3) is 9.026 Å ($1\sigma = 0.014$).

Devonian to Permian arc volcanic and related sedimentary rocks of the Taylor, Peale, and Arlington formations unconformably overlie the Shoo Fly Complex in the Hough block. Metabasites and metabasic tuffs of the Taylor Formation in the Hough block contain assemblages dominated by chlorite, actinolite, and epidote, along with minor pumpellyite. As in the Butt Valley block, a strong foliation is present, the orientation of which is also Nevadan (i.e., northwest-southeast). Pumpellyite is found most commonly in plagioclase and clinopyroxene crystals, lithic clasts, and deformed vesicles, or in pressure-shadow regions, and forms spongy aggregates in the groundmass.

A single pelite specimen analyzed from the Peale Formation of the Hough block gave an IC value of 0.189 $\Delta^\circ 2\theta$ (i.e., epizone grade).

Metabasites and metabasic tuffs of the Arlington Formation, like those in the Taylor Formation, are strongly foliated, and contain chlorite, actinolite, epidote, and pumpellyite. A single pelite from the Arlington Formation gave an IC value of 0.199 $\Delta^\circ 2\theta$ (i.e., epizone grade), with a b_0 value of 9.042 Å.

Grizzly block. The Grizzly block comprises primarily rocks of the Sierra City melange of the Shoo Fly Complex, and there are no rocks appropriate for low-grade studies. A dioritic mass northwest of Taylorsville, which is probably of pre-Devonian age, contains abundant, randomly oriented actinolite, indicative of greenschist facies metamorphism, although the relation of this intrusion to rocks of the Sierra City melange is not clear.

Keddie Ridge block. We investigated 14 samples from the Keddie Ridge block, which comprises a sequence broadly similar to that of the Hough block. The oldest strata are those of the Shoo Fly Complex; they are overlain unconformably by Devonian to Permian arc volcanic and related sedimentary rocks of the Sierra Buttes, Taylor, Peale, Reeve, and Robinson formations.

A single pelitic specimen from the Shoo Fly Complex on the eastern shores of Lake Almanor, assumed to belong to the Keddie Ridge block, gave an epizone IC value of 0.195 $\Delta^\circ 2\theta$, which is almost identical to the mean of 20 pelites from the Hough block (see above).

Metabasites from the Taylor and Reeve formations, however, contrast markedly with those from the Hough block.

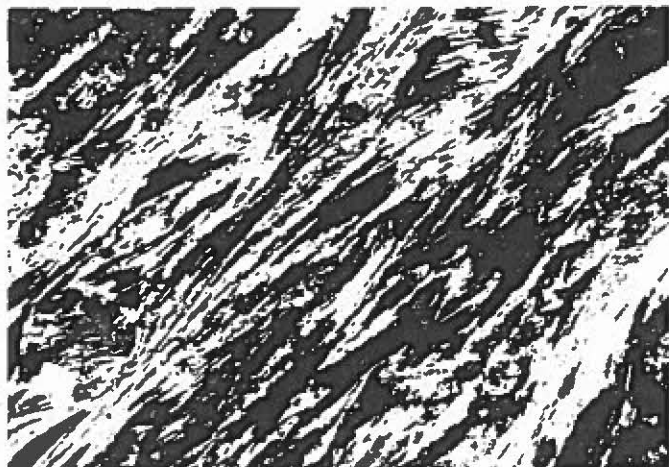
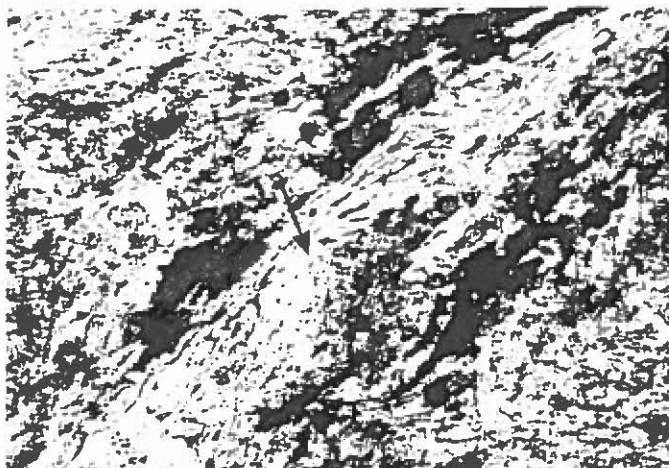
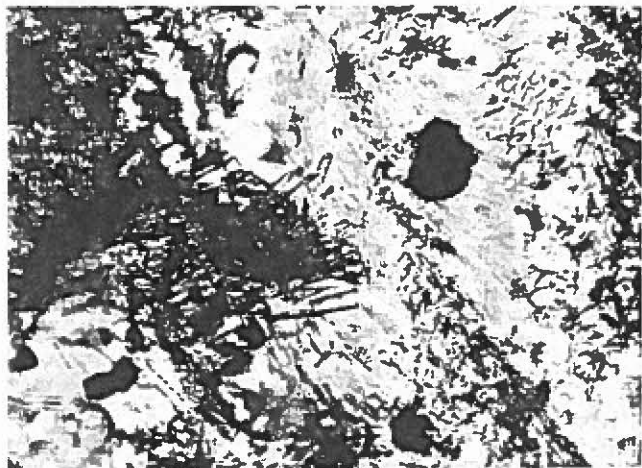
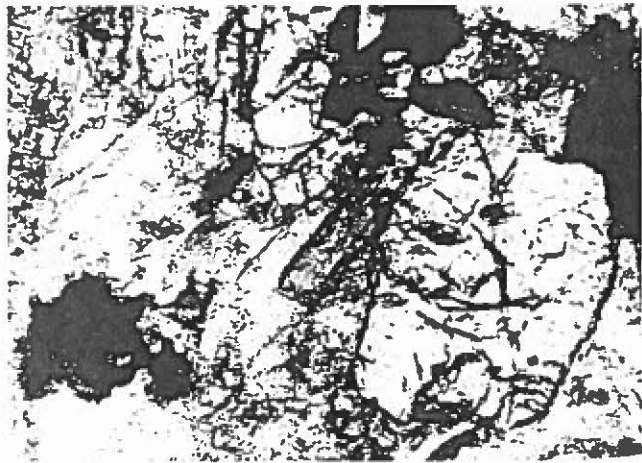
**A****B****C****D****E****F**



Figure 4. Back-scatter scanning electron microscope image of spongy pumpellyite aggregate in sample 1747 from the Taylor Formation, near Caribou, showing complex variations in composition. The lighter areas are relatively richer in Fe, whereas the darker areas are richer in Al. Scale indicated in photomicrograph. Note the chlorite (dark gray) and actinolite (white) wrapping around the aggregate.

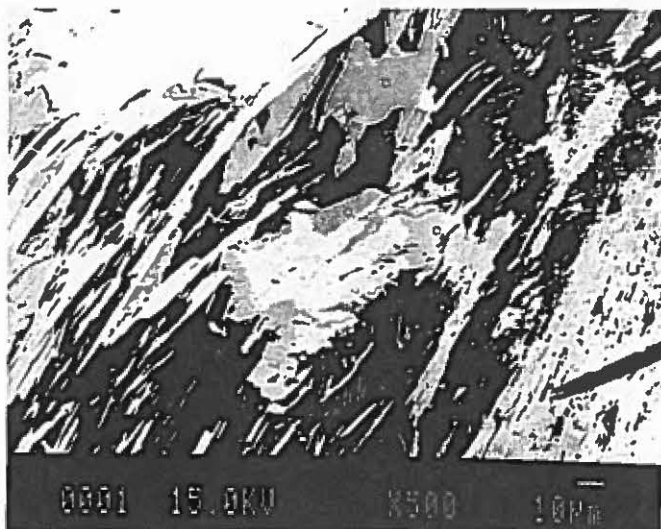


Figure 5. Back-scatter scanning electron microscope image (detail from Fig. 3E) of a zoned pumpellyite crystal (center) from sample 1747 from the Taylor Formation, near Caribou, showing relatively Fe rich core (light area) and relatively Mg/Al rich rim (darker area). Notice the tendency for the Mg/Al-rich pumpellyite to be oriented randomly in relation to the foliation, defined by actinolite (white) and chlorite (similar gray to Mg/Al-pumpellyite). The black is predominantly quartz. The large gray crystal at center top is an Mg/Al-rich pumpellyite that has also grown at an angle oblique to the foliation. Scale indicated in photomicrograph.

They lack the strong foliation present in rocks of the Hough block and igneous textures are typically preserved (Fig. 3F); in addition, mineral assemblages in the Keddie Ridge block metabasites lack actinolite, whereas prehnite, pumpellyite, and chlorite are present. These findings are in accord with the investigation of Hannah (1980).

Mt. Jura block. Seven specimens were collected from the Jurassic volcanic, volcanoclastic, and sedimentary rocks of the Mt. Jura block. The volcanic and volcanoclastic rocks are intermediate to acid in composition, and hence lack any diagnostic secondary mineral assemblages. Plant-bearing shales from the Beardsley Grade, north of Mt. Jura (Fig. 1), have a mineralogy distinct from that of the older pelitic rocks in that

they are characterized by illite and chlorite that contain variable amounts of mixed layering. IC values are generally indicative of low anchizone to diagenetic grade, which contrasts with the epizone grade for the pre-Mesozoic rocks.

Genesee block. We investigated 26 specimens from the Genesee block. Like those of the Keddie Ridge block, volcanic and related rocks of the Taylor, Peale, Goodhue, Reeve, and Robinson formations of the Genesee block are little deformed, and have secondary mineral assemblages containing prehnite, pumpellyite, and epidote, but lacking actinolite. In the Little Grizzly Creek area, to the south of Genesee, and even farther south, around Clio, the volcanic and related intrusive metabasic rocks are in close proximity to the Sierra Nevada batholith; contact metamorphic, randomly oriented biotite and green amphibole are developed in abundance and overprint original igneous textures, as well as the effects of any earlier metamorphic events.

Two epizone IC values, of 0.219 and 0.236 $\Delta^{\circ}2\theta$, were recorded from pelite samples from the Peale Formation in the Genesee block (Table 3).

Kettle Rock block. Two specimens were collected from the Kettle Rock block. Like those of the Mt. Jura block, Jurassic volcanic rocks of the Kettle Rock block are chiefly silicic, and lack diagnostic secondary mineral assemblages. A single pelite specimen gave a diagenetic IC value of 0.390 $\Delta^{\circ}2\theta$ (Table 3).

Figure 3. Photomicrographs showing the mode of occurrence of critical secondary minerals in metabasites from the Eastern belt. A: Actinolite (light) and chlorite (dark) forming the Nevadan foliation. Sample 1747. Taylor Formation, Caribou. Crossed polarized light. Field of view is 0.67 mm across. B: Spongy pumpellyite crystal associated with chlorite. Sample 1747. Details as in A, but plane polarized light. Field of view is 0.45 mm across. C: "S" shaped pumpellyite aggregate (arrowed center) elongated along the Nevadan foliation. Sample 1747. Details as in A, but plane polarized light. Field of view is 0.40 mm across. D: Fe-rich pumpellyite (core of crystal at left center) overgrown by colorless Mg/Al-rich pumpellyite. Sample 1747. Details as in A, but plane polarized light. Field of view is 0.35 mm across. E: Fe-rich pumpellyite (center) overgrown by colorless, radiating Mg/Al-rich pumpellyite needles and also a discrete colorless Mg/Al-rich pumpellyite crystal (center above). Note that both overgrow the Nevadan foliation. Details as above, but plane polarized light. Field of view is 0.42 mm across. F: Pumpellyite (dark crystal, center) in metabasite sample 2318 from the Taylor Formation, Keddie Ridge. Note the lack of any foliation in the rock. Plane polarized light. Field of view is 0.44 mm across.

MINERAL PARAGENESES IN EASTERN BELT METABASITES

The extensive biotite and green amphibole in metabasites of the Eastern belt that are exposed along its eastern margin result from contact metamorphism by the Sierra Nevada batholith. This intrusive complex, of Late Jurassic to Cretaceous age, appears to overprint the effects of any earlier regional metamorphic events. To the west, Paleozoic arc volcanic rocks in the Butt Valley and Hough blocks contain actinolite and pumpellyite, whereas only pumpellyite and prehnite are found in the Keddie Ridge and Genesee blocks. The time at which the actinolite, pumpellyite, and prehnite formed is critical, as is whether they are related to one or more metamorphic events. Petrographic evidence presented above has highlighted that pumpellyite in the Butt Valley and Hough blocks occurs typically in spongy aggregates, feldspar phenocrysts, lithic clasts, deformed vesicles, or pressure-shadow regions; it is also found in the foliation, which is defined chiefly by actinolite and chlorite, as well as locally growing across the foliation. Chlorite and actinolite analyses (Table 2, a and b) show relatively restricted compositions, with low standard deviations. In contrast, pumpellyite analyses (Table 2c) show more variable compositions that can be related mainly to the varying forms described above.

In order to establish more fully the relations between pumpellyite, prehnite, actinolite, and chlorite in Paleozoic rocks of Eastern belt, these phases were investigated using chemographic projections, which offer the potential of identifying equilibrium mineral assemblages. Typically the analyzed metabasites contain albite + chlorite + quartz + titanite, in addition to one or more of the following: epidote, actinolite, prehnite, and pumpellyite; assemblages in the analyzed metabasites are listed in Table 4. This mineral assemblage can be approximated by the eight component system $\text{Na}_2\text{O}-\text{MgO}-(\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3)-\text{SiO}_2-\text{CaO}-\text{FeO}-\text{TiO}_2-\text{H}_2\text{O}$, which allows projection of phase relations in two dimensions from epidote onto the image plane 'AF' – $\text{MgO}/(\text{MgO} + \text{FeO})$, similar to projections by Harte and Graham (1975) and Laird (1980). This particular projection has been utilized recently by Springer et al. (1992) in their investigations on the Smartville Complex.

Figure 6 shows AF' – $\text{MgO}/(\text{MgO} + \text{FeO})$ projections for metabasites from the Butt Valley (sample 1747), Hough (samples 1683, 1696, and 1776), and Keddie Ridge (sample 2318) blocks. Although the tie lines show a general internal consistency, the three-phase assemblage in this projection should represent a divariant assemblage. The crossing tielines might therefore be taken as evidence of disequilibrium. However, as mentioned above, Fe_2O_3 is combined with Al_2O_3 as a single component, whereas in the analyses of the three phases, Fe is treated as FeO. In the cases of pumpellyite and chlorite, and less so for actinolite, this simplification is to some extent unsatisfactory. In order to make correction for this feature, Springer et al. (1992) and Beiersdorfer (1993) considered vari-

TABLE 4. MINERAL ASSEMBLAGES IN METABASITE SAMPLES
SELECTED FOR ELECTRON MICROPROBE ANALYSIS

Sample	Block	Relict minerals*	Metamorphic minerals* (+Ab+Ttn+Qz+Wm)
1683	Hough	Cpx	Chl+Act+Pmp+Ep
1696	Hough	Cpx	Chl+Act+Pmp+Ep
1747	Butt Valley	Cpx	Chl+Act+Pmp+Ep
1776	Hough	Cpx	Chl+Act+Pmp+Ep
2318	Keddie Ridge	Cpx	Chl+Pmp+Prh+Cc

*Cpx = clinopyroxene; Chl = chlorite; Act = actinolite; Pmp = pumpellyite; Prh = prehnite; Ep = epidote; Ab = albite; Ttn = titanite; Qz = quartz; Wm = white mica.

ous recalculation schemes to estimate possible contents of $\text{Fe}^{3+}/\text{Fe}^{2+}$ in pumpellyite and actinolite. Although the values of calculated ferrous and ferric iron in pumpellyite are subject to considerable error, Springer et al. (1992) argued that such treatment was better than assumption of a single iron component in pumpellyite. Springer et al. (1992) thus used recalculated pumpellyite Fe ratios in their epidote projections, although they retained FeO as the only variety in chlorite and actinolite. This approach was also adopted by Beiersdorfer (1993), although his conclusion was that the interpretations based on mineral projections remained the same no matter what assumption of Fe content in pumpellyite. Here we have chosen to retain iron in all phases as FeO, rather than generate further distortion by application of an imperfect correction to only one of the three phases, when Fe^{3+} will be present to some degree in both other phases, and possibly to as high a ratio in chlorite as in pumpellyite. Whatever the merits of applying Fe^{3+} estimations to one or none of the phases, Fe^{3+} no doubt enters the system to some degree but its presence is not accommodated in the chosen projection. Ferric iron treated as a separate component will result in some phases plotting out of the plane of the projection, and accordingly the crossing tielines seen may well be the result of this feature.

Actinolite-chlorite tielines in samples 1683, 1696, 1776, and 1747 from the Butt Valley and Hough blocks are nearly parallel with a range in $K_d^{\text{Mg-Fe}}$ values of 1.73–1.82 (mean = 1.76). This is very similar to the K_d of ca. 1.72 for pumpellyite-actinolite facies rocks from Loèche reported by Coombs et al. (1976), from Wakatipu, reported by Kawachi (1975), and also for pumpellyite-actinolite facies rocks from the central part of the Western belt of the Sierra Nevada, which have a mean $K_d^{\text{Mg-Fe}}$ value of 1.76 (data from Beiersdorfer, 1993).

In contrast, pumpellyite-chlorite tielines are more complex. Two samples from the Hough block, 1683 and 1776, have nearly parallel, positive tielines (Fig. 6), reflected in $K_d^{\text{Mg-Fe}}$ values of 0.56 and 0.60, respectively. These data suggest that these mineral pairs are in equilibrium, and by inference therefore the pumpellyite is in equilibrium with actinolite

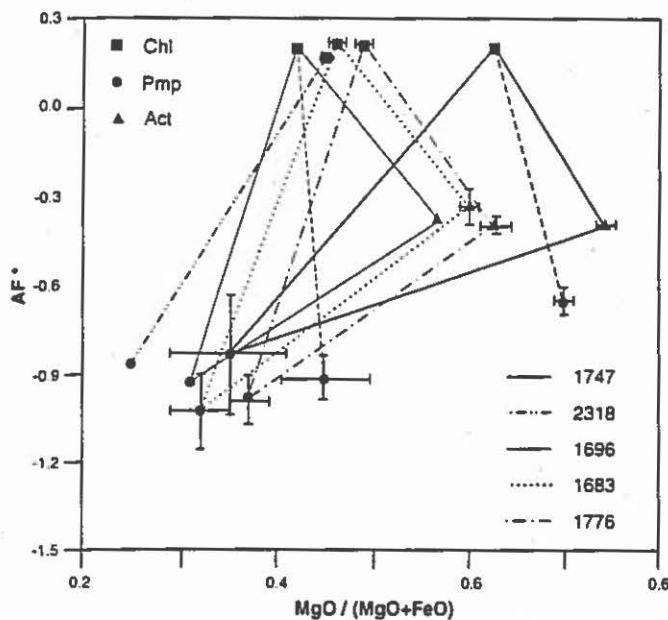


Figure 6. Epidote projection for metabasite samples from the Eastern belt. Tielines are for means of analyses from individual samples. Dashed tielines indicate a later generation of Mg-Al pumpellyite. Chl = chlorite; Pmp = pumpellyite; Act = actinolite. Error bars are for 1 σ standard deviation. $AF^* = 100 (Al_2O_3 + Fe_2O_3 - 0.75 CaO - Na_2O + 0.75 TiO_2) / (Al_2O_3 + Fe_2O_3 - 0.75 CaO - Na_2O + 0.75 TiO_2 + FeO + MgO)$.

in these rocks. This is interpreted as being part of a pumpellyite-actinolite facies assemblage.

More complicated patterns are seen for samples 1696, 1747, and 2318. In sample 1696, the mean of two analyses for relatively Fe rich pumpellyite (Table 2c) results in a tieline with associated chlorite that is positive and nearly parallel to that for pumpellyite-chlorite pairs ($K_d^{Mg-Fe} = 0.61$) in samples 1683 and 1776. This implies that this association is also part of the pumpellyite-actinolite facies assemblage. In contrast, relatively Mg/Al rich pumpellyite analyses from the same sample result in a slightly negative slope to the chlorite-pumpellyite tieline shown as a dashed line in Figure 6, and reflected in a K_d^{Mg-Fe} value of 1.12. Unfortunately, the spongy pumpellyite aggregates that give these contrasting pumpellyite compositions are too small to enable detection of textural relations between the two varieties.

In sample 1747, from the Butt Valley block, spongy pumpellyite aggregates (Figs. 3B and 4) clearly show complex compositional patterns, reflecting minor chemical zoning of each radiating spherule in the aggregate; this is most evident in back scattered electron images, as illustrated in Figure 4. The compositional zoning in these spongy aggregates is from relatively Fe rich cores to relatively Al rich rims. The tieline to the mean analysis for these aggregates is represented by the positive slope for sample 1747 in Figure 6, which has a shallower slope than tielines for the pumpellyite-actinolite facies mineral pairs described above, and is reflected in a lower

K_d^{Mg-Fe} value of 0.32. Calculation of K_d^{Mg-Fe} values for core and rim compositions actually show little variation, being 0.32 and 0.28, respectively, in the chosen example. However, the mean tieline slope and K_d^{Mg-Fe} value of sample 1747 are very close to those from sample 2318 ($K_d^{Mg-Fe} = 0.39$) from the Keddie Ridge block. In the undeformed rocks from Keddie Ridge, such as sample 2318, pumpellyite occurs in association with prehnite, and, because of a lack of deformation, is attributed to the effects of burial. Accordingly, it might be that the cores of the spongy aggregates from sample 1747 are remnants of pumpellyite that grew at an early, predeformation stage and that were overgrown later, during deformation, by a more Al-rich pumpellyite. Nevertheless, Bevins and Robinson (1993) gave examples of pumpellyite-chlorite tielines that have shallower slopes in the AF^* versus $MgO/(MgO + FeO)$ diagram from subgreenschist metabasites that have high (>0.53) $MgO/(MgO + FeO)$ ratios in chlorite, and sample 1747 has a markedly higher $MgO/(MgO + FeO)_{Chl}$ ratio (0.63) than the other analyzed samples (see Table 2a and Fig. 6). Therefore it is possible that the pumpellyites in sample 1747 are actually in equilibrium with associated chlorite and actinolite, despite their low K_d values, and that they are part of the pumpellyite-actinolite facies assemblage. A tieline between the colorless Mg/Al-rich pumpellyites and associated chlorite in sample 1747 (dashed line, Fig. 6) has a slope opposite to those for the Fe-rich pumpellyite in the same sample, with a K_d^{Mg-Fe} of 1.39, broadly similar to that for the Mg/Al-rich pumpellyites in sample 1683. The marked difference in composition is also seen in the Al-Fe*-Mg diagram (Fig. 7), the Mg/Al-rich pumpellyites in 1747 plotting away from the more Fe-rich pumpellyites. These Mg/Al-rich pumpellyites are not part of the pumpellyite-actinolite facies assemblage, a consideration supported by the textural evidence for their growth at a later stage than the main actinolite-bearing assemblage (Fig. 3E). Hence they appear to be of posttectonic age.

METAMORPHIC EVOLUTION OF THE EASTERN BELT

From the results presented above it is clear that different parts of the stratigraphic sequence exposed in the Eastern belt have been affected by contrasting conditions of low-grade metamorphism, with abrupt breaks in grade across tectonic boundaries. The breaks indicate that metamorphism occurred prior to imbrication of the sequences in Middle to Late Jurassic time. However, contact metamorphism occurred after the imbrication, because granitoid intrusions of the Sierra Nevada batholith crosscut the various tectonic slices. More detailed information, available from geologic and petrological evidence, indicates that rocks of the Eastern belt have been subjected to more than one episode of low-grade regional metamorphism. These episodes are described below, considering first metamorphism of the older Shoo Fly Complex sequences, followed by discussion of the various episodes of regional

Eastern belt pumpellyites

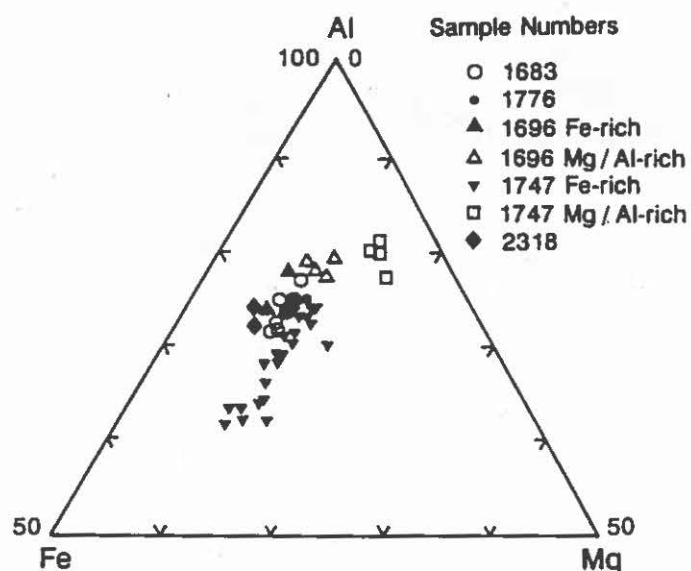


Figure 7. Al-Fe-Mg diagram for pumpellyites from metabasites of the Eastern belt.

metamorphism that have affected the Paleozoic and Mesozoic arc volcanic and related rocks.

Metasedimentary rocks of the Shoo Fly Complex in the Hough and Genesee blocks are overlain unconformably principally by the younger arc volcanics and were almost certainly metamorphosed under epizone-grade conditions in pre-Devonian time. This is indicated principally by the occurrence of foliated metasedimentary clasts of Shoo Fly type in the lower part of the Devonian succession elsewhere in the Eastern belt (Varga and Moore, 1981). In addition, however, from b_0 studies it has been shown in this study that rocks of the Shoo Fly Complex have undergone intermediate-pressure Barrovian-type metamorphism with a mean b_0 of 9.026 Å. This contrasts with the markedly higher b_0 values for pelites associated with the younger arc volcanic rocks of the Butt Valley and Hough blocks; the pelites are indicative of higher pressures of metamorphism because they have the same mean b_0 value as reported from the Otago Schists (9.039 Å; Sassi and Scolari, 1974). It is clear that the Shoo Fly Complex underwent different conditions of metamorphism than the overlying arc rocks.

Rocks younger than those of the Shoo Fly Complex have undergone at least three episodes of low-grade regional metamorphism at greenschist to subgreenschist facies levels, the grade varying between the various tectonic slivers. Locally, in the east, these effects have been overprinted by contact metamorphism as a result of emplacement of the Sierra Nevada batholith granitoids. The earliest event is seen most obviously in the undeformed arc volcanic rocks of the Keddie Ridge and Genesee blocks. Metabasite mineral assemblages are diagnos-

tic of the prehnite-pumpellyite facies. In the absence of any signs of deformation, we attribute this metamorphism to the effects of burial, although the timing of this event is difficult to determine any more closely than being younger than the Reeve Formation (mid-Permian), but older than the age of thrusting (Middle to Late Jurassic), because abrupt breaks in metamorphic grade are seen across the thrust contacts.

In the Mt. Jura and Kettle Rock blocks, Jurassic mudstones associated with arc volcanics show only very low grades of metamorphism, generally in the diagenetic zone to lower anchizone. In the absence of any signs of deformation, this metamorphism is attributed to the mild effects of burial in Early to Middle Jurassic time. It is possible that it is the same event that was responsible for metamorphism of the earlier arc volcanic rocks of the Keddie Ridge and Genesee blocks, although this cannot be established firmly with the data currently available.

The following metamorphic event is reflected in the pumpellyite-actinolite facies assemblages in metabasites of the Butt Valley and Hough blocks. Such assemblages are characteristic of intermediate to high pressures, and textural evidence indicates that metamorphism occurred coincident with the development of the Nevadan foliation, that is in Middle to Late Jurassic time. This is supported by the fact that associated pelitic rocks in these blocks have relatively high b_0 values ($x = 9.039$ Å) similar to the intermediate- to high-pressure Otago-type facies series. It is reasonable to assume that these reflect a single metamorphic event, which on the basis of stratigraphic evidence occurred post-Early Jurassic (the youngest age of strata exposed in the Butt Valley block).

As described earlier, Fe-rich cores of spongy pumpellyite aggregates in the Devonian Taylor Formation metabasites in the Butt Valley and Hough blocks may well relate to an earlier metamorphic event, possibly the early (pre-Nevadan) burial event detected in the Keddie Ridge and Genesee block metabasites. This is suggested by the nearly parallel pumpellyite-chlorite tielines in Figure 6 for sample 2318 (Taylor Formation, Keddie Ridge) and the Fe-rich pumpellyite cores in sample 1747 (Taylor Formation, Butt Valley block).

The final regional metamorphic event is indicated in sample 1747 (and possibly also in sample 1696) by the presence of Mg/Al-rich pumpellyite crystals, either radially overgrowing Fe-rich cores, or forming discrete Mg/Al-rich pumpellyite crystals that grow at an angle oblique to the strong Nevadan foliation defined by actinolite and chlorite. These growth patterns indicate that the Mg/Al-rich pumpellyites are not pre-tectonic or syntectonic: in the former case they might have been expected to be seen only in pressure shadow regions, whereas in the latter case they would tend to be elongated along the foliation; hence they are considered to be post-tectonic. A post-foliation genesis is further indicated by the very delicate nature of these Mg/Al-rich pumpellyite crystals (Fig. 3, D and E), which would not have remained unaffected by the processes leading to generation of the strong foliation during the Nevad-

an orogeny. We consider, therefore, that they represent a further stage of metamorphic recrystallization.

Either coincident with or possibly slightly later than the development of the Nevadan foliation and metamorphism, the area was disturbed by thrusting. The effects of this are seen clearly; important breaks in metamorphic grade are recorded across major faults, which have been interpreted by Day et al. (1985) as eastward-directed thrusts. Those units originally from the deepest structural levels are exposed in the west and record the highest grades and show the strongest deformation effects, whereas those originally from the highest structural levels, exposed in the east, record the lowest grades and are relatively little deformed. Imbrication of the succession during Middle to Late Jurassic time led to inversion of the succession, leading to the current disposition; i.e., the highest grades are now seen in rocks of the highest structural levels, whereas the lowest grades occur in rocks of the lowest structural levels. Such inversion has been reported in low-grade belts from a number of other orogenic regions, such as the Caledonides of Finnmark, North Norway (Rice et al., 1989).

It would be possible to produce the current disposition of the various blocks of country rocks with contrasting metamorphic patterns simply by strike-slip movements along the two major faults. However, the similarity of the various Paleozoic arc successions exposed in the different blocks leads us to favor the simple interpretation of an inverted metamorphic sequence related to thrusting, the contrasting metamorphic grades relating to depth of burial and subsequent tectonic effects.

Finally, an interesting problem arises from a comparison of metamorphic conditions determined for pelitic rocks of the Shoo Fly Complex and those of the younger arc volcanic sequences in the Butt Valley and Hough blocks. Rocks of the Shoo Fly Complex are thought to be overlain unconformably by the younger arc volcanic rocks, yet they preserve a regional Barrovian-style of metamorphism (similar grades and character of metamorphism have been detected by the authors as far south as the North Yuba River), whereas in the overlying rocks an Otago-type metamorphism is recorded. It seems unlikely that the earlier Barrovian metamorphism would have been unaffected by the later, higher pressure metamorphic episode if the two sequences had been juxtaposed at that time. Whether the data reflect a real difference in metamorphic grade, however, remains to be determined.

CONCLUSIONS

Rocks of the Eastern belt of the northern Sierra Nevada have undergone low-grade polygenetic metamorphism at greenschist and subgreenschist facies levels. The earliest episode of metamorphism, which was of Barrovian type, occurred prior to accumulation of the first volcanic arc rocks, probably in Devonian time; this resulted in epizonal crystallinities of illite in pelitic rocks of the Shoo Fly Complex. The younger arc rocks have all been affected by metamorphic

alteration, which is variable across the region, decreasing in grade from west to east. The grade ranges from pumpellyite-actinolite facies in the highly deformed volcanic rocks in the west, to prehnite-pumpellyite facies in the undeformed volcanic rocks farther to the east, and diagenetic to lowermost anchizone grades are recorded in pelitic rocks associated with Jurassic arc rocks exposed in the extreme eastern part of the belt. On the basis of textural and chemographic evidence, at least three discrete metamorphic events affected the various arc volcanic rocks.

Pumpellyite-actinolite facies assemblages in the Eastern belt metabasites are indicative of relatively high pressures of metamorphism, in agreement with the Otago-type character of metamorphic indicators in the pelitic rocks. Such conditions have not been recorded previously in the Eastern belt, and indicate metamorphic conditions markedly different than suggested previously. In addition, evidence for the development of pumpellyite development prior, during, and following growth of the foliation minerals, of probable Nevadan age, indicates that the metamorphic history is complex. Whether the different pumpellyite generations relate to a sequence of different events or reflect a continuum is not clear. Pumpellyite composition has been thought to reflect geobarometric conditions of alteration, high Al contents indicating relatively high pressures (see Coombs et al., 1976). If this is the case, then maybe the high Mg/Al pumpellyites in metabasites of the Butt Valley and Hough blocks in the Eastern belt relate to tectonic loading effects following emplacement of the thrust slices during the Nevadan orogeny. In contrast, however, chlorite and actinolite have less variable compositions. In the case of chlorite it has been shown (Bevins et al., 1991) that composition is directly related to whole-rock chemistry at grades at and above the prehnite-pumpellyite facies. Similarly, actinolite composition has been considered to reflect closely whole-rock chemistry in view of the parallel tielines between chlorite and actinolite in subgreenschist and greenschist facies metabasites from Wales (Bevins and Robinson, 1993), eastern North Greenland (Bevins and Rowbotham, 1984), and the Eastern belt (this study). The suggestion is, therefore, that three metamorphic events can be detected in the Eastern belt arc volcanic rocks: a pre-tectonic prehnite-pumpellyite facies burial event, a syntectonic pumpellyite-actinolite facies event coincident with development of the Nevadan foliation, and a post-tectonic static event, possibly due to loading effects related to thrusting, also in the pumpellyite-actinolite facies.

Finally, rocks in the east of the area were affected by contact metamorphism as a result of emplacement of the Sierra Nevada batholith granitoids, which overprinted effects of the earlier regional metamorphic episodes.

ACKNOWLEDGMENTS

This investigation was supported by a research grant from NATO to R. E. Bevins, D. Robinson, H. W. Day, and P.

Schiffman. We thank Schiffman and Day for introducing us to the area and its problems, for providing support for the field studies, and, along with R. E. Beiersdorfer, for fruitful discussions on metamorphism in the Sierra Nevada. Constructive reviews by D. S. Harwood and H. W. Day are gratefully acknowledged. This is a contribution to IGCP Project 294.

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MANUSCRIPT ACCEPTED BY THE SOCIETY MARCH 25, 1994