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Stratigraphy and Depositional Environments of Middle Proterozoic Rocks, Northern Part of the Lemhi Range, Lemhi County, Idaho

By R.G. Tysdal

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Stratigraphy and Depositional Environments of Middle Proterozoic Rocks, Northern Part of the Lemhi Range, Lemhi County, Idaho

By R.G. Tysdal

ABSTRACT

Middle Proterozoic rocks in a region of detailed geologic mapping in the northern part of the Lemhi Range are separated into two packages by the Tertiary Lem Peak normal fault. Strata north of the fault, the main focus of this report, contain thicknesses and lithofacies of the Big Creek and Apple Creek Formations of the Lemhi Group that contrast with those south of the fault. Strata south of the fault, examined mainly in reconnaissance, may have been thrust eastward prior to being downdropped.

The Big Creek north of the Lem Peak fault is light-gray coarse-grained siltite to medium-grained metasandstone with prominent silty laminae of rusty-brown-weathering carbonate and dark-gray heavy-mineral laminae. Many beds comprise two-dimensional dunes (megaripples) that display planar (tabular) crosslamination; dune wavelengths are as much as 3 meters. Beds composed of three-dimensional dunes that display trough crosslamination occur in the upper part of the sequence. Dark-gray argillaceous siltite forms sequences less than 5 meters thick in the upper part of the formation. Reactivation surfaces and double clay drapes were observed locally and are indicative of tidal current processes. Bipolar current activity is evident in the sedimentary structures. Other sedimentary structures accord with the tidal interpretation: flaser and lenticular bedding, herringbone crosslamination, interbedded dunes and siltite (mudstone) lenses and beds, and tidal channel deposits. An amygdaloidal andesite flow 2–4 meters thick occurs within the upper part of the Big Creek in one area.

The Big Creek south of the fault, in the type area of the formation, was examined in reconnaissance traverses. In the lower part of the formation, gently inclined planar strata of dark-gray heavy minerals form prominent laminae in gently inclined trough crosslaminae, and in 2–3 centimeter thick lenses that extend laterally as much as 100 meters or more. These strata are interpreted as beach deposits. The uppermost part of the Big Creek in the type area is composed of two-dimensional dunes that are stacked one atop another. The dunes display wavelengths of 2–3 meters. The dominant current transport in these upper strata was to northeast; subordinate current transport was to southwest. Reactivation surfaces and double clay drapes are present within the dunes, indicating deposition from tidally controlled currents.

The Apple Creek Formation north of the Lem Peak fault consists of three gravity-flow units that, in ascending order, are the fine siltite unit, the diamictite unit, and the coarse siltite unit. The thickness of the three units totals 4,000–5,000 meters. South of the fault, the Apple Creek is only 700+ meters thick and is a single lithofacies. The Apple Creek is unconformable above the Big Creek Formation in both areas.

North of the fault, the fine siltite unit of the Apple Creek is planar-laminated siltite, ripple crosslaminated siltite, and argillaceous siltite. Many beds are graded, with 1–2 centimeter thick layers of siltite grading upward into argillite. The unit locally contains matrix-supported granule- to pebble-size argillite clasts. Strata attributed to reworking by bottom currents form ripples within the fine siltite unit. Graded-stratified siltite is common, forming bands of coarse-grained siltite to fine-grained metasandstone that are of finest grain size in the upper part; uppermost parts of some bands grade to fine-grained siltite, but argillite is absent. These strata fit the Bouma sequence of graded turbidite beds.

Abundant beds of poorly sorted conglomerate—diamictite—characterize a succession of otherwise fine-grained strata within the Apple Creek north of the Lem Peak fault. Most of the conglomerate beds are composed of disorganized matrix-supported clasts; they are interpreted as turbidites or debris flows. Argillite, argillaceous siltite, siltite, and lesser metasandstone form successions as much as 10 meters or more thick between conglomerate beds. Grading is obvious where deformation is not intense, and Bouma sequences are most prominent in the upper part of the unit. Paleocurrent directions determined from current ripples reveal transport from both the northeast and southwest. These fine-grained strata are attributed to a turbidite origin.

The coarse siltite unit is composed of gray-green medium- to coarse-grained siltite and fine-grained metasandstone. Siltite beds observed are normally graded. Soft-sediment deformation structures are widespread: ball-and-pillow

structures are fairly common; flute casts and tool marks were observed only locally. The unit derives its name from distinctive graded beds of sharp-based light-gray quartz-rich fine-grained metasandstone interspersed within the sequence. The graded bedding of the siltite and the sharp-based light-gray metasandstone beds suggest deposition from turbidity currents.

Apple Creek strata south of the Lem Peak fault consist of dark-gray medium- and fine-grained finely laminated siltite, and locally argillite in the lower part. The siltite is very finely planar laminated and many of the fine-grained siltite beds are graded; ripple crosslaminae are common. Other beds exhibit scoured bases and graded tops. Slump folds are common and indicate gravity-driven downslope movement. Silty dolomite forms thin distinctive interlayered beds in the bottom half of the unit. Some of the dolomite forms the base of beds that fine upward to noncalcareous siltite. Other distinctive characteristics include the overall fine to medium grain size of the siltite, and in the upper part of the section, sporadic interbeds of sharp-based, graded, light-gray metasandstone. The unit is generally coarser grained in its upper third, reflected both in the coarser grain size of the siltite beds and in the presence of the metasandstone beds. The assemblage of sedimentary structures in the lower part of the Apple Creek south of the fault is indicative of turbidites. Strata generally are finer grained than the lithofacies units north of the fault and likely were deposited from lower energy turbidity currents. Metasandstone of the upper part of the unit suggests shallow water deposition, perhaps influenced by waves. This would be in accord with shallowing of the depositional environment and a depositional transition into the overlying Gunsight Formation.

The Gunsight Formation, present only in a small part of the mapped area north of the Lem Peak fault, consists of cross-laminated orthoquartzite lenses as thick as 10 meters within siltite and silty feldspathic metasandstone. The lenses are interpreted as channel deposits of meandering streams within a flood plain environment, in which siltite strata constitute a large part of the rocks and the channels make up a small part.

The Swauger Formation, exposed only south of the Lem Peak fault within the mapped area, is mainly crosslaminated orthoquartzite of medium to coarse well-rounded grains. Two-dimensional dunes occur locally and display wavelengths of 4–6 meters, heights of 0.75–1 meter. The dominant current transport direction was to the northeast. Upper surfaces of some dunes contain asymmetrical ripples that show transport to the southwest, capping dune foreset laminae inclined to the northeast. Planar-laminated to ripple crosslaminated siltite, some beds containing flaser and lenticular bedding, is interbedded with orthoquartzite in the upper part of the Swauger. Herringbone crosslamination, formed by bipolar currents, occurs in close stratigraphic association with dunes that contain reactivation surfaces, indicating the herringbone structures to be of tidal origin. The interlayering of 0.5–1 meter thick beds of orthoquartzite and fine-grained siltite units indicates deposition from currents of contrasting flow speeds, and suggests that the transition strata were formed by tidal processes.

The Lawson Creek Formation, present only south of the Lem Peak fault in the mapped area, is conformable above the Swauger. It is generally quartz-rich metasandstone but ranges from about equal parts feldspar and quartz to locally orthoquartzite; a fine-grained matrix is typical. Ripple cross-laminae are common; rip-up clasts of argillite chips "float" within quartzite beds locally. Siltite and argillaceous siltite, interlayered with thin beds of metasandstone, form sequences as thick as 10 meters between beds chiefly composed of metasandstone and orthoquartzite. These strata range from planar laminated to ripple crosslaminated and display abundant flaser and lenticular bedding. The Lawson Creek is an intertidal sequence. Many of the sedimentary structures are typical of those found in tidal flats.

INTRODUCTION

The Lemhi Range trends southeastward for about 150 km from the vicinity of Salmon in the eastern part of central Idaho (fig. 1). The backbone of the range is generally 1,200–1,500 m higher than the valley floors to the northeast

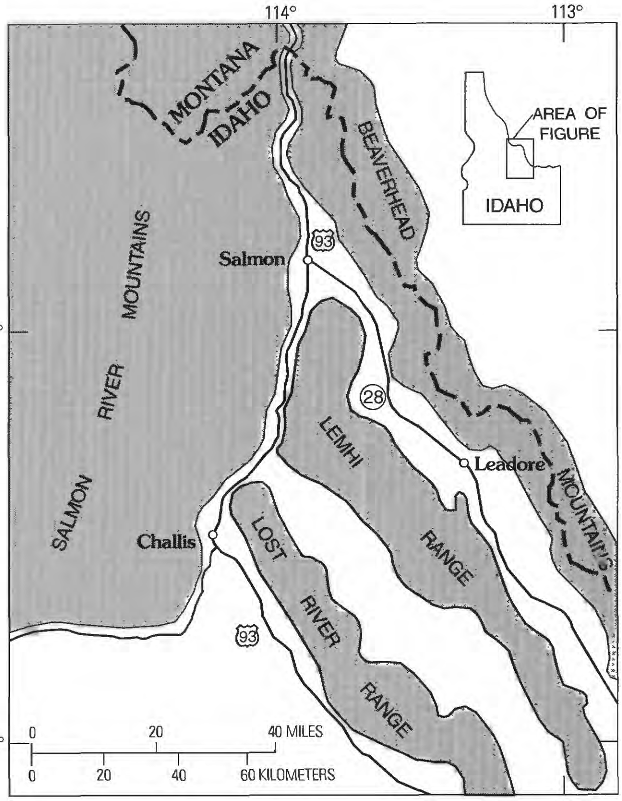


Figure 1. Index map of east-central Idaho.

and southwest. Paleozoic strata are the chief rocks exposed in the southeastern part of the range and gradually give way to Proterozoic strata in the northwestern part.

The stratigraphic sequence for Proterozoic strata in the central part of the Lemhi Range was established by Ruppel (1975) during the course of geologic mapping of three 15-minute quadrangles—Leadore (Ruppel, 1968), Patterson (Ruppel, 1980), and Gilmore (Ruppel and Lopez, 1981) (fig. 2). The basis for this report is from mapping of two 7.5-minute quadrangles; a quadrangle-size area composed of the northern part of the Mogg Mountain quadrangle and the adjacent southern part of the Hayden Creek quadrangle (Tysdal, 1996a); and the northern part of the May Mountain quadrangle (Tysdal, 1996c). The Mogg Mountain quadrangle coincides with the northwest corner of the Patterson 15-minute quadrangle, and the Hayden Creek quadrangle lies directly north of it. The Lem Peak (Tysdal, 1996b) and Allison Creek (Tysdal and Moye, 1996) quadrangles, and the May Mountain quadrangle (Tysdal, 1996c), lie northwest of the area of Ruppel's work.

The 7.5-minute quadrangles, and the area equivalent to a 7.5-minute quadrangle, were mapped as part of a project to study the regional setting of strata associated with cobalt-bearing rocks. Stratabound cobaltiferous rocks in the Salmon River Mountains west of the Lemhi Range were assigned to the Middle Proterozoic Yellowjacket Formation (Hughes, 1983; Hahn and Hughes, 1984) and delineated in quadrangle maps (Bennett, 1977; Lopez, 1981; Connor and Evans, 1986; Evans and Connor, 1993). Quadrangle mapping in the northern part of the Lemhi Range was undertaken at the behest of Connor to establish the stratigraphic relationship of the Yellowjacket Formation of the Salmon River Mountains to the Middle Proterozoic sequence of the central part of the Lemhi Range. Mapping was conducted in several quadrangles by Tysdal (1996a, b, c), Tysdal and Moye (1996), K.V. Evans (in progress), and G.R. Winkler (in progress). This report presents a general description of the Proterozoic sedimentary units mapped by Tysdal and a general interpretation of the depositional environment for each of them.

GEOLOGIC SETTING

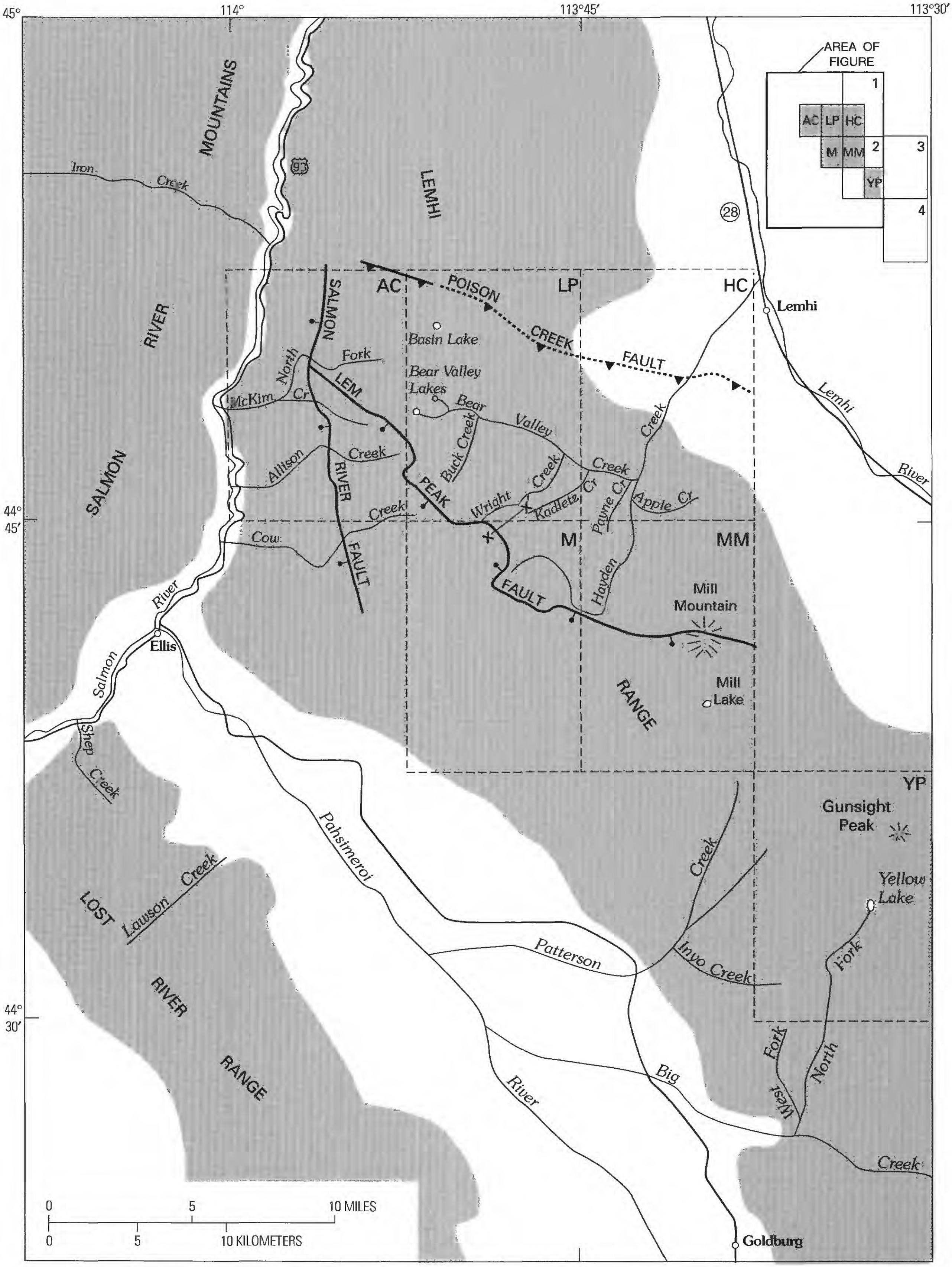
Rocks in the vicinity of the 7.5-minute quadrangles mapped by Tysdal (1996a, b, c) and Tysdal and Moye (1996) are largely composed of the Middle Proterozoic Lemhi Group and overlying Swauger and Lawson Creek Formations (table 1). Small areas of lower Paleozoic strata occur locally, and fairly large areas of Tertiary volcanic rocks flank these strata on the north. The Proterozoic and Paleozoic strata underwent compressional deformation, probably in the Cretaceous, creating a series of thrust faults and related folds. The trace of the Poison Creek fault, a major thrust that dips to the southwest, extends east-west across the northernmost part of the Lem Peak quadrangle (fig. 2). Subsequent Tertiary and (?)Cretaceous extension in the region was accompanied by formation of normal faults, some with major displacement. This Cretaceous to Tertiary deformation is in addition to (1) Middle Proterozoic compressional deformation reported for local areas of the general region (for example, Evans, 1986; Evans and Zartman, 1990), and (2) Late Proterozoic extension (Ruppel and Lopez, 1988), both of which may have affected rocks in the Lemhi Range.

The Lem Peak normal fault trends eastward across the southern part of the Allison Creek, Lem Peak, and Mogg Mountain quadrangles and dips steeply to the south (fig. 2). It underwent a large amount of displacement, south side down, as indicated by juxtaposition of Swauger Formation on the south against Big Creek Formation on the north. Several thousand meters of displacement are implied by stratigraphic separation (Tysdal, 1996a, b; Tysdal and Moye, 1996). Swauger strata adjacent to the fault locally contain tightly folded rocks formed during compression, but directly adjacent Big Creek strata north of the Lem Peak fault lack corresponding folded rocks. This contrast suggests that the structural features of the Swauger directly south of the fault were formed prior to juxtaposition against the Big Creek Formation along the Lem Peak normal fault. The Swauger and other strata south of the Lem Peak fault are believed to have been thrust eastward, then downdropped, accounting for the contrast in structures, the contrast in thickness of the Big Creek and Apple Creek Formations on opposite sides of the fault (table 1), and the contrast in lithofacies of each of these formations on opposite sides of the fault.

The Inyo Creek and West Fork Formations, named and described by Ruppel (1975), are known only from the southwest flank of the central part of the Lemhi Range, in the vicinity of creeks by these names (fig. 2). The formations are not present in the mapped quadrangles or the directly adjacent region and are not described or considered further here. The reader is referred to Ruppel (1975, 1980) and Ruppel and Lopez (1988) for data on these formations. The Yellowjacket Formation, as defined and mapped by Ross (1934) in the Salmon River Mountains, is not present in or adjacent to the mapped area and is not considered further here. Yellowjacket stratigraphy as interpreted by some authors since the work of Ross (1934) was reinterpreted and revised by Tysdal (2000) and is summarized briefly in this report in the section on the Apple Creek Formation.

TERMINOLOGY

Proterozoic rocks throughout most of the northern part of the Lemhi Range discussed here have been metamorphosed to the lower greenschist facies. Biotite-grade rocks exist in the central to northern part of the Allison Creek quadrangle (fig. 2), where biotite has replaced some to all of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RIVER
LEMHI
RANGE
Iron
Creek
93
28
POISON CREEK FAULT
SALMON RIVER FAULT
LEMHI
PEAK
FAULT
Lemhi
Lemhi River
Basin Lake
Bear Valley Lakes
North Fork
McKim Cr
Bear Valley Creek
Buck Creek
Allison Creek
Wright Creek
Kadletz Cr
Payne Cr
Apple Cr
Creek
Cow Creek
Hayden Creek
Mill Mountain
Mill Lake
Salmon River
Ellis
Shep Creek
Lawson Creek
LOST RIVER RANGE
Pahsimeroi
Patterson Creek
Inyo Creek
Gunsight Peak
Yellow Lake
West Fork
North Fork
Big Creek
River
Goldburg
0 5 10 MILES
0 5 10 KILOMETERS

Figure 2 (facing page). Map showing major faults and geographic features referenced in text. Bar and ball on downthrown side of normal fault; sawteeth on upthrown side of thrust fault; dotted where concealed. 7.5-minute quadrangles: AC, Allison Creek; HC, Hayden Creek; LP, Lem Peak; M, May Mountain; MM, Mogg Mountain; YP, Yellow Peak. 15-minute quadrangles: 1, Lemhi; 2, Patterson; 3, Leadore; 4, Gilmore. *X–X′*, line of measured section in Big Creek Formation.

the muscovite. In this report, the following terminology is used for the metamorphosed clastic rocks.

Argillite. Metamorphosed claystone.

Siltite. Metamorphosed siltstone or mudstone.

Metasandstone. Metamorphosed sandstone; generally applied only to rocks composed of less than 90 percent quartz grains.

Quartzite. Metamorphosed sandstone composed of at least 90 percent quartz grains.

Orthoquartzite. Metamorphosed sandstone composed of at least 95 percent quartz grains.

This terminology differs from the "standard" usage for metamorphosed Proterozoic clastic rocks, wherein "quartzite" denotes a metamorphosed sandstone regardless of composition.

BIG CREEK FORMATION

The Big Creek Formation was named by Ruppel (1975) for strata exposed in the central part of the Lemhi Range, on the southwest side. The type locality is directly west of the North Fork of Big Creek (Ruppel, 1975) (fig. 2). Rocks of the type area lie south of the Lem Peak fault, on a structural block that contains Big Creek strata somewhat different in character from Big Creek north of the fault. The following descriptive sections illustrate the variety of sedimentary features present within the Big Creek north of the Lem Peak fault. For comparison, a brief description and a depositional interpretation for Big Creek strata of the type area are presented at the end of this section.

Because some users of this report will not be familiar with some of the sedimentologic terms that are used, definitions of several terms used in the interpretation of depositional environments of the Big Creek Formation are presented.

Dune. Flow-transverse bedforms that develop on a sediment bed under a unidirectional current. They display a spacing of greater than 0.6 m, thus are larger than ripples. (In some reports, the term megaripple was previously used for these features.) Dunes that have straight crests are termed two-dimensional; those that are lunate or have sinuous crests are termed three-dimensional (Ashley, 1990).

Reactivation surface. A gently inclined erosional surface that separates foresets [in ripples or dunes] of similar orientations. The erosion surface is produced when one ripple or dune overtakes [migrates over] another, or is produced during current reversal in a tidal environment. When the tide again reverses to the original direction, sediment deposition is reactivated to form more foresets (McCabe and Jones, 1977; de Mowbray and Visser, 1984).

Clay drape. In a diurnal tidal environment, a strong (dominant) current and a subsequent weak (subordinate) current exist during the course of a tidal cycle. A slack-water stage follows both the dominant current stage and the weak current stage as the tide reverses. Clay particles deposited during the slack-water stage following the dominant current may be deposited on top of existing sedimentary structures, forming a "clay drape." A thin layer of sediment deposited during the subsequent weak current stage may overlap the clay drape. If clay also is deposited during the slack-water stage that follows the subordinate (weak) tidal current, then a "double clay drape" is formed. Double-clay drapes are indicative of a tidal environment (Visser, 1980; de Mowbray and Visser, 1984; Nio and Yang, 1991).

NORTH OF LEM PEAK FAULT

The Big Creek north of the Lem Peak fault is mainly light gray coarse-grained siltite to medium-grained metasandstone composed of quartz, feldspar, auxiliary muscovite and tourmaline, and matrix. Distinguishing characteristics throughout much of the formation include silty laminae of limestone and dolomite that weather pale yellowish brown (rusty brown), and dark-gray heavy-mineral laminae, typically 1–2 grains thick. Large-scale tabular and trough cross-lamination is widespread and was formed from straight-crested and sinuous-crested dunes. Beds commonly are about 1 m thick. Dark-gray argillaceous siltite zones, generally less than 5 m thick, are present locally and contain current ripples, and flaser and lenticular bedding. An amygdaloidal andesite flow 2–4 m thick lies within the upper part of the formation west of Wright Creek (fig. 2) (Tysdal, 1996a).

The sequence has been metamorphosed to the lower greenschist facies throughout most of the mapped area, but biotite-grade rocks exist in the central to northern part of the Allison Creek quadrangle (fig. 2), where biotite has replaced some to all of the muscovite. The rusty-weathering carbonate laminae, a prominent criterion for recognition of Big Creek strata, are not so obvious in the biotite-grade rocks, possibly due to the increased metamorphic grade. The upper contact of the formation is unconformable (discussed in a later section of this report), marked by the abrupt appearance of gray-green siltite of the Apple Creek Formation. The Big Creek Formation is about 2,700 m thick.

Table 1. Stratigraphic sequence of Middle Proterozoic units exposed in vicinity of mapped area.

[Yellow Lake unit of Apple Creek Formation south of Lem Peak fault is not necessarily the stratigraphic equivalent of all three units of the Apple Creek north of fault—see text for discussion. Leaders (--), unit not present or not exposed; +, minimum thickness, due to erosion or fault]

	North of Lem Peak fault			South of Lem Peak fault		
Group	Formation		Thickness (meters)	Thickness (meters)	Formation	
Lemhi Group			----	[2]300+	Lawson Creek Formation	
	Swauger Formation		3,100(?)	[3]3,100	Swauger Formation	
	Gunsight Formation		(?)	[4]1,725+	Gunsight Formation	
	Apple Creek Formation	Coarse siltite unit	[1]2,500+	[5]700+	Yellow Lake unit	Apple Creek Formation
		Diamictite unit	[1]600-1,500			
		Fine siltite unit	[1]1,000			
	Big Creek Formation		[1]2,700	[3]3,100	Big Creek Formation	
			----	[6]600	West Fork Formation	
			----	[6]380+	Inyo Creek Formation	

[1]Tysdal (1996a, b). Tysdal and Moye (1996).
[2]Tysdal (1996c).
[3]Ruppel (1975).
[4]McBean (1983).
[5]Thickness measured by R.G. Tysdal, G.R. Winkler, K.V. Evans, and J.J. Connor.
[6]Thickness measured by R.G. Tysdal, G.R. Winkler, K.V. Evans.

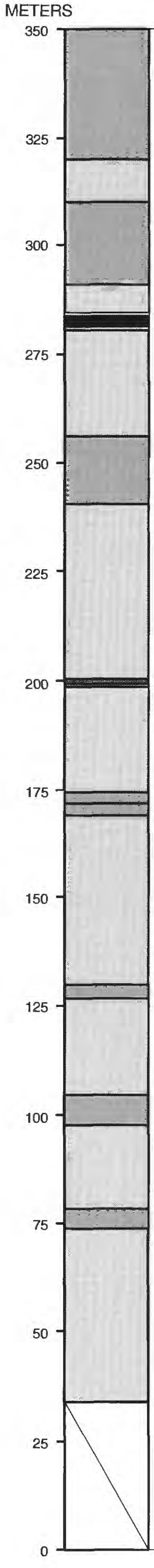
On the ridge between the headwaters of Wright and Kadletz Creeks (fig. 2), a section measured (fig. 3) in the upper part of the Big Creek contains many features representative of those found in much of the formation. The measured section, based at the Lem Peak fault, displays thick successions of metasandstone, dunes, and thin interlayered zones of dark-gray fine-grained siltite. The section characterizes the sedimentological interplay of the dominantly metasandstone succession as it intertongues with siltite, and provides the basis for much of the following discussion.

LIGHT-GRAY HEAVY-MINERAL-BEARING METASANDSTONE

Metasandstone of the measured section is chiefly composed of 50–60 percent quartz, 10–20 percent feldspar, 5–15 percent matrix, and as much as 5 percent heavy minerals of tourmaline, zircon, and ilmenite that are dispersed within 1–2 mm thick laminae. Carbonate laminae are common, interpreted as originally composed of detrital grains. Recrystallized during metamorphism, the carbonate grains form laminae that range from mainly carbonate with minor siliciclastic grains, to carbonate that cements mainly siliciclastic grains. Planar-layered beds 1–2 m thick are interstratified with planar and trough crosslaminated dunes that display wavelengths of 1–3 m and heights of 0.3–0.5 m. Beds of ripple crosslaminated metasandstone also are present.

About 200–300 m laterally southeast of the line of the measured section, contiguous strata display planar-laminated beds 1.5–3 m thick. The beds are composed of two-dimensional dunes that display planar (tabular) crosslamination in sets 0.5–1 m high; dune wavelengths are as much as 3 m and heights are 0.3–0.5 m. Reactivation surfaces were observed in some beds of the two-dimensional dunes, locally marked by a 0.1–1 cm thick siltite (mudstone) layer (fig. 4). Dominant current transport was to the southwest. Prominent bed-thick foresets indicating transport to the northeast are common within these strata, although the beds are thinner and less abundant than beds with southwest-directed foresets.

Figure 3 (facing page). Graphic log of partial thickness of Big Creek Formation, between Wright and Kadletz Creeks, May Mountain and Lem Peak quadrangles (fig. 2).



UNIT	DESCRIPTION
1	Siltite, medium- and dark-gray; flaser bedding, ripple crosslamination; transport direction to both the northeast and southwest
2	Metasandstone, light- to medium-gray, fine-grained; 0.5-1.0 m thick crossbeds; some dark-gray heavy-mineral laminae; sparse rusty-brown-weathering carbonate laminae
3	Interbedded siltite and metasandstone in units 1-2 m thick. Siltite, dark-gray; flaser bedding; metasandstone, light-gray, fine-grained; ripple crosslaminae, carbonate laminae
4	Metasandstone, medium-gray, fine-grained; two-dimensional dunes with wavelength 1.5-2.0 m, height about 0.5 m; rusty-brown-weathering carbonate laminae; sparse dark-gray heavy minerals in laminae 1 grain thick; ripples show transport to northeast
5	Siltite, dark-gray, medium- to coarse-grained; rusty-brown-weathering carbonate laminae
6	Andesite flow; chalcedony-filled amygdules, most abundant and largest in upper part of flow; flow is well cleaved, in continuity with the sedimentary sequence. Chemical analyses showing major oxides are in table 2
7	Siltite, dark-gray, medium- to coarse-grained
8	Metasandstone, medium-gray, fine-grained; local rusty-brown-weathering carbonate laminae; 1-2 m thick zones of siltite with flaser bedding
9	Siltite, dark-gray, medium- to coarse-grained; rusty-brown-weathering carbonate laminae; ripple crosslaminated; asymmetrical ripples on bedding surfaces show transport to northeast; sparse interbeds of siltite in zones about 1 m thick
10	Metasandstone, medium-gray, fine-grained; two-dimensional dunes with wavelength of 1-2 m, height about 0.5 m; rusty-brown-weathering carbonate laminae; ripple crosslaminated; blocky weathering
11	Orthoquartzite, light-gray to medium-light-gray, medium-grained; rounded grains
12	Siltite, grayish-yellow-green, fine-grained
13	Metasandstone, medium-gray, fine-grained; two-dimensional dunes with wavelength 1-2 m, height about 0.5 m; rusty-brown-weathering carbonate laminae; ripple crosslaminated; blocky weathering
14	Siltite, green and gray-green, abundant muscovite
15	Siltite, olive-gray, fine- to medium-grained, finely laminated; rusty-brown-weathering carbonate laminae; well cleaved
16	Metasandstone, fine-grained, to coarse-grained siltite, grayish yellow green, in beds 0.5-2.0 m thick; rusty-brown-weathering carbonate laminae in lower 10 m; crossbeds in sets 0.5-1.0 m high; some dark-gray heavy-mineral laminae; one 4 cm thick lens of heavy minerals—zircon, tourmaline, and ilmenite
17	Siltite, gray-green, fine- to medium-grained; planar laminated to very small ripple crosslaminae
18	Metasandstone, fine-grained, to coarse-grained siltite, grayish yellow green, in beds 0.5-2.0 m thick; rusty-brown-weathering carbonate laminae; crossbeds in sets 0.5-1.0 m high; some dark-gray heavy-mineral laminae
19	Siltite, medium-gray, medium- to coarse-grained, finely laminated to ripple crosslaminated; some rusty-brown-weathering carbonate laminae; contains metasandstone planar-laminated interbeds like those in upper part of unit 18; muscovite prominent on some bedding surfaces
20	Metasandstone, fine-grained, to coarse-grained siltite, medium gray; platy weathering; poor outcrop; topmost surface of unit displays two-dimensional dunes, wavelength about 2 m, height about 0.3 m
21	Siltite, medium-gray, planar and ripple crosslaminated; flaser bedding
22	Metasandstone, olive-green, fine-grained, platy-weathering, planar-laminated to ripple cross-laminated; dark-gray heavy-mineral laminae; rusty-brown-weathering carbonate laminae
23	Covered
	Fault at base

Beds comprising three-dimensional dunes are present locally within the sequence, are spaced 1–2 m apart, and have heights of 0.3–0.5 m. Heavy-mineral laminae are common in basal strata of these trough crosslaminated structures. In one outcrop, heavy minerals form a 5–10 mm thick layer directly above a scour surface that separates two dunes. The scour surface is inclined to the northeast, opposite to the transport direction indicated by the foreset laminae of the dunes that lie above and below the surface, suggesting reversing tidal currents (fig. 5).

Siltite lenses as long as 2 m and as thick as 15 cm occur locally between the beds of metasandstone (fig. 4). In one outcrop a siltite lens is underlain by asymmetrical ripples that show transport to the southwest, which is opposite to that indicated by the large-scale foresets of the 1 m thick underlying part of the bed (fig. 6). The ripples have a wavelength of about 8 cm and height of about 1 cm.

The uppermost few millimeters of planar-laminated beds locally contain soft-sediment load structures. The loading is of sediment that contains abundant heavy minerals. The upper part of the load structures has been eroded. The sequence of events apparently is as follows: deposition of the lower bed, by a dominant current; erosion of the upper surface; deposition of the heavy-mineral layer, by a weak current; erosion of the upper part of the deformed heavy-mineral layer, (?)by a weak current; and, subsequently, deposition of the overlying bed, by a dominant current. In another case, a heavy-mineral layer about 2 mm thick occurs between two 0.5 m thick beds in which the bed-thick foreset laminae are inclined to the southwest. The heavy-mineral layer is inclined to the northeast in concert with the underlying erosion (scour) surface. The layer is a subordinate current cap, a depositional structure produced on the crest of a dune by a subordinate current (de Mowbray and Visser, 1984, p. 817).

Northwest of Wright Creek, beds on strike with those of the measured section show that, over a distance of several tens to hundreds of meters parallel to bedding, 1–3 m thick beds of metasandstone taper laterally and intertongue with other metasandstone beds, producing slight angular relationships. Some beds are eroded deep into underlying beds. In other places metasandstone fills 1–1.5 m deep by 2–5 m wide channels cut into underlying metasandstone.

A 1 m thick quartzite bed (fig. 3, unit 11), and underlying 0.5 m thick dark-gray fine-grained siltite, occur near the middle of a 75 m thick succession of metasandstone. The quartz-rich bed is medium grained, about 85 percent subangular to rounded quartz grains, 10 percent feldspar, and 5 percent matrix. Basal strata of one metasandstone, directly above siltite of unit 19 (fig. 3), contain dark-gray heavy minerals in 1-lamina-thick layers in some beds, although local 4–5 cm thick planar laminated layers are present. These heavy-mineral laminae comprise mostly zircon, tourmaline, and ilmenite(?) grains. These strata show sorting and selective concentration of the kinds of grains that generally are dispersed or within laminae of the metasandstone of the formation.

Two-dimensional dunes are well exposed on a ridge east of Buck Creek (figs. 2, 7). The dunes are in fine- to medium-grained metasandstone, display wavelengths of 2–3 m and heights of 0.5–1 m, and indicate sediment transport to northeast. Zones of dark-gray siltite are not common in this area and are only 1–2 m thick where they do occur. The size of the dunes and the scarcity of fine-grained sediment suggest high-energy conditions. The structures here are larger than those of the section measured near Wright Creek (figs. 2, 3) and stratigraphically are higher in the formation. In the upper 200–300 m of the formation in the Buck Creek area, the metasandstone is fine grained, crosslamination is small scale, heavy minerals are nearly absent, and thin zones of dark-gray siltite are fairly common. Argillaceous rip-up clasts of pebble to cobble size are present in the basal part of a few thick metasandstone beds.

DARK-GRAY SILTITE STRATA

The upper part of the measured section (fig. 3, units 1 and 3) displays dark-gray argillite and fine-grained siltite interbedded with light-gray coarse-grained siltite to fine-grained metasandstone. Rocks of these contrasting colors and grain sizes alternate in layers generally ranging from 2–3 mm thick to 3–4 cm thick, although beds as thick as 10–15 cm occur locally. The finer grained rocks tend to be planar laminated and the coarser grained rocks are ripple crosslaminated. Both flaser bedding and lenticular bedding are common, as are rippled bedding surfaces. Ripples are mainly longitudinal current forms and typically have wavelengths of 2–5 cm and heights of 0.5–1 cm. Ripple transport directions are generally to the northeast, but a few beds indicate transport to the southwest; herringbone crosslamination displays the opposing transport directions indicated locally by the ripples of bedding surfaces. Some of the coarser grained beds display small soft-sediment deformation features, including ball-and-pillow structures 1–3 cm across, flame structures, and water-escape pillar structures.

The thick dark-gray siltite of units 1 and 3 (fig. 3) of the upper part of the measured section contains a wider variety of structures than the other, thinner siltite zones. But the structures of all zones within the measured section, and throughout the formation, show similar size features and ripples that generally indicate transport to the northeast. The zones of dark-gray siltite in the formation are lens-shaped and laterally discontinuous. Some zones extend for only a few tens of meters; thicker zones extend for a few hundred meters. None was physically traceable from one ridge to the next.

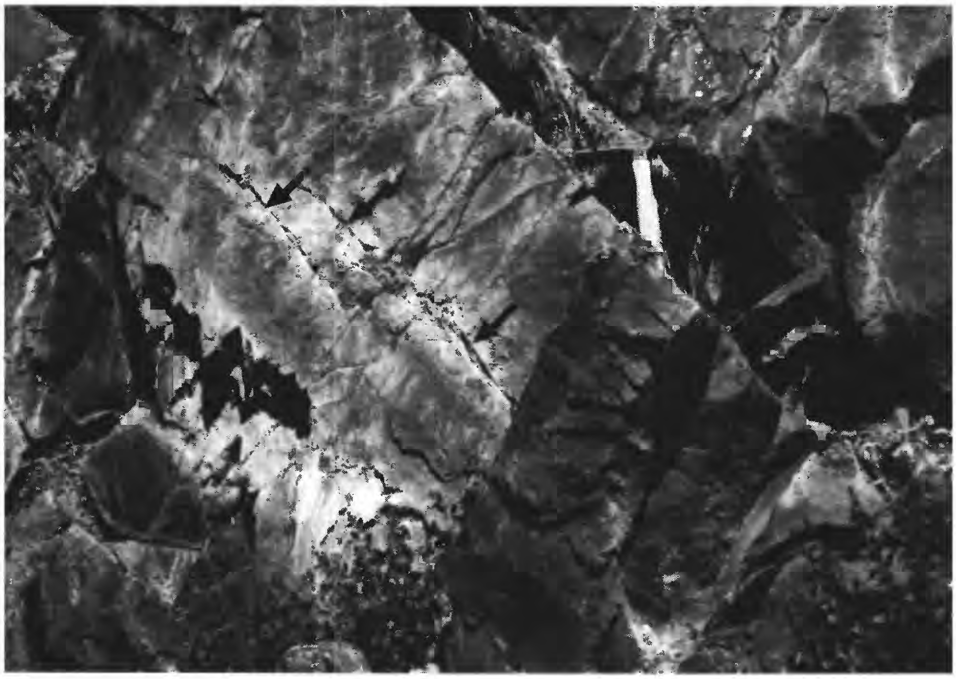


Figure 4. Reactivation surfaces (indicated by arrows) of dune in Big Creek Formation in Kadletz Creek area (fig. 2), vicinity of measured section of figure 3. Siltite (mudstone) along each reactivation surface is up to 1 cm thick. Lens of siltite at upper right occurs between dunes and has maximum thickness of about 10 cm, length of about 3 m; layering in this lens is cleavage. (See fig. 6 for closeup.) Hammer for scale, handle 24 cm long.

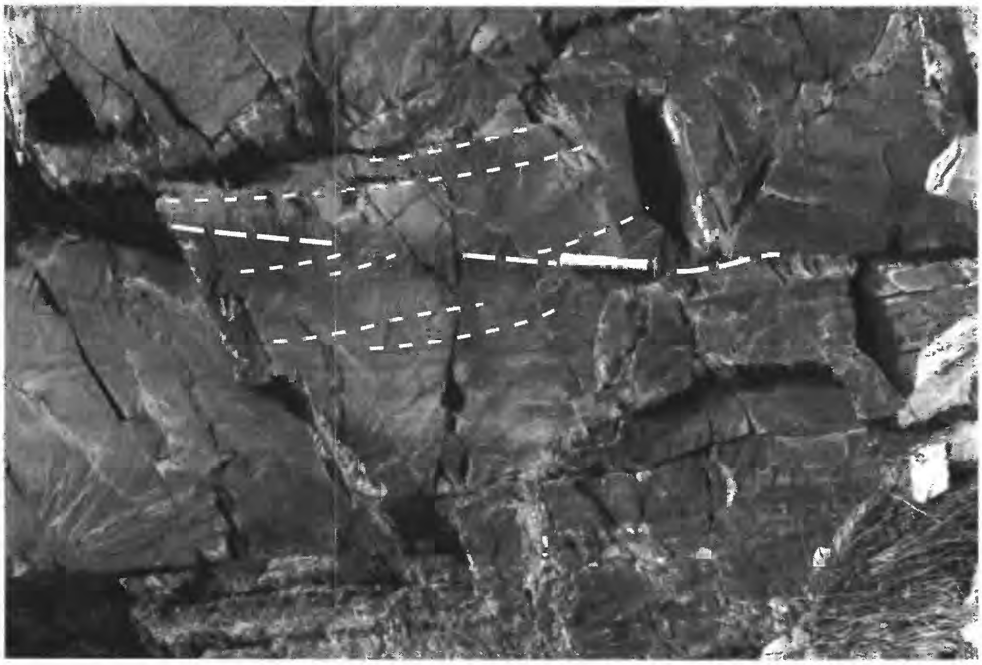


Figure 5. Dunes with foreset laminae (short-dashed lines) indicating transport to the southwest (to left), separated by a scour surface that is inclined to the northeast. Heavy minerals form a 5–10 mm thick layer along the scour surface (intermittent heavy dashed line). Dunes are in Big Creek Formation in Kadletz Creek area (fig. 2), vicinity of measured section of figure 3. Hammer for scale, handle 24 cm long.

STRATA DIRECTLY ABOVE MEASURED SECTION

Stratigraphically directly above the measured section, extending north about 1,000 m to the Hayden Creek fault (not shown in fig. 2), zones of dark-gray fine-grained siltite are absent. The sequence consists of fine- to medium-grained metasandstone that contains two-dimensional dunes with spacing of 3–4 m and heights of about 1 m; three-dimensional dunes that display spacing of 1–1.5 m and heights of about 0.5 m; and interbeds 1–2 m thick, planar laminated, and generally lacking in heavy minerals. Soft-sediment slump structures are common in the plane-bedded rocks, and in one outcrop include double clay drapes.

Three-dimensional dunes are well developed in fine-grained metasandstone in the upper part of the Big Creek Formation. At the head of Payne Creek (fig. 2), for example, three-dimensional dunes occur in 1–2 m thick beds and display trough crosslamination. The basal half of each bed is finely planar laminated and grades abruptly upward into trough crosslamination of dunes that have spacing of 1–3 m

Figure 6. Closeup of upper surface of dune and siltite lens (directly above hammer) in upper right of photograph of figure 4. Upper surface of dune displays asymmetrical ripples that indicate transport to the southwest (to upper left), which is opposite to that indicated by reactivation surfaces within the dune. Hammer for scale, handle 24 cm long.

Figure 7. Small two-dimensional dune in upper middle part of Big Creek Formation in vicinity of Buck Lakes (west of Buck Creek, fig. 2). Wavelength is about 1.5 m and height about 0.3 m. Transport was to the northeast, to right in photograph. Hammer for scale, handle 24 cm long.

and heights about 0.5 m (fig. 8). Some beds display ripple crosslamination directly above the basal strata. Rusty-weathering carbonate laminae are common in the crosslaminated strata but generally are lacking from the planar-laminated lower strata. Dark-gray fine- to medium-grained siltite locally forms isolated lenses as much as 10 cm thick and 1 m long, within troughs. Chips of argillite and argillaceous siltite are present locally within basal strata of the metasandstone beds, and dark-gray heavy-mineral laminae occur within trough crosslaminated strata. Sparse load structures formed where trough crosslaminated sediment settled into planar-laminated sediment.

The lower, planar strata of each bed are interpreted as deposits of the upper flow regime, overlain by sediments deposited from decelerating currents of the lower flow regime. The local lenses of dark-gray siltite were deposited during slack water or ebb stages of sedimentation. The lenses may be remnants from extensive siltite beds that were

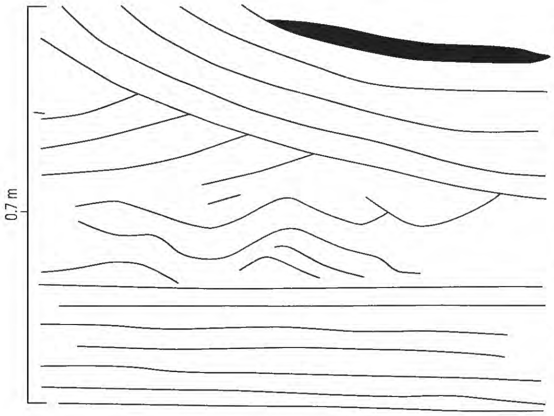


Figure 8. Sketch of features in small three-dimensional dune in upper strata of Big Creek Formation. Near Payne Creek (fig. 2).

largely eroded during a subsequent flood tide. Load structures in planar-laminated rocks indicate water-saturated sediments.

CHANNEL DEPOSIT

West of Buck Lakes (not shown in fig. 2, but directly west of central part of segment of Buck Creek shown), large soft-sediment slump structures occur within a 50+ m thick sequence that has an exposed width of 50+ m—its full width is not exposed. The strata are composed of fine-grained metasandstone that contains carbonate laminae, emphasized by differential weathering. Deformed strata form zones 0.5–4 m thick between undeformed beds of planar-laminated metasandstone (fig. 9). Individual slump folds are as thick as the thickest bed and are 2–3 m across. The largest slumps show progressively less deformation (less dewatering) from base to top. In the upper part of the sequence, zones 0.3–0.5 m thick contain massive to planar-laminated metasandstone that grades upward into interbedded metasandstone and 1 cm thick dark-gray argillite (fig. 10). Strata of these zones overlie deformed metasandstone, although the zones themselves typically are not deformed.

The above sequence is confined to the one locality and is interpreted as sediment deposited within a tidal channel in an intertidal setting. The largest soft-sediment deformation structures are in the lower part of the sequence, the interstratified metasandstone and argillite layers in the upper part. This sequence suggests a channel that contains thick beds of rapidly deposited, water-saturated sediment in its lower part, giving way upward to thinner beds of water-saturated sediment, and in the upper part to sediment that included silt and clay deposited during lower energy sedimentation or slack water conditions. Interbeds of undeformed strata reflect deposition of nonsaturated sediments.

Features similar to those described, and shown in figures 9 and 10, have been described by Glendinning (1988) in Upper Proterozoic rocks of Scotland. There, however, the dewatering structures are not confined to a local zone but form sheets. Glendinning attributed their origin to earthquake activity. In the Lemhi Range, the localization of the affected strata and the interlayering of distorted and nondistorted beds argue against such a catastrophic origin.

OTHER STRATA OF MAPPED AREA

The stratigraphically lowest exposed Big Creek strata north of the Lem Peak fault are in the southwesternmost corner of the Lem Peak quadrangle (fig. 2). The sequence is chiefly fine grained to medium-grained metasandstone. Some beds are quartz rich and contain well-rounded quartz grains, associated with potassium feldspar, plagioclase, 1–2 percent matrix, and heavy-mineral laminae. Trough crossbeds have a wavelength of 1–3 m and height of 0.3–0.5 m. Dark-gray lenticular and flaser crosslaminated fine-grained siltite in zones 1–3 m thick is fairly common in this part of the formation. Some zones are directly overlain by metasandstone that displays 0.5 m high sets of trough crosslamination. Argillite chips occur in the basal part of some metasandstone beds. These strata probably were deposited in an environment similar to that of the Payne Creek area, described previously.

VOLCANIC FLOW

A volcanic flow composed of amygdaloidal andesite lies within the upper part of the Big Creek Formation adjacent to the upper reaches of Wright Creek. The flow has a strike length of about 2 km, assuming that it is continuous beneath glacial deposits in the valley of Wright Creek. The flow is 2 m thick southeast of Wright Creek, within the measured section (fig. 3), and attains a maximum observed thickness of about 4 m on the ridge northwest of the creek. Amygdules are most abundant and largest in the upper part of the flow. Northwest of Wright Creek, amygdules also form zones lower in the flow and are about parallel to layering. All amygdules are filled with chalcedony. The flow rocks are well cleaved, in continuity with the enclosing sedimentary sequence. Major-oxide chemical analyses of the

Figure 9. Outcrop interpreted as strata within a tidal channel deposit, upper part of the Big Creek Formation in vicinity of Buck Lakes (fig. 2). Bedding surfaces accentuated by dashed lines. Upper part of sequence (right side of photo) shows soft-sediment deformation— slumping due to dewatering. Note that lower part of the main "slump" (vicinity of hammer) shows greater deformation than upper part of structure, and that deformation of beds within slump decreases upward. This suggests that dewatering of strata was a process ongoing at time of deposition, with least dewatering taking place in upper sediment of slump. This also is indicated to right of hammer where upper strata, in area of "anticline," overlie erosionally truncated lower strata. Lower part of sequence is nearly planar layered strata. Photo is looking approximately along axis of transport. Hammer for scale, handle 24 cm long.

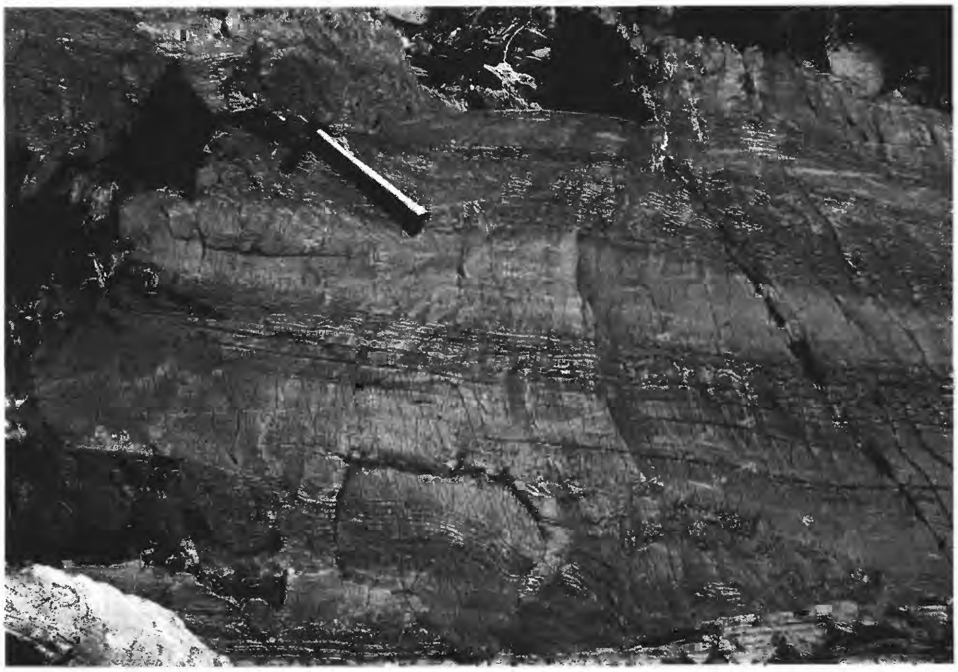


Figure 10. Outcrop interpreted as upper strata within a tidal channel deposit, upper part of the Big Creek Formation in vicinity of Buck Lakes (fig. 2). Lower part of photo shows soft-sediment deformation—slumping due to dewatering—prior to deposition of overlying strata. Photo is looking approximately along axis of transport. Hammer for scale, handle 24 cm long.

flow are shown in table 2. Care must be taken in use of the analyses because the loss-on-ignition value is high, indicating significant mobility of the alkali elements (Ca, Na, K).

Southwest of Wright Creek the flow directly overlies 1 m of fine-grained siltite, into which its base locally forms small load casts. The flow is overlain by 0.5 m of the siltite. Northwest of Wright Creek the flow directly overlies fine-grained crosslaminated metasandstone. No fragments from the flow were found in strata directly above the flow. The Big Creek of the region was rotated to near-vertical dips

Table 2. Oxides of major elements from amygdaloidal andesite flow within Big Creek Formation.

[<, less than; analysts: D.F. Siems, J.E. Taggart]

			Major oxides (percent)										
Field No.	Lat N.	Long W.	SiO_2	Al_2O_3	$FeTO_3$	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	LOI
89ITz107	44-45-01	113-48-27	52.4	10.8	11.0	6.15	5.39	<0.15	3.16	0.91	0.17	0.19	9.90
90ITz34B	44-45-22	113-49-31	52.7	15.8	11.4	8.77	0.63	3.64	0.53	1.38	0.21	0.02	5.15

during Cretaceous deformation, and the lower and upper contacts of the flow commonly served as slip planes during rotation; hence, contact relationships are clear only locally.

The upward increase in the number and size of the amygdules is interpreted to indicate top of the igneous body at the time of emplacement, reflecting decreasing pressure while the flow was fluid. This is consistent with top direction determined from sedimentary structures of the host clastic strata. These observations could indicate either a subaerial flow or an intrusion at a very shallow depth in unconsolidated sediments. No other extrusives are known in the Big Creek Formation; thus the intrusion interpretation is favored.

SOUTH OF LEM PEAK FAULT

Big Creek strata of the type area were examined in reconnaissance traverses. The lowermost strata, exposed in an unnamed cirque about 1.5 km northeast of the head of Inyo Creek (fig. 2; Yellow Peak 7.5-minute quadrangle), are light-gray fine-grained quartz-rich metasandstone that contains dark-gray heavy minerals. Strata on the floor of the southwestern part of the cirque display planar and trough crossbeds and minor heavy-mineral laminae; calcareous metasandstone beds are common. The heavy minerals typically form laminae 1–2 mm thick. Repetition of the following cyclical sequence occurs in intervals 0.3–1 m thick:

Top
Scour surface
Metasandstone, quartz-rich
Fine-grained metasandstone, heavy-mineral laminae
Metasandstone, calcareous
Scour surface
Base

In a few places, beds 0.5–1 m thick of argillite to fine-grained siltite lie upsection of quartz-rich metasandstone beds; pebbles of argillite locally are associated with these strata.

On the floor of the northeastern part of the cirque, gently inclined to planar strata of dark-gray heavy-mineral laminae are exposed. Trough crossbedding and calcareous metasandstone are less common. The heavy minerals form prominent laminae 1–2 mm thick in very gently inclined trough crosslaminae, and in lenses 2–3 cm thick in flat-planar-laminated strata (fig. 11). The flat-planar-laminated layers that host the units are at a slight angle to one another. Heavy minerals of the lenses extend laterally for as much as 100 m or more. Thin sections show the heavy minerals to be zircon, tourmaline, and hematite. Polished sections examined by G.A. Desborough (oral commun., 1990) revealed ilmenite surrounded by hematite that has replaced titaniferous magnetite.

Reconnaissance examination of strata higher in the Big Creek of the type area revealed repetition of trough cross-laminated metasandstone beds that commonly are about 1 m thick. Crosslamination of these beds is more steeply inclined than that described in the preceding paragraph, approaching the angle of repose, with widths of several meters. Dark-gray heavy minerals in bands 1 mm thick form laminae of the troughs; no lenses of heavy minerals were observed. These crosslaminated beds commonly have erosional bases. Calcareous beds are common. In other areas the erosional base of an overlying bed contains a zone 2–3 cm thick of interlaminated dark-gray heavy minerals and quartz grains; the zone gives way upward to the broadly trough shaped strata of the remainder of the bed. In still other areas, beds either do not contain trough crosslamination or are composed of very gently inclined laminae. The beds truncate one another at very low angles.

About 2 km southwest of Yellow Lake (fig. 2), the uppermost 50 m of the Big Creek, and probably a much greater thickness, is composed of two-dimensional dunes that are stacked atop one another. The dunes display heights of 0.5–1.5 m and wavelengths of 2–3 m (fig. 12). Individual beds pinch and swell, such that the thickest parts of some beds are overlain by thinner parts of succeeding beds. The beds are 1–1.5 m thick and are composed of quartz-rich metasandstone that is medium to coarse grained; they lack the rusty-brown-weathering calcareous metasandstone that characterizes other strata of the Big Creek Formation in the cirque northeast of the head of Inyo Creek. No siltite beds were observed in the sequence.

The dominant current transport was to northeast, as shown by northeast inclination of foresets of the dunes.

Figure 11. Heavy-mineral lens, about 2 cm thick, in lower part of Big Creek Formation in type area. Lens is at very low angle to lamination of host fine-grained metasandstone. Hammer head at top of lens; handle for scale, about 24 cm long.

Figure 12. Small two-dimensional dunes in upper strata of Big Creek Formation in type area. Dashes emphasize bedding. Wavelength is about 1 m, height about 0.2 m. Hammer for scale, handle 24 cm long.

Subordinate current transport was to southwest, shown by smaller scale crosslaminated beds that are thinner and dip to the southwest. The rippled upper surface of some dunes contains two-dimensional asymmetrical ripples that show transport to the southwest. Subordinate currents deposited sediment directly to the southwest of the crestal area of some dunes; the strata show oppositely directed (that is, southwest-dipping) laminae. The upper parts of beds are erosionally truncated; thus, topsets of crosslaminae have been removed. Strata and reactivation surfaces are inclined at slightly lower angles than foreset lamination of dunes (fig. 13).

Some dunes display closely spaced double laminae of heavy minerals, separated by a lamina of quartz and feldspar grains (fig. 14). The laminae may represent deposition during slack water and weak current tidal stages, analogous to double clay drapes. Toes of some of the foreset laminae contain small mudchips and pebbles. Bottomset laminae are tangential with the underlying strata; some show slumping.

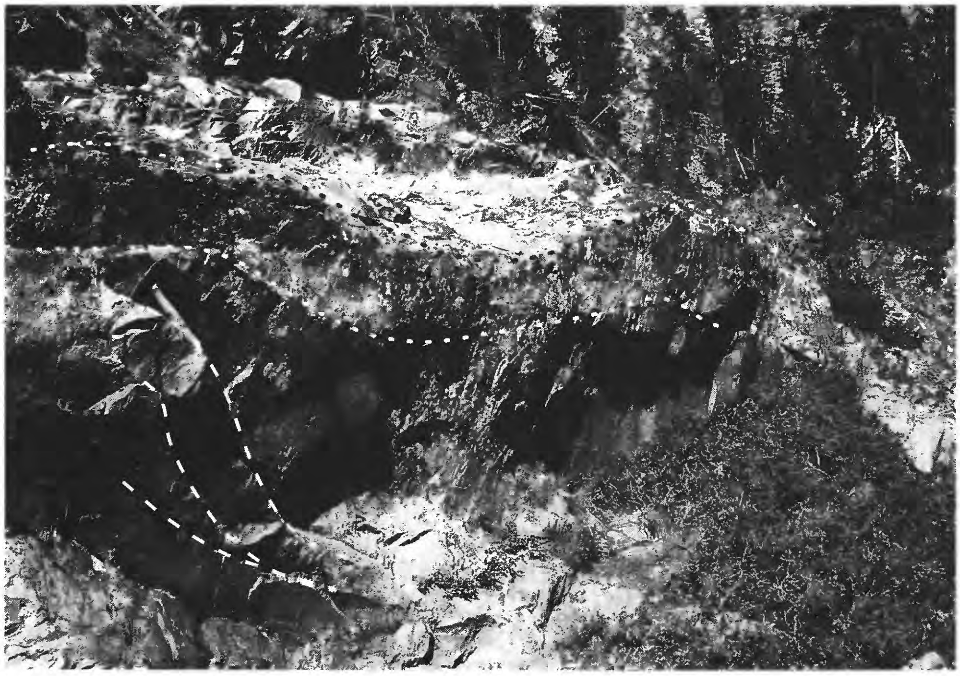


Figure 13. Reactivation surfaces (dashed lines) in dunes of Big Creek Formation in type area. Overlying dune (dotted lines) has wavelength of about 2.5 m and height about 0.25 m. Hammer for scale, handle 24 cm long.

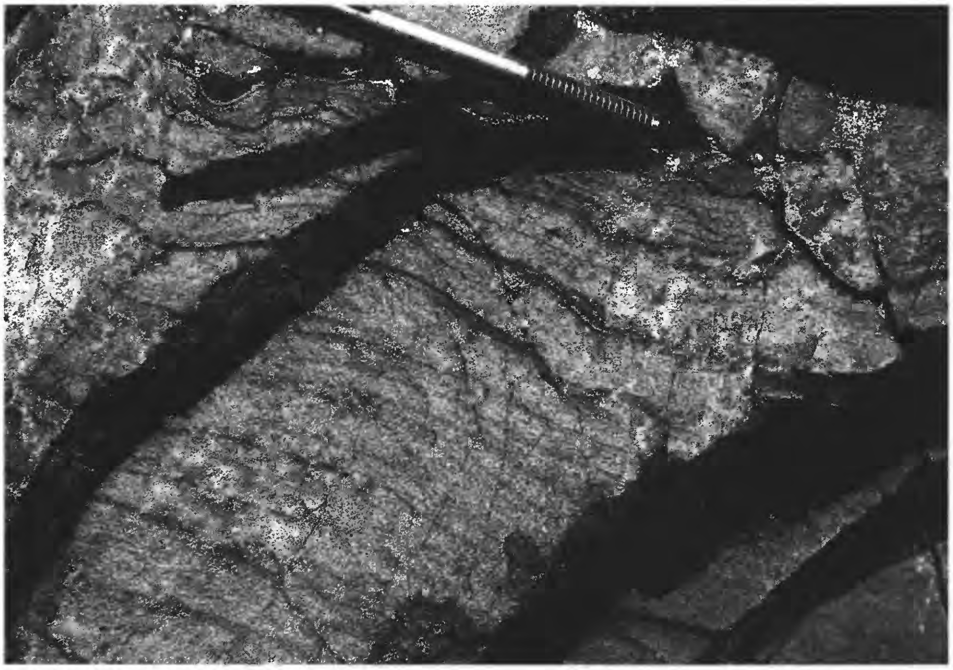


Figure 14. Double heavy-mineral laminae that may have been deposited by slack water and weak tidal current stages. Upper strata of Big Creek Formation in type area. Pencil for scale, 13 cm long.

UPPER CONTACT

The contact surface of the Big Creek Formation with the overlying fine siltite unit of the Apple Creek Formation is a discontinuity and is here considered to be an unconformity. The contact is interpreted as a flooding surface—"a surface separating younger from older strata across which there is evidence of an abrupt increase in water depth" (Van Wagoner and others, 1990, p. 8). Shallow-water strata of the Big Creek are abruptly overlain by "deep" water turbidites of the Apple Creek. As defined by Van Wagoner and others (1988; 1990, p. 22) in their discussions of the concepts of sequence stratigraphy, an unconformity is "a surface separating younger from older strata across which there is evidence of subaerial erosional truncation and, in some areas, correlative submarine erosion, or subaerial exposure, with a significant hiatus indicated." These authors stated that deepening may be accompanied by minor submarine erosion or nondeposition. I found no direct evidence for subaerial exposure, such as a transgressive lag deposit, ravinement surface, transgressive sandstone capping the Big Creek, or indications of a paleosol at the contact. But I do not believe the surface has been examined over a sufficiently wide area to be certain if it underwent subaerial erosion, nor to determine if angularity exists. Further study in the region may cause this interpretation to be reevaluated.

ORIGIN

The Big Creek contains many features in common with modern sediments deposited in intertidal and shallow subtidal environments. Several studies cited in paragraphs following indicate general conditions under which the Big Creek strata may have been deposited. None of the examples of modern-day depositional environments is considered to be a direct analogy; rather, each contains a variety of sedimentary features that are present in Big Creek strata. The features suggest that Big Creek strata were tidally controlled, possibly deposited in a macrotidal setting (daily tidal range greater than 4 m). A brief interpretation of depositional environments for the Big Creek of the type area, south of the Lem Peak fault, closes this section.

Sedimentary features unique to tidal processes include (1) reactivation surfaces, (2) double clay drapes, and (3) sediment cyclicity patterns of thickness variation and sequence repetition that correspond to diurnal and neap/spring tidal cycles (Nio and Yang, 1991). Sedimentary features (1) and (2) are present in the Big Creek strata of the Lemhi Range; no investigation of item (3), cyclicity patterns, was undertaken. These features (1–3) are preserved mainly in a subtidal environment (Nio and Yang, 1991).

Other sedimentary structures present in the Big Creek, but which by themselves are not unique to tidal environments, include (4) flaser and lenticular bedding, (5) herringbone crosslamination, (6) interbedded dunes and siltite (mudstone) lenses and beds, and (7) tidal channel deposits. These features generally are preserved in shallow subtidal to upper intertidal environments. They occur within wave-dominated environments as well as tide-dominated environments, but their direct and intimate association with Big Creek structures diagnostic of tidal origin indicates that they also are of tidal origin.

Most tidal deposits display sedimentary structures that indicate deposition from bipolar currents. The structures are mainly formed during a dominant direction of sediment transport, reflecting either a flood current or an ebb current. Strong tidal asymmetry is indicated for Big Creek strata, with dominant transport to the southwest, and the opposite direction for sedimentary structures produced by subordinate tidal currents.

Dunes of both the two-dimensional and three-dimensional types make up a significant part of the rocks of the Big Creek Formation. Measured two- and three-dimensional dunes are mainly small (wavelength 0.6–5 m), although a few two-dimensional dunes are of medium size (wavelength 5–10 m). Tabulations of dune wavelength and height in many modern environments clearly show that dune size generally increases as water depth increases, and that small to medium dunes generally occur on intertidal flats (Dalrymple and Rhodes, 1995, p. 367–369). (These authors stated that large to very large dunes (wavelength >10 m) generally occur in deep subtidal channels and inlets.)

Three-dimensional dunes are present mainly in the upper part of the Big Creek Formation north of the Lem Peak fault and are of the small size. Flume studies have shown that three-dimensional dunes are formed at greater current speeds, over a greater range of speeds, and in sediment of a wider range of grain sizes, than two-dimensional dunes—the latter have a fairly narrowly restricted range of formation (Southard and Boguchwal, 1990). This suggests that upper strata of the Big Creek, the stratigraphic horizon of the upper part of the measured section (fig. 3) and above, were deposited under higher energy conditions than lower strata. Such conditions reflect an intertidal setting rather than a subtidal one.

Dalrymple and Rhodes (1995, p. 365) stated that three-dimensional dunes develop in the most seaward extent of intertidal sediments exposed during low tides. They are particularly abundant in tide-dominated estuaries, where they are widespread on elongate sand bars or shoals in areas of tidal inlets, tidal channels, and in open-mouthed estuaries. The three-dimensional dunes of the Big Creek resemble, for example, dunes pictured by Dalrymple and others (1978, 1990: their type 2 dunes) in the seaward intertidal deposits of the Bay of Fundy, Nova Scotia, although the Big Creek dunes are smaller; dunes pictured by Elliott and Gardiner (1981) in the macrotidal beaches of the Loughor Estuary, Wales; and those pictured by Hawley (1982) in the inner rough facies of the unbarred macrotidal beaches of the north coast of the Bristol Channel, Wales.

Discontinous layers and lenses of siltite (mudstone) interbedded with dunes composed of fairly clean metasandstone of the Big Creek north of the Lem Peak fault are indicative of highly contrasting flow velocities. The discontinuous layers and lenses of siltite may be analogous to sediments in The Wash, a large (>600 km^2), square-shaped embayment of the North Sea into the southeast side of England. The Wash has a tidal range of 5–6 m. During low tide about half of the sediment in The Wash is exposed, including a complex of offshore banks and shoals toward the central part of the embayment (Wingfield and others, 1978). Sand is the dominant surface sediment of the subtidal areas and the sand flats and offshore banks that are exposed at low tide (Ke and others, 1996).

Cores from the sand banks of The Wash are characterized by sand-with-mud-laminae. The mud laminae are flat lying, usually less than 4 mm thick, and have sharp tops and diffuse bases. They occur in groups, as isolated laminae, and frequently are cut out by erosion. Much of the area of sand-with-mud-laminae is exposed at extreme low tides (Wingfield and others, 1978). Mud also is present in subtidal areas, as thin discontinuous layers (flasers) within the sands (Ke and others, 1996). The sand of the banks is medium grained (Wingfield and others, 1978) but sand-with-mud-laminae occur in both fine and medium sands according to maps of Wingfield and others (1978), and Ke and others (1996). Further, McCave and Geiser (1978) reported the sand banks to be composed of well-sorted fine sand with mud lenses 5 cm thick and 100 m in lateral extent in the outer banks of The Wash.

By analogy with the preceding data on modern depositional environments, the mud lenses and layers of the Big Creek may indicate an upper subtidal to lower intertidal depositional environment. The nonpillowed andesite flow of the Big Creek measured section area (fig. 3) suggests extrusion onto subaerially exposed strata, supporting an intertidal depositional environment for the directly adjacent flaser and lenticular bedded siltite. In addition, the sparse occurrence of double clay drapes in the Big Creek north of the Lem Peak fault is suggestive of an intertidal setting. The presence of mainly a single clay drape suggests that only the drape of slack water at high tide was deposited. The tidal channel deposit of the Buck Lakes area is in the upper strata of the Big Creek and is interpreted as an intertidal feature.

Big Creek strata of the type area, south of the Lem Peak fault, differ from strata north of the fault in being coarser grained, cleaner, richer in quartz, containing lenses of heavy minerals, and lacking layers and lenses of dark-gray siltite (mudstone). The abundance and concentration of heavy minerals in the cirque directly north of the head of Inyo Creek (fig. 2) are indicative of the upper part of a beach. The very broad, low-angle crosslamination of some of the strata is suggestive of beach cusps. Sequences of strata that contain troughs, steeply inclined crosslamination, and beds that cut deeply into one another are suggestive of beds seaward of an upper beach environment. In the cirque, the depositional picture is of a sea shallowing from southwest to northeast, from shoreface to beach.

About 2 km southwest of Yellow Lake (fig. 2), uppermost beds of the Big Creek are composed of small two-dimensional dunes (wavelength 0.6–5 m) that are stacked atop one another. Strong tidal asymmetry is indicated, with a dominant northeast transport and subordinate transport in the opposite direction. Fine sediment is represented only by the thin clay drapes and sparse pebbles, indicating that fines were generally flushed from the environment. Double clay drapes are more common here than in dunes of the Big Creek north of the Lem Peak fault, suggesting that the dunes of the type area were formed in a subtidal environment.

APPLE CREEK FORMATION

The Apple Creek Formation was named by Anderson (1961) for strata in the southern part of the Lemhi 15-minute quadrangle, on the northeast flank of the central part of the Lemhi Range, north of the Lem Peak normal fault. Anderson (1961) designated the type area in the vicinity of Apple Creek, a short tributary of Hayden Creek (fig. 2). Originally called the Apple Creek Phyllite, the name was changed to Apple Creek Formation by Ruppel (1975) because the phyllitic appearance is due to intensely developed cleavage in the type area; the intense cleavage, thus phyllitic appearance, is not characteristic everywhere. Tietbohl (1981, 1986) separated a unit of conglomerate (diamictite) from the Apple Creek, studied its depositional environment, and mapped part of its extent. I remapped the conglomerate (Tysdal, 1996a) and other rocks of the Apple Creek in the southern part of the Lemhi quadrangle map area of Anderson (1961) and contiguous rocks to the west (Tysdal, 1996b; Tysdal and Moye, 1996). I recognized three genetically related gravity-flow units within the Apple Creek. Two of the units, as well as Big Creek strata that are in fault contact with the Apple Creek, were mapped as Apple Creek by Anderson (1961). I mapped the three gravity-flow units separately and gave them informal names, which in ascending order are the fine siltite unit, the diamictite unit, and the coarse siltite unit.

The fine siltite unit is unconformable above the Big Creek Formation and conformable beneath the diamictite unit (Tysdal, 1996a, b; Tysdal and Moye, 1996). In the central part of the Lemhi Range, north of the Lem Peak fault, Ruppel (1980) generally mapped the fine siltite in the upper part of the Big Creek Formation, but he did not recognize its character as being distinct from that of most of the Big Creek (Ruppel, 1975; Ruppel and Lopez, 1988). The diamictite unit, conformable beneath the coarse siltite unit (Tysdal, 1996b), was assigned to the lower subunit of the Yellowjacket strata by Evans (in press). The diamictite was reassigned to the Apple Creek by Tysdal (1996a, b, 2000). The coarse siltite unit also correlates with the lower subunit of the Yellowjacket Formation of Connor and Evans (1986), Connor (1990; 1991), Evans and Connor (1993), and Evans (in press) in the Salmon River Mountains west of the Lemhi Range, as Connor (1990, 1991) recognized previously. The name Apple Creek Formation, coarse siltite unit, was applied to these rocks in the Salmon River Mountains by Tysdal (2000).

The Apple Creek name was applied to rocks in the west-central part of the Lemhi Range, in the vicinity of Yellow Lake (fig. 2), by Ruppel (1975, 1980). These strata lie directly above the Big Creek Formation, as do Apple Creek strata north of the Lem Peak fault. The Apple Creek is thinner south of the fault than north of it (table 1) and constitutes a single lithofacies that generally differs from each of the three lithofacies north of the fault. Apple Creek strata south of the Lem Peak fault are described beginning on page 28.

NORTH OF LEM PEAK FAULT

FINE SILTITE UNIT

The fine siltite unit was so named to convey that its general grain size is less than that of either of the other two units of the Apple Creek Formation north of the Lem Peak fault. The major part of the unit is composed of turbidites. Deposits that may be turbidites or debris flows are interspersed within the sequence and contain stratified clasts of coarse silt to pebble size.

The fine siltite unit is planar-laminated and ripple cross-laminated fine- to medium-grained siltite and argillaceous siltite. In some beds planar laminations grade upward to small-scale (1–3 cm) sets of ripple crosslaminated siltite. Water-escape structures are present locally. Sole marks were not observed. Many beds are graded, with 1–2 cm thick strata of light-gray, medium- to fine-grained siltite grading upward into dark-gray fine-grained siltite and argillite. The unit locally contains matrix-supported granule- to pebble-size argillite clasts in horizons 1–2 clast diameters thick; thicker units occur locally in the upper part. Fine silt and clay content is greater in the upper part of the unit than in the lower part. The unit is approximately 1,000 m thick.

The fine siltite unit generally is greenish gray, although the lower part in particular contains strata that are a distinctive medium bluish gray, grayish blue green, and locally light bluish gray. The greenish-gray color is typical of the entire Apple Creek Formation, but the blue-gray colors are unique to the fine siltite unit. The greenish-gray and blue-gray colors contrast sharply with the light- to medium-gray colors of the underlying Big Creek Formation. The contrast is especially noticeable from the air and where the two formations are extensively exposed in the rugged, nearly treeless terrain of the western part of the Lem Peak quadrangle and adjacent eastern part of the Allison Creek quadrangle (fig. 2). The blue tints are lost in the central and western part of the Allison Creek quadrangle where the metamorphic grade increases from lower greenschist facies to biotite-grade greenschist facies.

The lower contact is marked by the change in color and by change from the coarser grained, clay-free underlying rocks. The upper contact is conformable, marked by the abrupt appearance of beds of diamictite.

CURRENT RIPPLES

Two kinds of current ripples are present within the fine siltite unit. Both kinds occur within zones a few meters thick and are made up almost entirely of rippled, well-sorted medium- to coarse-grained siltite. Grains are chiefly quartz and lesser feldspar, 1–2 percent nonmagnetic opaque minerals in some rocks, and trace tourmaline. Clay matrix is absent.

1. Ripples of the McKim Creek outcrop area (fig. 15), in the westernmost part of the Lemhi Range (fig. 2), are similar to those pictured by Shanmugam and others (1994, fig. 12) from the North Sea, Shanmugam and others (1993, figs. 9, 10; 1995) from the Gulf of Mexico, and Ito (1996, fig. 5B) from the Sea of Japan. They include migrating ripples, some of which are draped by thin clay layers. A few ripples have a sigmoidal shape and display one- to several-laminae-thick clay "offshoots" (discontinuous dark-colored clay "drapes" on ripples or in ripple crosslaminae). The ripples exhibit multidirectional crosslamination and both preserved and eroded tops.

2. In the Bear Valley Creek area (fig. 2), ripples observed only in one place contain heavy-mineral laminae, one lamina thick, at the base of crosslaminae. These current ripples generally are about 0.3–1 cm high and have a wavelength of about 1–3 cm (figs. 16 and 17). The ripple cross-lamination is multidirectional. No clay in ripple troughs or clay "offshoots" were observed in the Bear Valley Creek area.

The two kinds of rippled strata are attributed to reworking by bottom currents for the following reasons. The siltites are well sorted and generally lack a matrix. This is in marked contrast to the associated turbidites of the sequence, which contain poorly sorted silt grains and several percent clay in the matrix. The differing dip directions of crosslaminae suggest multiple current directions, in contrast to the generally unidirectional crosslaminae of ripples of turbidity current origin. The ripples form zones within the turbidite sequence and are not at the top of a depositional unit such as a Bouma turbidite $T_{a\text{–}e}$ succession. The clay "offshoots" of some ripples suggest fluctuation of high and low energy conditions. The association of both preserved and eroded ripple crests (fig. 15) also suggests variable current speeds. In their discussions of bottom-current reworked sands (contourites), Shanmugam and others (1993, 1995) and Ito (1996, 1997) argued that all these features, as well as others not observed in the fine siltite unit of the Lemhi Range, are indicative of traction-formed structures that are different from those of turbidites.

FLOATING ARGILLITE (MUDSTONE) CLASTS

The fine siltite unit contains some beds characterized by isolated clasts of argillite. The beds are much like those termed "slurried beds" by Wood and Smith (1959, p. 173, and pl. VIII, fig. 4). In the classification scheme of Pickering and others (1988), these beds include (but may not be limited to) graded-stratified pebbly siltite and fine-grained metasandstone and stratified gravel.

The common feature of the beds in the Lemhi Range is argillite clasts that are isolated ("floating") in a matrix of coarse-grained siltite to medium-grained metasandstone.

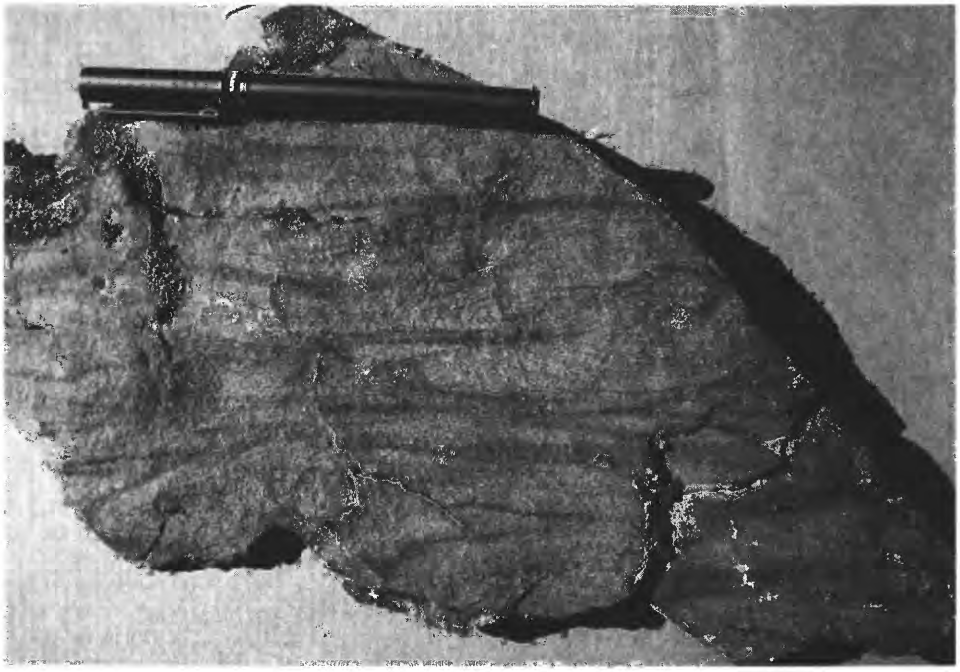


Figure 15. Current ripples, some of which are draped by thin clay layers, in fine siltite unit of Apple Creek Formation. The ripples exhibit multidirectional crosslamination. Near McKim Creek, western part of Lemhi Range (fig. 2). Pen for scale, 13 cm long.

The matrix is stratified but generally is not graded, although grading of argillite clasts was observed at one locality in the eastern part of the mapped area. The clasts are elongate and range in size from granules to pebbles as large as about 10 cm in longest dimension. The packing—or closeness—ranges from clasts that touch to those that are widely dispersed within the matrix. Floating clasts occur at specific horizons within a sequence and are isolated from one another at that horizon (fig. 18). The clasts are not graded within a bed—the largest clasts may occur at any horizon within a bed. The beds exhibit planar clast fabric—clasts are oriented such that the flat side is about parallel to bedding.

The beds range from about 15 to 100 cm thick. Lateral dimensions range from about 1 m for thin beds to several tens of meters for thicker beds. The beds occur in zones and are more abundant in some parts of the section than others, but they do not appear to have a regular pattern. Their base can be erosional or nonerosional. Beds erosional into underlying turbidites were observed only where argillite clasts are closely spaced; conversely, not all beds of closely packed clasts display erosional bases. Some beds are sharply based, and soles of beds in one area north of Mill Mountain (fig. 2) show lineation.

The argillite clasts are foreign to the depositional setting in which they occur—no argillite beds were observed within the fine siltite unit of the Apple Creek Formation. Further, the matrix of these beds generally contains well-rounded grains of quartz sand, including some grains that exhibit overgrowths.

Interpretations of conglomeratic gravity-flow deposits that display the previously described features are in dispute. According to Shanmugam (1996), planar clast fabric, which characterizes the beds, is indicative of laminar flow conditions, the dominant flow process in debris flows. Preservation of rafted clasts requires deposition en masse by freezing, a property characteristic of plastic debris flows rather than fluidal turbidity currents (Shanmugam and others, 1995, p. 483; Shanmugam, 1996; Shanmugam and Moiola, 1997). In contrast, Lowe (1997) pointed out that the importance of "floating" mudstone clasts in turbidites and debris flow deposits has been discussed by many workers over the last few decades and remains poorly understood. He stated that mudstone clasts cannot be used as an unambiguous indicator of flow rheology. No data for choosing between the two interpretations is presented here.

GRADED-STRATIFIED SILTITE

Graded-stratified siltite (classification of Pickering and others, 1988, p. 58) is prominent throughout the areal extent of the fine siltite unit and is the most abundant rock type. The siltite consists mainly of bands, which are very prominent planar, parallel, and horizontal layers. The bands are 0.5–2 cm thick, and locally as thick as 10–20 cm, within the lower 0.5 m to the entire thickness of a bed; beds range up to about 1 m thick (fig. 19). The bands consist of coarse-grained siltite to fine-grained metasandstone that are of finest grain size in the upper part; uppermost parts of some bands grade to fine siltite, but argillite is absent. The bands are rhythmically stratified repetition of Bouma T_b and T_c intervals (T_{bcbc}, for example). Grading is normal; light-colored, coarser grained laminae locally have eroded into underlying dark-colored, finer grained laminae. Some beds

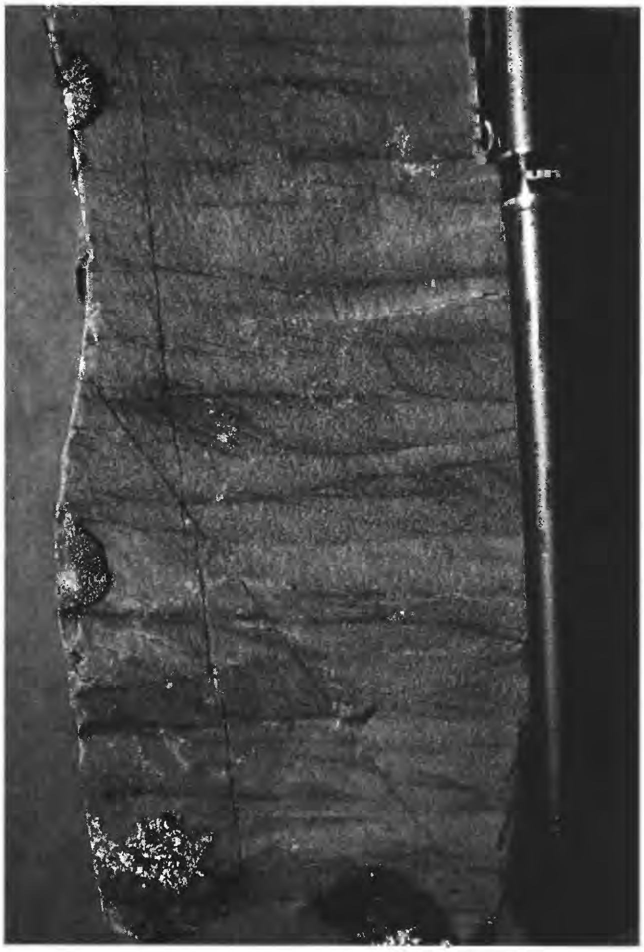


Figure 16. Ripple crosslaminae in fine siltite unit of Apple Creek Formation. Bear Valley Lakes area (fig. 2). Pen for scale, 13 cm long.

give way upward to large ripples (fig. 20), succeeded upward by small ripple crosslaminated siltite (figs. 20 and 21), then planar-laminated siltite. In some areas, the beds formed of the graded siltite are gently undulatory, with wave lengths of several meters and heights of only a few centimeters. These strata fit the Bouma sequence: the bed of bands as T_{bc} layers, grading upward to only T_c and locally T_d layers. Bases of some beds contain a T_a layer of granule- to pebble-size clasts of argillite (mudstone).

Soft-sediment deformation structures are fairly common. Fluid-escape structures are the most abundant and typically extend through several bands. The largest structures observed were about 30 cm high and their cross section is teepee shaped (fig. 22). Dish structures were observed only locally. Convolute laminations are uncommon but include local slump folds that are recumbent.

The graded-stratified siltite beds are interpreted as turbidite deposits. The repeated T_{bc} strata that make up most (to all of some) beds are similar to the vacillatory turbidites described and pictured by Larue and Speed (1983) and Larue and Provine (1988). Vacillation refers to the repetition of the Bouma T_{bc} intervals within what is regarded as a single bed or a single flow event (Larue and Provine, 1988).

DIAMICTITE UNIT

Abundant beds of poorly sorted conglomerate characterize a succession of otherwise fine-grained strata within the Apple Creek Formation north of the Lem Peak fault. These pebbly strata were first reported by Anderson (1961) in his Apple Creek map unit in the Apple Creek–Hayden Creek

Figure 17. Ripples of type that produced crosslaminae illustrated in figure 16. Pen for scale, 13 cm long.

Figure 18. Conglomerate bed (across middle of photograph) in upper part of fine siltite unit of Apple Creek Formation, about 4 km northwest of Mill Mountain (fig. 2). Bed exhibits planar clast fabric—clasts (light gray) are oriented such that the flat side is about parallel to bedding, but they are not graded according to size within bed. Note that most clasts are not touching, but rather are floating within the argillaceous matrix. Hammer for scale, handle 24 cm long.

Figure 19. Rhythmically graded beds of stratified siltite within fine siltite unit of Apple Creek Formation. Light-gray layers are coarser grained siltite, dark-gray finer grained. Youngest strata are at top of photograph. From eastern part of Salmon River Mountains (fig. 2). Pen for scale, 13 cm long.

area of the Lemhi 15-minute quadrangle (fig. 2). The succession was separated as a distinct unit by Tietbohl (1981, 1986), who used the term diamictite for the poorly sorted, matrix-rich conglomerate beds and applied the name generally to the entire unit. Tietbohl confirmed the sedimentary origin of this pebbly mudstone-bearing unit, mapped its distribution in the vicinity of Hayden Creek–Apple Creek, and attributed its origin to submarine slumping in combination with normal sedimentation. The diamictite unit generally is intensely cleaved where it crops out on the eastern flank of the Lemhi Range, commonly obscuring sedimentary features. Tietbohl (1986) interpreted the cleavage as a tectonic overprint. The upper contact of the diamictite unit is gradational through tens of meters into the coarse siltite unit of the Apple Creek Formation.

The thickness of the diamictite unit is uncertain due to deformation, but is estimated to be 1,000–1,500 m in the vicinity of Hayden Creek on the east and about 600 m near the Salmon River on the west, where it is depositionally thin

Figure 20. Planar-laminated stratified siltite of Bouma T_b layer that gives way upward to large ripple (form shown by dashed line) of T_c layer, wavelength about 0.6 m; succeeded upward by siltite containing abundant small crosslaminated rippes (above and to right of ripple trough), then by planar-laminated siltite of T_d layer. Hammer spans basal part of overlying bed. Hammer for scale, handle 24 cm long. Apple Creek Formation.

Figure 21. Closeup of ripple crosslaminated siltite like that above trough axis of large ripple shown in figure 20. Exposed part of hammer handle is about 22 cm long. Apple Creek Formation.

(Tysdal, 1996b; Tysdal and Moye, 1996). The regional, along-strike, outcrop pattern of the diamictite unit thus is a fan shape. The conglomerate is tightly folded in the footwall of the Bear Valley thrust fault (not shown in fig. 2) in the Hayden Creek area.

Rocks here assigned to the diamictite unit of the Apple Creek Formation, and mapped as such by Tysdal (1996a), were shown as Yellowjacket Formation by Ruppel (1980) in the northwest quarter of the Patterson 15-minute quadrangle. Ruppel and Lopez (1988, p. 15) recognized the diamictite unit of the Patterson map as being structurally deformed and stated that in places the strata resemble those of the Apple Creek Formation. They apparently did not recognize the conglomeratic nature of the unit, however, stating (Ruppel and Lopez, 1988, p. 76) that on Mill Mountain " ***the Big Creek [Formation] is thrust over a coarse turbidite facies of

Figure 22. Fluid-escape structure in stratified siltite of fine siltite unit of Apple Creek Formation, eastern part of Salmon River Mountains (fig. 2). Hammer for scale, handle 24 cm long.

the Yellowjacket Formation, and is strongly sheared and brecciated." The area shown as sheared and brecciated by Ruppel (1980) is intensely cleaved conglomerate of the diamictite unit, and locally of the underlying fine siltite unit, of the Apple Creek Formation.

SILTITE

Nonconglomerate beds of the diamictite unit are mainly composed of gray-green argillite, argillaceous siltite, fine- to medium-grained siltite, and lesser metasandstone. The beds form successions as thick as 10 m or more between conglomerate beds. Graded beds are obvious where deformation is not intense, and Bouma sequences are most prominent in the upper part of the unit. Beds are generally only a few centimeters thick and are finely laminated. Tietbohl (1986) observed sole marks along the base of some metasandstone beds that directly overlie conglomerate beds. He also reported load structures and convolute beds, the latter including some that were truncated by overlying diamictite beds. Water-escape structures occur locally. I observed sparse laminae and bands of magnetite as thick as 2 cm in the Wright Creek area. Paleocurrent directions were determined from current ripples. The few determinations revealed transport from both the northeast and the southwest. The significance of the few observations is uncertain. These fine-grained strata are attributed to a turbidite origin, based on the Bouma sequences and the associated sedimentary structures.

MATRIX-SUPPORTED CONGLOMERATE

Most of the conglomerate beds are composed of disorganized matrix-supported clasts of argillite, siltite, metasandstone, and rock fragments. Clasts are commonly 1–2 cm in diameter but locally are as large as 20–25 cm; one 50 cm long clast was observed. Clasts range from subangular to well rounded. The concentration of clasts is variable, and the larger clasts are dispersed within deposits that also contain abundant pebbles; hence, deposits are poorly sorted. Of more than 500 clasts examined in thin section by Tietbohl (1986), about 90 percent were detrital rock fragments, which ranged from argillite to fine-grained metasandstone. Foliated low-grade metamorphic rock fragments also were observed by Tietbohl (1986), who believed that the foliation formed before the clasts were incorporated into the conglomerate. I observed a 5 cm diameter clast of white bull quartz in a conglomerate bed near the junction of Hayden and Bear Valley Creeks. The matrix of the conglomerate beds is composed of sericite, muscovite, chlorite, and silt of quartz and plagioclase, as well as local medium-grained, rounded, quartz sand grains (Tietbohl, 1986).

Fine layering within the matrix-supported conglomeratic beds, or imbrication of clasts in the beds, was not observed everywhere in the unit. The sequence of Proterozoic rocks in the Lemhi Range was deformed during thrusting, and the silt in the matrix of the conglomerate units "flowed." Fine layering is commonly obscured or destroyed, and clasts are rotated such that their long axes are oriented about parallel to cleavage. Conglomeratic beds have a tabular geometry in the few places where exposures are sufficient to view the beds over a broad area and are tens to several tens of meters wide.

These conglomerate beds contain many of the features described under "Floating Argillite (Mudstone) Clasts," pertaining to beds of the fine siltite unit. The beds are either turbidites or debris flows; distinguishing between these two kinds of gravity flows is a matter in dispute, as stated in the aforementioned section of this report.

GRAIN-SUPPORTED CONGLOMERATE

Conglomerate that contains a small amount of clay was observed on the ridge west of Wright Creek (fig. 2). The beds are composed of poorly sorted granules and pebbles of claystone and mudstone that are more or less in contact with one another—grain supported—thus are similar in packing and clast composition to some conglomerate beds in the underlying fine siltite unit of the Apple Creek Formation. The clasts are tabular shaped and are aligned such that their broadest sides are about parallel to bedding. They range from a few millimeters to as much as 3 cm across and are disorganized (no grading, no stratification, no strongly preferred fabric). In a few outcrops, crosslaminated metasandstone forms the basal part of a bed of mudstone-granule conglomerate, which is ungraded and of a uniform granule size. No grading is evident within the conglomerate.

Silt constitutes about 75 percent of the matrix of grain-supported conglomerate beds and is chiefly fine grained to coarse-grained quartz and feldspar. Sand grains in the matrix are entirely quartz of fine and medium grain size; many of the quartz grains are well rounded and some display overgrowths. Sericite makes up 1–3 percent of the matrix. Beds of the granule conglomerate commonly are 10–15 cm thick, lack internal lamination, and show little evidence of erosion into the underlying strata.

These strata probably are either turbidites or debris flow deposits, as discussed in the section entitled "Floating Argillite (Mudstone) Clasts."

MAGNETITE BANDS

Magnetite bands are present locally within the finely laminated, fine- to medium-grained siltite that occurs in sequences between beds of conglomerate on the ridge north of Wright Creek. The bands generally are less than 5 mm thick, although a 2 cm thick band was found at one locality. Some of the thicker bands locally sag into the underlying siltite, forming small load casts. Magnetite appears to form the basal 1–5 mm of 1–2 cm thick graded beds; dark-gray fine-grained magnetite and magnetic siltite grade upward into nonmagnetic siltite.

Magnetite bands present in the conglomerate unit are considered to be primary features. Millimeter-thick microbands of magnetite are undisturbed, implying accumulation below wave-base of storms and not reworked by bottom currents. The magnetite laminae may have been deposited directly on the sea floor as a chemical sediment. In addition, or alternatively, magnetite laminae may have precipitated directly onto the ocean floor and subsequently were resedimented as turbidites, as proposed by Barrett and Fralick (1985; 1989) for Late Archean rocks of Ontario, Canada.

Structural relationships indicate a predeformation timing for formation of the magnetite bands in the Lemhi Range. At one place, a 1 cm thick band of magnetite within the core of a fold 4 m across is deformed into small folds of 1–2 cm wavelength. Axial plane cleavage of the large fold cuts the magnetite bands. These structural features and relationships indicate that the magnetite layers predate deformation. Magnetite grains that are considerably coarser than host siltite grains also are scattered throughout some beds. These late-formed magnetite grains are undeformed and postdate cleavage.

Magnetite-bearing beds were reported previously in strata of central Idaho. Connor (1990, 1991), in his interpretation of mineralization in the Salmon River Mountains, tentatively considered the diamictite unit of the Lemhi Range to be related to his lower subunit of the Yellowjacket Formation, which I (Tysdal, 2000) consider to be the coarse siltite unit of the Apple Creek Formation. Within this unit near Iron Creek in the Salmon River Mountains, Modreski (1985, p. 211) had reported magnetite in "thin laminae along bedding planes, in irregular streaks and veinlets, and in layers composed entirely of massive magnetite." Connor (1991) stated that the rocks of the Iron Creek area are variably magnetic. Connor (1990, p. 20–21) discussed the iron content of the unit, stating that euhedral grains of magnetite are disseminated in the siltite and that the euhedral form of the magnetite suggested diagenetic or metamorphic crystallization. He followed Hughes (1983), Hahn and Hughes (1984), Nash and Hahn (1989), and Nash (1989) in attributing mineralization in the Salmon River Mountains to submarine thermal venting.

COARSE SILTITE UNIT

The coarse siltite unit, present north of the Lem Peak fault, is composed of gray-green medium- to coarse-grained siltite and fine-grained sandstone, metamorphosed to the lower greenschist facies. Distinctive graded beds of light-gray quartz-rich fine-grained metasandstone to coarse-grained siltite, as thick as 1 m, are interspersed within the sequence. These beds are most abundant in the lower part of the unit. The coarse siltite unit of the Apple Creek Formation derives its informal name from these light-gray beds. Upper

Figure 23. Sharp-based fine-grained light-gray metasandstone bed (T_b) within siltite of coarse siltite unit of Apple Creek Formation. Metasandstone grades upward into rippled siltite (T_c). Siltite clast is present within upper part of bed. From Basin Lake area (fig. 2). Pen for scale, 13 cm long.

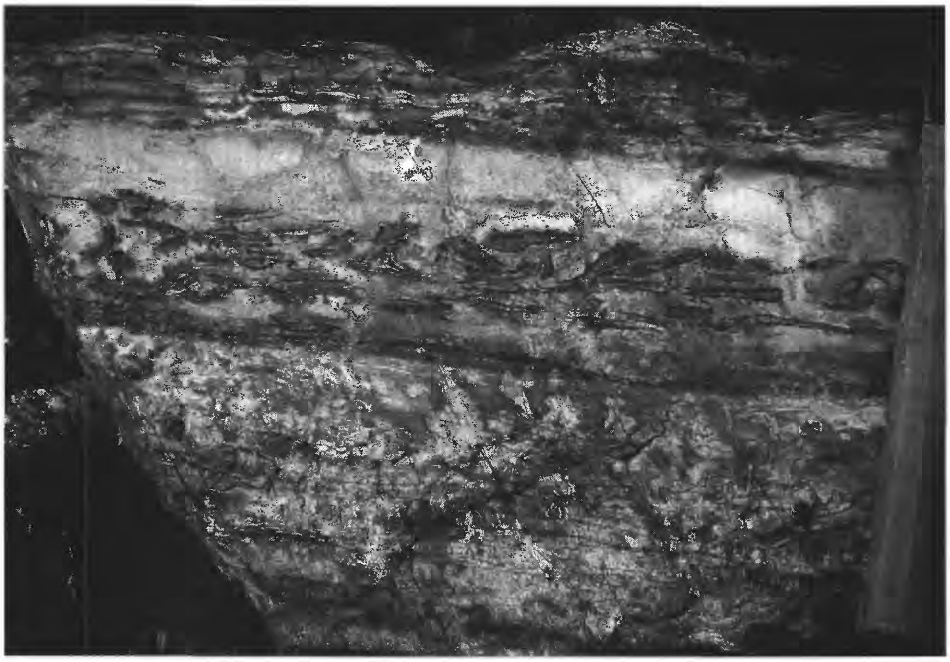


Figure 24. Light-gray fine-grained metasandstone bed (T_b) that contains disrupted mudstone layer in lower part (T_a). Siltite layer was broken into pieces when still soft mudstone, as indicated by curved and sharply folded shapes of some pieces. From coarse siltite unit of Apple Creek Formation, Basin Lake area (fig. 2). Hammer for scale, handle 24 cm long.

strata of the unit generally are fine- to medium-grained siltite that locally contain soft-sediment deformation structures. The most complete sequence of the coarse siltite unit extends from near the easternmost Bear Valley Lake to Basin Lake, upsection from south to north, in the westernmost part of the Lem Peak quadrangle (fig. 2). The preserved thickness of the unit in the northern part of the Lemhi Range is 2,000–2,500 m (Tysdal, 1996b; Tysdal and Moye, 1996).

LIGHT-GRAY METASANDSTONE

Light-gray metasandstone beds are the unifying characteristic of the coarse siltite unit. The beds first appear abruptly at the base of the unit, and except for one known occurrence of a few thin beds within the upper part of the underlying diamictite unit, are absent from other strata of the Apple Creek Formation north of the Lem Peak fault. No

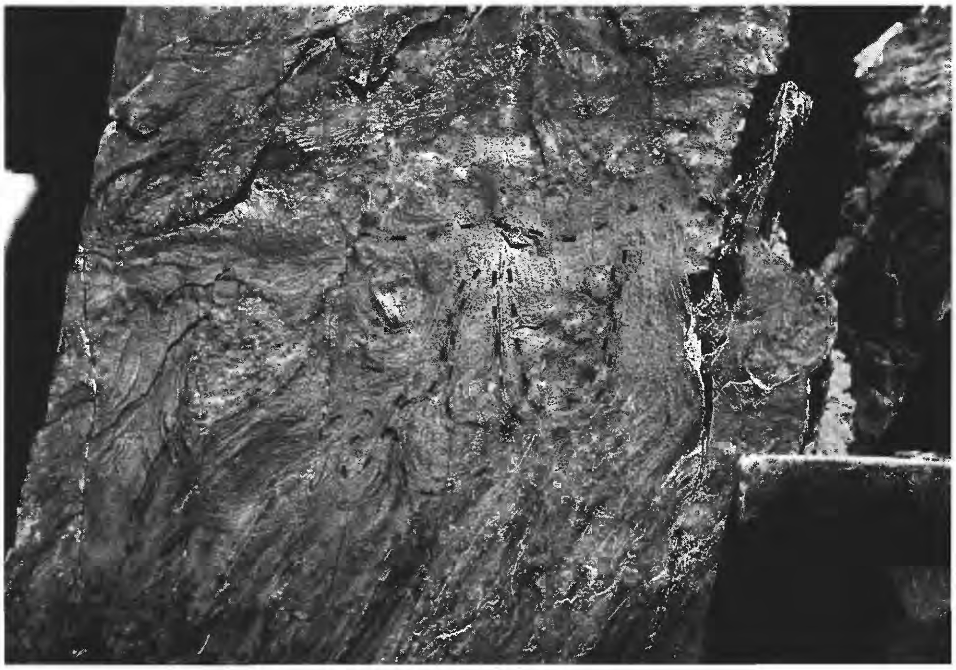


Figure 25. Convolute lamination of Bouma T_c layer, including pillar structures between U-shaped areas. Coarse siltite unit of Apple Creek Formation, Basin Lake area (fig. 2). Hammer for scale, exposed part of hammer head 10 cm long.

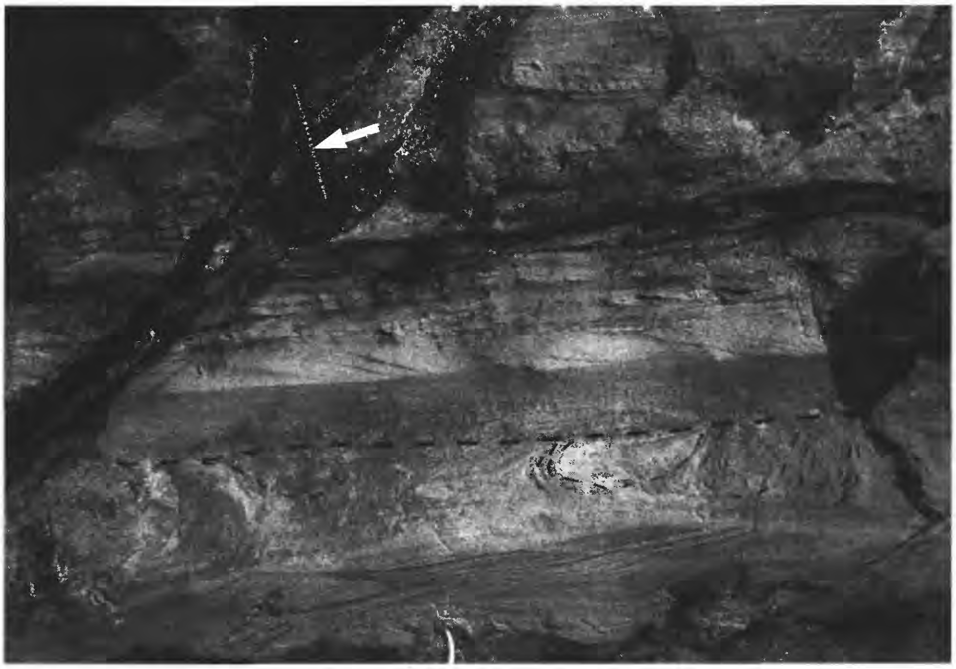


Figure 26. Climbing ripples in Bouma T_c subdivision of graded bed that give way upward to convolute lamination, emphasized by dashed lines, then to planar lamination of T_d layer. Coarse siltite unit of Apple Creek Formation, Basin Lake area (fig. 2). Exposed part of pen (arrow) is 11 cm long.

diamictite beds are present within the coarse siltite unit. The light-gray metasandstone beds are commonly 10–30 cm thick, although some as thick as 1 m occur locally. They are sharp based and generally nonerosive (fig. 23), except for some thick beds that fill scours cut into underlying strata. Load casts occur at the base of some beds. Ripple crosslamination is a common feature of the metasandstone and is most pronounced and thickest in the thicker beds.

The light-gray metasandstone beds are graded. The grain size ranges from sand to silt, but sand-size grains constitute well over half of each bed, hence the general name of metasandstone. Grain size grades upward from very fine grained or fine-grained sand into coarse silt, and, in about the top 10 percent of each bed, into gray-green silt that is medium to fine grained. The metasandstone is medium gray on fresh fracture, but weathers light gray and contrasts sharply with the gray-green color of associated strata. The light-gray metasandstone and coarse siltite are 80–90 percent quartz, the remainder mainly plagioclase and 1–2 percent muscovite. The beds display Bouma T_{b-c} and T_{b-c-d}

Figure 27. Soft-sediment deformation features in upper part of coarse siltite unit of Apple Creek Formation, including ball-and-pillow structures and pillar structures. Basin Lake area (fig. 2). Exposed part of pen (upper right corner) is 10 cm long.

sequences. The beds are planar laminated or structureless in the lower part, grading upward to ripple crosslaminated, then to planar-laminated gray-green siltite. Pebbles (Bouma T_a) were observed at the base of a few beds. Water-escape structures were observed in a few beds.

Chips of dark-gray fine-grained siltite occur in a few beds, where they are dispersed within a matrix of light-gray fine-grained metasandstone or coarse-grained siltite. The chips generally are 0.1–0.5 cm long, although some tabular argillite clasts as long as 5 cm were observed; their flat sides are parallel to bedding. Some "clasts" are disrupted, broken beds that apparently were soft during downslope gravity-driven transport; they are folded (fig. 24).

The best exposures of the light-gray metasandstones are on the ridge north of the cirque that contains the Bear Valley Lakes (fig. 2). The metasandstone beds are most abundant, thickest, and display the greatest range of sedimentary features on the southern slope of this ridge. In one zone, metasandstone beds are stacked one atop another. Strata of this area are in the upper part of the lower third of the coarse siltite unit. Up- and downsection from this area the light-gray metasandstones are less common and thinner, but beds are present at least every several tens of meters.

GRAY-GREEN SILTITE

Gray-green siltite constitutes most strata of the coarse siltite unit, which mainly contains siltite, local beds of argillite, and fine-grained metasandstone. The siltite beds observed are normally graded. Siltites are composed predominantly of quartz, plagioclase, and less than 10 percent matrix that has been recrystallized to fine mica. The coarser grained siltites generally occur in the thicker beds. The beds are as thick as 1 m, but most commonly are about 10–25 cm thick. In some areas beds are 1 cm or less thick, their grading indicated by a color change from medium gray to dark gray upward in each bed. Magnetite bands, about 0.5 cm thick, were observed in the coarse siltite unit in two places: directly above the diamictite unit along the Hayden Creek Road (downstream from junction with Bear Valley Creek) and in the northeast part of the S1/2 of Hayden Creek quadrangle (fig. 2).

Soft-sediment deformation structures are widespread in this unit. They are particularly common in the Basin Lake area (fig. 2), which contains the stratigraphically highest (youngest) rocks of the unit in the mapped area. Some of the fine-grained siltites and argillites were very water rich when deposited and host spectacular convolute lamination structures (fig. 25), the largest of which is about 50 cm high. Dish and flame structures are typical of some beds. Some thick beds show an upward change from massive metasandstone at the base through dish structures, thin pillars, to convolute bedding in the upper part (generally 1/4–1/3 of the entire bed). Ripple crosslamination characterizes many of the turbidites in the coarse clastic unit. Climbing-ripple crosslaminations, in the Bouma T_c subdivision of a few graded beds, occur directly above nonclimbing ripples and give way upward to metasandstone displaying convolute lamination structures 1–5 cm across (fig. 26).

Ball-and-pillow structures, which are generally 5–10 cm across but as large as 25 cm across, are common (fig. 27). Pillar structures (Lowe, 1975) are present between some of

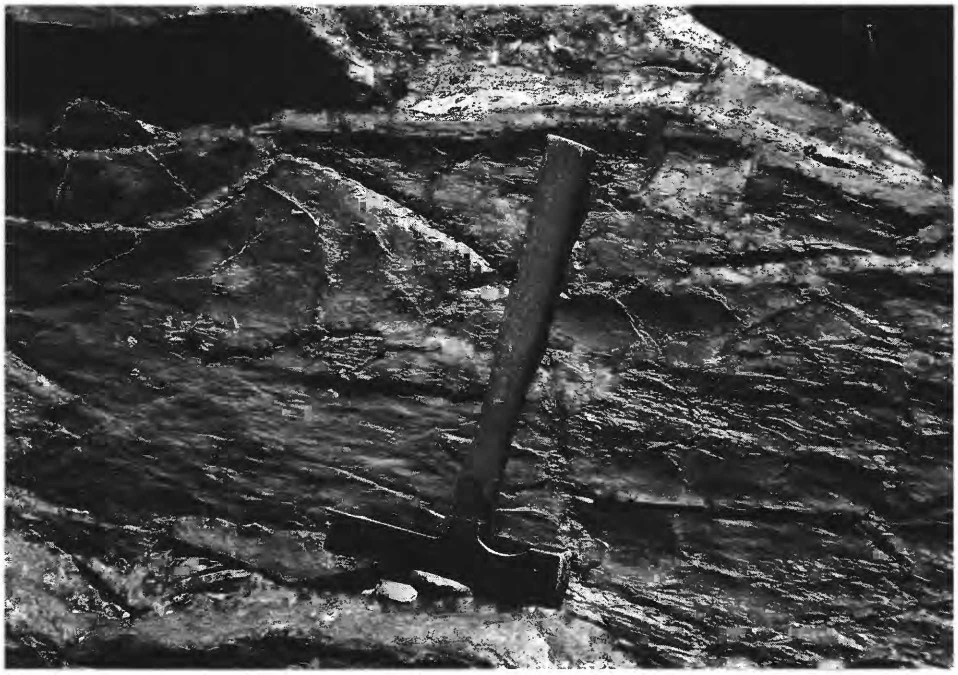


Figure 28. Flute and groove casts and syneresis cracks in coarse siltite unit of Apple Creek Formation. Bear Valley Lakes area (fig. 2). Hammer for scale, handle 24 cm long.

the ball-and-pillow structures, shown in the figure. Differential compaction and formation of ball-and-pillow structures took place before deposition of directly overlying beds, which show no soft-sediment deformation.

Syneresis cracks (fig. 28) are fairly common in the siltite beds of this unit, in contrast with their absence from the other two units of the Apple Creek Formation north of the Lem Peak fault. Flute casts and tool marks were observed locally (fig. 28).

ORIGIN OF APPLE CREEK FORMATION NORTH OF LEM PEAK FAULT

The graded bedding and sharp bases of the light-gray-weathering metasandstone beds indicate deposition from turbidity currents or storm currents. The close spatial association of the gray-green siltites and interbedded light-gray metasandstones with the resedimented material in debris flows/turbidites of the diamictite unit favors a turbidite interpretation. The gray-green siltites display characteristics of turbidites. Soft-sediment deformation recorded by the convolute folds and associated pillar structures (figs. 25, 27) is similar to that commonly found at the head of pro-delta slope deposits. The general lack of wave reworking of sediment of the unit indicates deposition below normal wave base.

The few pebble beds in the sequence could be either turbidites or debris flows. See section on the "Fine Siltite Unit" (of the Apple Creek Formation) for discussion concerning controversy of interpretation of origin of the types of deposits.

A turbidite origin was proposed by Sobel (1982), Hughes (1983), and Hahn and Hughes (1984) for strata in the vicinity of the Blackbird mine (not shown in fig. 1) and directly to the east, in the Salmon River Mountains, about 30 km west of Salmon (fig. 2). These strata were assigned to the Yellowjacket Formation by the above cited workers, and to a lithofacies mapped as the "middle subunit of the Yellowjacket" by Connor and Evans (1986). Strata of this lithofacies conformably overlie rocks that Tysdal (2000) correlated with the coarse siltite unit of the Apple Creek Formation, and therefore are younger than the Apple Creek lithofacies preserved in the Lemhi Range.

A main goal of this report was to determine the general depositional environment for the strata of the Apple Creek Formation. No attempt was made to determine the regional structural setting at the time of deposition because the mapped area is only a small part of the region within which the formation is distributed. However, my working hypothesis is that the Apple Creek strata were deposited in an extensional structural setting, not a compressional setting in which thrusting was ongoing at the time of deposition. This interpretation is based in part on the work of Hahn and Hughes (1984) and coworkers in the Blackbird area of the Salmon River Mountains.

SOUTH OF LEM PEAK FAULT

YELLOW LAKE UNIT

The description of this unit is based mainly on a section measured on the ridge directly southwest of Yellow Lake (fig. 2). (This lake was called Golden Trout Lake by Ruppel (1975), is unnamed on the Yellow Peak 7.5-minute topographic quadrangle published in 1989, but is known as Yellow Lake to U.S. Forest Service personnel.) The section is in the Patterson 15-minute quadrangle that was mapped by Ruppel (1980), who (Ruppel, 1975) first applied the Apple Creek name to these strata. It lies about 1 km west of the principal reference section designated by Ruppel (1975, fig. 2) and was selected because it affords nearly complete exposure of moderately to steeply north dipping strata of an anticlinal limb. The measured section does not include the entire formation due to structural complications in the lower strata. However, reconnaissance traverses, combined with the mapping of Ruppel (1980), suggest that this is the most complete sequence. Ruppel (1975) stated that the entire Apple Creek (that is, mainly in the Patterson 15-min. quadrangle that he mapped) "***is present, unfaulted, high on the ridge between Patterson Creek and its East Fork." Examination of Ruppel's (1980) map shows the formation to be much thinner there than in the Yellow Lake area, and my reconnaissance indicates that a normal fault accounts for the absence of lower strata of the unit in the Patterson Creek area.

The Apple Creek strata in the Yellow Lake area mainly consist of dark-gray medium- and fine-grained finely laminated siltite, and locally argillite in the lower part. Carbonate strata are the unifying characteristic of the sequence and serve to distinguish this unit from the other units of the Apple Creek Formation. Other distinctive characteristics include the overall fine to medium grain size of the siltite, and in the upper part of the section, sporadic interbeds of light-gray metasandstone. Dark-gray and reddish-purple colors reported by Ruppel (1975, 1980) and Ruppel and Lopez (1988) in the lower part of the Yellow Lake lithofacies characterize many beds of fine siltite and argillite. The lithofacies is generally coarser in its upper third, reflected both in the coarse grain size of the siltite beds and in the presence of the metasandstone beds.

The fine-grained siltite is very finely planar laminated in layers that are 1–2 mm thick, typically forming beds 5–20 cm thick. Beds 1–5 cm thick are repetitively interlayered with the siltite in the lower part of the lithofacies. Carbonate laminae 1–5 mm thick typically occur at irregular intervals throughout much of the upper two-thirds of the section. Many of the fine-grained siltite beds are graded; slabbing of rock probably would show that most of the beds are finely laminated and graded. Ripple crosslamination is common in the unit. Mudcracks reported by Ruppel (1975, 1980) and Ruppel and Lopez (1988) are here termed syneresis cracks: their origin cannot be demonstrated to indicate subaerial exposure.

Some siltite beds are composed of interlaminated layers of fine- to medium-grained siltite and argillite. Laminae are commonly 1–2 mm thick and normally graded. Other beds exhibit scoured bases and graded tops. Ripple crosslamination is fairly common. These siltite strata commonly occur in beds as thick as 0.5 m, appearing abruptly above other strata.

Slump folds are common within the sequence and indicate gravity-driven downslope movement (fig. 29). Movement apparently was toward the northeast, but further examination is needed to determine the general direction with some certainty.

Lenticular bedding is present locally, composed of siltite ripples that are isolated within argillite beds (starved ripples of some authors) (fig. 30). The same photograph also shows graded fine siltite and argillite layers 0.5–1 cm thick, which are directly associated with some of these strata. Where the isolated ripples have settled into underlying water-saturated clay (now argillite), they formed load structures called pseudonodules (Stow and Shanmugam, 1980) in which the isolated ripples are separated farther from one another (fig. 31). In other cases, the pseudonodules formed from beds a few millimeters thick of horizontally laminated silt that settled into underlying water-saturated clay, breaking into segments separated by upward-protruding flame structures.

Larger structures related to water-saturated sediment are fairly common. Local fluid-escape structures, generally 5–10 cm high but some 25–30 cm high, show dewatering across several beds. Convolute lamination takes the shape of ball-and-pillow structures in a few beds and U-shaped soft-sediment deformation structures flanked by pillars in fine-grained siltite beds as thick as 10 cm.

Thickness of the Apple Creek in the area mapped by Ruppel (1980) was calculated at 760–900 m (Ruppel, 1975; Ruppel and Lopez, 1988). The thickness of 725 m that colleagues and I measured (table 1) in the section near Yellow Lake does not include the entire unit.

CARBONATE BEDS

Carbonate beds in the Yellow Lake lithofacies of the Apple Creek include dolomite and locally calcareous dolomite. Ruppel (1975, 1980) reported that the carbonates are ferrodolomite, but X-ray examination of five samples from the unit revealed only dolomite: no significant amounts of ferrodolomite, ankerite, siderite, or other iron-carbonate minerals were detected (G.A. Desborough, written commun., 1996). The outcrop surface of many of the dolomite beds weathers a rusty-brown color, indicating the presence of iron. The iron likely precipitated from rainwater during chemical reaction with the limestone; iron in the rainwater probably was derived from siltite beds upsection (G.A. Desborough, oral commun., 1996).

Silty dolomite forms distinctive interlayered beds 1–5 cm thick in the bottom half of the unit. Carbonate attains a maximum presence about 300 m above the base of the measured section where a 4 m thick unit of slightly silty

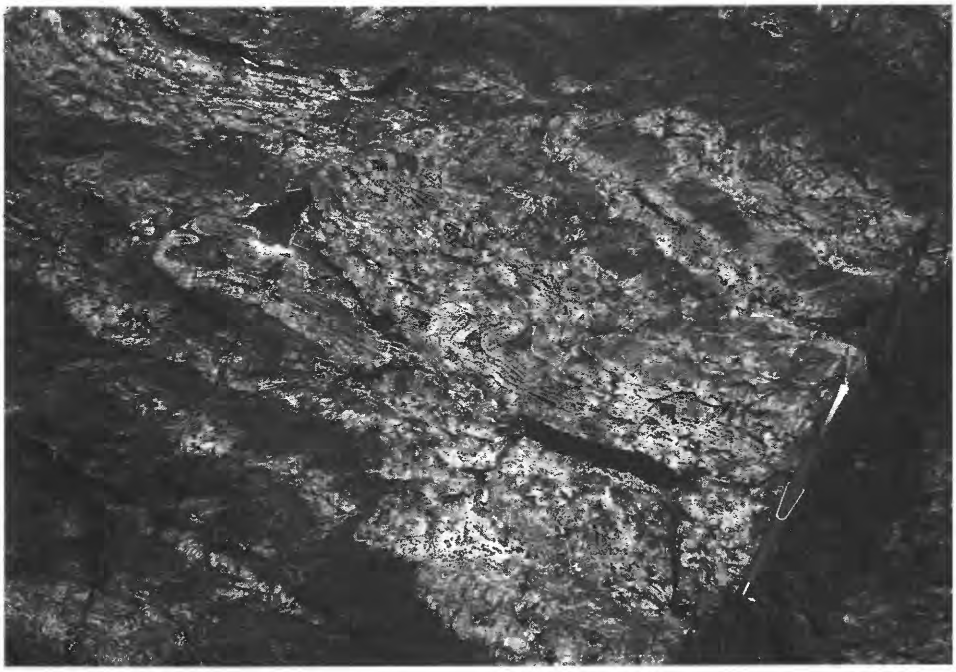


Figure 29. Slump folds in Yellow Lake unit of Apple Creek Formation. Slump folds are accentuated by cleavage, but note that beds directly beneath folds are *not* folded, thus folds are not of tectonic origin. Stud-finder magnet at right for scale, 12 cm long.

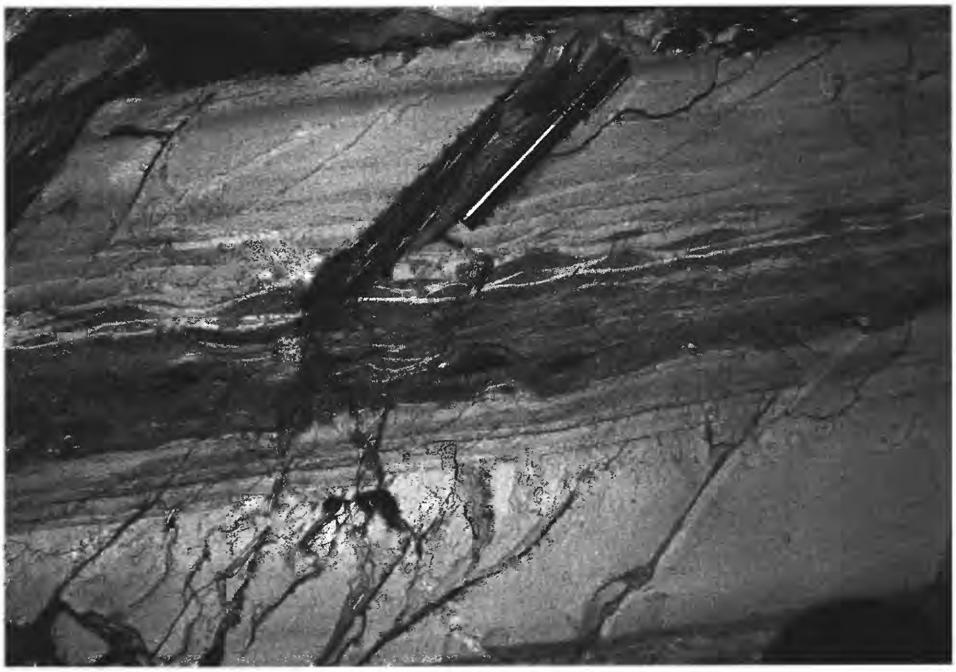


Figure 30. Lenticular bedding of siltite ripples isolated within argillite. Some ripples are fading ripples (Stow and Shanmugam, 1980), in which silt laminae of ripple crests pass gradually into ripple trough of argillite. Paleocurrent is from left to right. Photo also shows graded layers, 0.5–1 cm thick, of fine siltite and argillite. Yellow Lake unit of Apple Creek Formation, near Yellow Lake (fig. 2). Pen for scale, 13 cm long.

calcareous dolomite crops out. The dolomite contains sparse laminae of siltite that are planar bedded to ripple crosslaminated. Dewatering structures, in zones as thick as 25–30 cm, occur locally in siltite beds associated with these carbonate beds. Some of the thicker carbonate beds contain “floating” medium sand grains of rounded quartz and silt of fine- to medium-grained quartz and feldspar. Upsection, carbonate decreases in abundance and in bed thickness, forming laminae only a few millimeters thick. Some of the carbonate is at the base of 3–5 cm thick graded beds, which fine upward to noncalcareous siltite. Carbonate laminae and silty carbonate beds weather more readily than siltite, causing the carbonate layers to be recessive, prominently so in some beds.

Figure 31. Pseudonodules, load structures formed of isolated ripples of siltite that have settled into underlying water-saturated clay (argillite). Horizontal displacement (paleocurrent from left to right in photograph) of siltite layer took place during deposition, as shown by the general "tailing off" of layer to left, forming threads (tails) that connect many psudonodules; other pseudonodules are isolated, their threads broken. Yellow Lake unit of Apple Creek Formation, near Yellow Lake (fig. 2).

METASANDSTONE

Light-gray metasandstones and interbedded siltite in the upper part of the unit are sharp based, graded, and commonly 20–50 cm thick. They typically are fine grained and either plane bedded or massive in the lower part, grade upward to ripple crosslaminated siltite in the middle, and are capped by planar-laminated gray-green siltite. The metasandstone is 40–60 percent quartz, 25–30 percent potassium feldspar, 5–15 percent plagioclase, and lesser rock fragments; matrix is 0–3 percent. Reconnaissance examination of strata in the uppermost 100 m of the section showed chiefly fine grained metasandstone. Some beds display linguoid ripples and others straight-crested ripples. A few metasandstone beds as thick as 3 m are graded, capped by siltite that locally displays ripples.

CONTACTS

The Apple Creek is conformable and transitional into the overlying Gunsight Formation (Ruppel, 1975, 1980; Ruppel and Lopez, 1988; McBean, 1983), although the contact is sharp and not gradational at the one place I observed it northeast of Yellow Lake. Ruppel (1975) placed the contact of the two formations at the highest bed of siltite that contains lenses of dolomite-cemented metasandstone, even though dark-gray siltite interbeds occur within the overlying fine-grained metasandstone. Ruppel (1975) reported that the Yellow Lake unit of the Apple Creek Formation is conformable with the underlying Big Creek Formation in the central part of the Lemhi Range. The contact is a flooding surface and is here considered to be an unconformity, as in the northern part of the Lemhi Range, as discussed in the section on the Big Creek Formation. The lower contact is sharp, not gradational, and is exposed on the nose of a ridge, at about lat 44°32'36" N., long 113°33'30" W. (this location is in the Yellow Peak quadrangle (fig. 2), which is unsurveyed and thus is not divided into townships and ranges), southwest from the base of the measured section.

ORIGIN OF APPLE CREEK FORMATION SOUTH OF LEM PEAK FAULT

The assemblage of sedimentary structures present in the lower part of the Yellow Lake section is indicative of turbidites. The fine-grained siltite and argillite are organized silts and muddy silts in the classification scheme of Pickering and others (1988), who generally attributed such strata to transport by low-concentration turbidity currents. In general, lower strata of the section were deposited from lower energy turbidity currents than those in the three lithofacies of the Apple Creek north of the Lem Peak fault. Many of the sedimentary structures are of the types illustrated by Stow and Shanmugam (1980) in fine-grained turbidites of base-of-slope to basin plain environments. Reconnaissance examination suggests that the upper, metasandstone strata of the section may have been deposited in wave-influenced shallow water. This would be in accord with a conformable contact with the overlying Gunsight Formation observed by Ruppel (1975).

CORRELATION

Thin sections show that rounded quartz grains, and locally plagioclase grains, of medium-sand size float in the carbonate beds of the Yellow Lake strata. These grains indicate that the carbonate is not a chemical precipitate but likely was resedimented from shallow water. The rounded quartz grains may establish a genetic tie between the Yellow Lake lithofacies and the diamictite and coarse clastic units of the Apple Creek, the largely silt matrix of which contains scattered well-rounded quartz grains.

A geochemical study was made by Connor (1991) of the rocks assigned to the (1) Yellowjacket Formation in the Salmon River Mountains, (2) strata of the same lithofacies in the western part of the Lemhi Range, here considered to be Apple Creek Formation, and (3) Apple Creek Formation in the Yellow Lake area. Connor reported that the Yellow Lake unit differed (1) in lacking chlorite and biotite, and (2) in containing twice as much B and Ca, and marginally more Cr, Li, and Zr. He (Connor, 1991, p. 7) stated, however, that the chemical differences alone were not sufficient to consider the Yellow Lake strata to be a different stratigraphic unit, and that only geologic mapping could determine correlation of the Yellow Lake strata with those of the Salmon River Mountains and the western part of the Lemhi Range. The contrasting lithofacies of the Apple Creek strata north and south of the Lem Peak fault, representing different depositional settings, may account for the differing chemical makeup found by Connor (1991).

Because much of the Apple Creek is not readily accessible, Ruppel (1975) referred interested parties to a large outcrop near the hamlet of Ellis (now only a Post Office) on U.S. Highway 93, near the junction of the Pahsimeroi and Salmon Rivers (figs. 1, 2). This outcrop lacks carbonate strata and is composed of beds that I interpret as being of shallow-water origin, probably intertidal. This contrasts with the turbidite origin that I attribute to the Apple Creek in the Yellow Lake area. The Ellis outcrop may be strata of the West Fork Formation.

GUNSIGHT FORMATION

The Gunsight Formation was named by Ruppel (1975) for a sequence of strata in the central part of the Lemhi Range. The type locality extends north from near Yellow Lake to Gunsight Peak (Ruppel, 1975), which is south of the Lem Peak fault (fig. 2). Strata assigned to the Gunsight in the 7.5-minute quadrangles that I mapped crop out only in the northeastern part of the Lem Peak quadrangle, in the footwall of the Poison Creek thrust fault, where only about a 100 m thick, poorly exposed sequence is present (Tysdal, 1996b). Gunsight of the type area was examined only in reconnaissance, but is discussed briefly to place the thin Gunsight of the Lem Peak quadrangle in perspective. A summary description of the formation is presented first, based on McBean's (1983) study of the type section.

McBean's (1983) measured section shows that the Gunsight is 1,700+ m thick and is mainly a metasandstone unit composed of feldspar and quartz. The feldspar content ranges from 25 to 50 percent, although in the uppermost 100+ m, transitional into the Swauger Formation, the Gunsight is 80–90 percent quartz. The matrix content ranges from 0 to 8 percent, except in the lower 450 m where it is 2–40 percent and the formation comprises interbedded siltite, argillite, and very fine grained metasandstone. The remaining 1,275 m of the measured Gunsight is pale-brown to gray, very fine grained to medium-grained metasandstone that coarsens upward through the section. Sedimentary structures include trough and planar crosslaminated strata; parallel lamination; ripple and climbing ripple laminations; dewatering structures; and straight-crested, asymmetrical, and oscillation ripples. Heavy minerals also are present. McBean (1983) concluded that the sequence was deposited in a nearshore environment. The lowest part, with its higher content of fines, was considered subtidal and the remainder intertidal to possibly subaerial. McBean (1983) indicated that the Gunsight strata were derived from the northeast.

North of the Lem Peak fault, the Gunsight in the northeastern part of the Lem Peak quadrangle is not well exposed. It consists of lenses of orthoquartzite that are interstratified with siltite and silty feldspathic metasandstone, metamorphosed to the lower greenschist facies. The orthoquartzite is light gray to pale red purple, fine to medium grained, and composed of well-rounded quartz grains. Crosslamination includes both trough and tabular types and forms sets 20–50 cm thick, which are erosionally truncated at the top. Lenses are as thick as 10 m and form resistant ledges, in contrast to the adjacent generally poorly exposed slope-forming siltite and fine-grained metasandstone. Siltite is olive gray to yellowish gray, argillaceous, medium to coarse grained, and ripple crosslaminated. The feldspathic metasandstone is fine to medium grained, planar laminated, and locally contains dark-gray heavy-mineral laminae. Local ripple crosslaminae are in sets 2–10 cm high. The siltite and metasandstone are interbedded in some outcrops.

ORIGIN

Reconnaissance through much of the type section suggests that the Gunsight deposits are chiefly of fluvial origin; the trough crossbedded metasandstones occur in units 1–2 m thick that fine upward and give way to siltite of overbank deposits (D.A. Lindsey, oral commun., 1996). Uppermost strata of the formation lack fine-grained beds of siltite and are primarily medium grained to coarse-grained metasandstone of quartz and feldspar. Trough crossbedding is common. These uppermost strata could be shoreface deposits transitional upward from fluvial strata of the Gunsight into the marine orthoquartzite of the overlying Swauger Formation. Lowermost strata of the Gunsight may be marine, as suggested by McBean (1983), transitional into turbiditic strata of the Yellow Lake unit of the Apple Creek Formation. The lowermost part of the Gunsight and uppermost part of the Apple Creek were tightly folded and faulted during compressional deformation, as McBean (1983) recognized. My reconnaissance suggests that some lower strata of the Gunsight (but above the lower contact) may be missing due to normal faults(s) formed during subsequent extensional deformation. Thus, some shallow-marine strata of the lower Gunsight, transitional from the below-wave-base turbidites of the Apple Creek to the nonmarine fluvial Gunsight, may be omitted from the type section.

The crossbedded orthoquartzite lenses of the northern part of the Lem Peak quadrangle are interpreted as fluvial deposits. They may be channel deposits of meandering streams within a flood plain environment, in which siltite strata constitute a large part of the rocks and the channels make up a small part. Gunsight strata of the Lem Peak quadrangle, therefore, correspond to the fluvial deposits that make up the major part of the formation of the type area. The two areas are, however, on different thrust plates and the strata of each plate likely were deposited in somewhat different fluvial settings. The orthoquartzite composition of the lenses of the Lem Peak quadrangle suggests a sedimentologic tie to the orthoquartzite of the conformably overlying Swauger Formation, which G.R. Winkler (oral commun., 1991) has mapped in the Poison Peak quadrangle north of the Lem Peak quadrangle.

SWAUGER FORMATION

SOUTH OF LEM PEAK FAULT

The Swauger Formation was named by Ross (1947) for strata in the vicinity of the Swauger ranch near the hamlet of Goldburg on the southwest flank of the central part of the Lemhi Range (fig. 2). The formation, metamorphosed to the lower greenschist facies, is resistant to erosion and forms steep-sided ridges and cliffs that make up the backbone of the northern part of the range. Within the mapped area, the Swauger is exposed only south of the Lem Peak fault.

The Swauger displays a wide variety of colors, including light gray, pale to dark blue green, pale red purple, pink, and pale orange. The strata are mainly medium grained to coarse-grained orthoquartzite or quartzite with 5–10 percent feldspar, and locally metasandstone (less than 90 percent of rock is quartz). Quartz grains are well rounded, well sorted, tightly cemented, and glassy. Some orthoquartzite contains 1–2 percent matrix; grains in such rocks are not as well sorted; plagioclase makes up 1–2 percent of the rock. Beds are typically 0.5–1 m thick but range up to 2 m. Some beds appear massive, but others display crosslamination. All these features were reported previously by Ross (1947) and Ruppel (1975); Farooqui (1996) described similar compositional and textural features.

A speckled appearance of many beds is caused by 0.5–3 mm diameter spots of hematite, locally limonite, and uncommonly chlorite. The density of the spots is variable. Some spots are concentrated along crosslaminae, others along the coarser grains within rocks of variable grain size. As pointed out by Ross (1947), thin sections show the iron-oxide to form a coating on and between grains. It coats chlorite of metamorphosed matrix of some rocks, is concentrated along fractures, and occurs along folia of some sheared rocks. These data indicate that the spots formed well after lithification and deformation of their host rocks.

Throughout most of the formation exposed in the mapped area, sets of crosslaminae commonly are as thick as the host bed (0.5–2 m) and are erosionally truncated. Each bed in turn is overlain by another bed of like composition and structure. Siltite or argillite laminae 1–2 mm thick occur between some beds, but fines are lacking between most beds.

Dark-gray laminae of heavy minerals of tourmaline, zircon, and sphene were observed locally in the upper part of the Swauger, most commonly in fine-grained orthoquartzite or metasandstone in beds as thick as 1.5 m. Some of the heavy minerals formed laminae in broad, gently inclined troughs 1–3 m across, although it was difficult to determine if all such crosslaminae were trough shaped. In one area, heavy minerals and quartz grains form 1–2 cm thick layers. Some beds in the upper strata of the formation are capped by planar-laminated fine-grained metasandstone that becomes rippled in the uppermost part and also contains heavy-mineral laminae.

The upper contact is conformable with the Lawson Creek Formation, and the lower contact is gradational with the underlying Gunsight Formation (Ruppel, 1975). The thickness in the central part of the Lemhi Range was estimated at 3,100 m (10,000 ft) by Ruppel (1980).

DUNES AND RIPPLES

Dunes (defined in section on Big Creek Formation, p. 5) are spectacularly displayed directly west of Mill Lake (fig. 2) where they are stacked atop one another into beds that are composed of medium- to coarse-grained orthoquartzite. The beds pinch and swell, commonly range between 1.0 and 1.5 m thick normal to dune strike, and gradually pinch out in the downcurrent direction. The thickest dimension of some beds is complemented by the thinnest dimension of the directly overlying bed.

The dunes are two-dimensional and display wavelengths of 4–6 m and heights of 0.75–1 m (fig. 32), although one dune had a measured wavelength of 8 m and a height of 0.7 m. The dunes are small (wavelength 0.6–5 m) to medium (wavelength 5–10 m) in size according to the classification of Ashley (1990). The dominant current transport direction was to the northeast in the Mill Lake area, shown by northeast-inclined foresets and by asymmetry of dune crests. Bottomset laminae are tangential with the underlying strata. Upper parts of beds are erosionally truncated; thus, topsets of

Figure 32. Dune (megaripple) in orthoquartzite of Swauger Formation. Transport direction is to northeast, toward the viewer. Wavelength is about 5 m, height about 1 m. Dashed line shows upper surface of dune. Near Mill Lake (fig. 2).

Figure 33. Antidune in orthoquartzite of Swauger Formation. Foreset laminae of dune are inclined to northeast (right), except at top of left-center of bed where antidune (anticlinal shape) shows laminae inclined to southwest (left) as well. Bed is about 1 m thick. Mill Lake area (fig. 2).

crosslaminae have been eroded. Reactivation surfaces (defined in section on Big Creek Formation, p. 5) occur in many dunes and generally are inclined at a slightly lower angle than the lamination of dune foresets. Herringbone crossbedding characterizes some strata.

One antidune was observed in an orthoquartzite bed about 0.75 m thick. Foresets of the bed are inclined to the northeast, except in one part where laminae show a buildup of layers into an "anticlinal" shape that verges to the southwest, forming an antidune (fig. 33).

Double clay drapes (defined in section on Big Creek Formation, p. 5) were not observed in the orthoquartzites of the Swauger Formation. In fact, no mud chips, pebbles, or siltite beds were observed within most strata of the Swauger. However, tidal flat strata are present within the upper part of the Swauger in the upper Cow Creek area and north of the upper extent of Allison Creek (fig. 2), in the transition strata described in the following section.

Some strata display northeast-inclined foresets of dunes that are capped by a thin bed with southwest-inclined

Figure 34. Ripples on eroded surface of orthoquartzite bed of Swauger Formation. Foreset laminae of bed are inclined to northeast, indicating transport to northeast; slightly asymmetrical ripples indicate transport to southwest (toward upper left of photograph). Ripple wavelengths are 5–7 cm, heights about 1 cm. Cow Creek area (fig. 2).

foresets. The thin bed is a subordinate current cap, a depositional structure produced on the crest of a dune by a subordinate (weak) tidal current (de Mowbray and Visser, 1984, p. 817). Beds as thick as 0.3 m display foresets that are inclined to the southwest.

Ripples on the upper surface of erosionally planed orthoquartzite beds throughout the formation are two-dimensional and show a range of sizes: wavelength 12–15 cm and height 2–3 cm to wavelength of 2 cm and height of 0.3–0.5 cm (fig. 34). Transport directions are to the southwest for most beds; however, some are to the northeast. A few ripples are symmetrical. Linguoid ripples were observed locally in siltite beds in the upper part of the formation.

Rippled upper surfaces of some dunes in the Mill Lake area (fig. 2) contain two-dimensional asymmetrical ripples that show transport to the southwest, capping dune foreset laminae that are inclined to the northeast. Small longitudinal ripples occur within the troughs of a few dunes of the Mill Lake area. Ripple crests of the larger of these ripples (wavelength 10–20 cm, height 1–1.5 cm), are oriented about parallel to those of the dune crests. Crests of smaller ripples show transport about parallel to the trough axis of the dune. Virtually no siltite beds or lenses were observed in this area, only local fine-grained siltite partings on some beds.

TRANSITION STRATA

Siltite is interbedded with orthoquartzite in the upper part of the Swauger where a bed, or a few-meter-thick sequence of orthoquartzite beds, abruptly alternates with sequences of siltite. The siltite is planar laminated to ripple crosslaminated, some beds containing flaser and lenticular bedding.

On the ridge directly north of Allison Creek, and about 400 m below the upper contact, the Swauger contains an approximately 35 m thick sequence of interbedded flaser and lenticular siltite, metasandstone, and lesser orthoquartzite. The sequence could be mistaken for strata of the overlying Lawson Creek Formation if it were isolated within a fault sliver. North of Allison Creek, however, the sequence is overlain by about 250 m of well-exposed orthoquartzite that forms a rugged part of the ridge, showing that the 35 m thick sequence is within the Swauger.

Some upper beds of the formation display a repetitive sequence, from base to top, of beds 0.7–1 m thick: basal 30–70 cm of medium-grained massive orthoquartzite; 5–15 cm of fine-grained orthoquartzite; 1–5 cm of siltite, or interlaminated siltite and fine-grained orthoquartzite. Beds of fine-grained orthoquartzite commonly display planar lamination and locally are amalgamated, as shown by 1–2 mm thick interlaminae. Other transition beds, 0.5–1.5 m thick, are feldspathic metasandstone, grading upward into siltite in the uppermost part. The siltite contains current, oscillatory, and locally interference ripples.

ORIGIN

The Swauger strata are believed to have formed by tide-controlled depositional processes. The following interpretations are based on concepts and reasoning more fully explained in the section on the Big Creek Formation, to which the reader is referred.

The nearly 100 percent quartz content of most beds of the Swauger probably indicates extensive recycling and concentration of the quartz grains; other minerals were removed and exited the system. A high energy depositional environment for at least some of the strata is attested by the small to medium size two-dimensional dunes that have wavelengths as much as 8 m and amplitudes reaching 1 m. Flume experiments (Southard and Boguchwal, 1990) demonstrate that antidunes, observed in the Mill Lake area (fig. 2), form under the highest flow speeds, higher than those of ripples, dunes, and plane beds, indicating that these features formed by tidal rather than wave-dominated processes. Reactivation surfaces of the dunes are diagnostic evidence of tidal processes. Double clay drapes, also diagnostic of tidal deposits (Visser, 1980), were not observed. The general absence of fine-grained metasediment in the Swauger could indicate that high-strength tidal currents eroded silt and clay that may have formed drapes, as suggested by Mellere (1996, p. 260) for other tidal deposits.

Herringbone crosslamination, formed by bipolar currents, occurs in close stratigraphic association with dunes that contain reactivation surfaces, indicating that the herringbone structures are of tidal origin. Rippled surfaces present at the top of some thick beds of orthoquartzite reflect transport direction and current speed that contrast with those of the underlying bed, thus providing another argument for tidal origin. Flaser and lenticular bedding, which can be produced in a wave-dominated or tide-dominated environment, occurs in the transition strata of the upper part of the formation. The interlayering of 0.5–1 m thick beds of orthoquartzite and fine-grained siltite units indicates deposition from currents of highly contrasting flow speeds, and suggests that the transition strata were formed by tidal processes. Heavy-mineral-bearing trough crosslaminated metasandstone observed locally in the upper part of the Swauger in the Allison Creek area (fig. 2) is stratigraphically not far below the transition strata of the formation. The metasandstone probably was deposited in an upper intertidal (upper shoreface) environment.

Most of the orthoquartzite of the Swauger is believed to be of tidal origin, based on the arguments presented. The 1 m thick beds of orthoquartzite that make up most of the formation may be largely dune remnants, with the dune shapes not readily recognized because their topset and part of their foreset laminae have been eroded by strong tidal currents. Only steep foreset lamination generally is preserved. Conversely, the dunes of the Mill Lake area may represent tidal channel deposits, and other beds of the Swauger could have formed by tidal processes in other depositional settings, such as low-tidal sand flat (Tankard and Hobday, 1977, p. 151; Klein, 1977, p. 81), or an intertidal sand bar (Klein, 1970). A tidal-dominated estuarine setting (Bay of Fundy, for example) where currents are concentrated and of high speed is favored for the orthoquartzite strata. Reactivation surfaces indicate reversing tidal scour over dunes subjected to a combined constructional-destructional history. This repeated tidal action also may have acted to remove fines and nonresistant grains, but overgrowths on quartz grains indicate recycling of many of the grains of the Swauger.

LAWSON CREEK FORMATION

The Lawson Creek Formation was named by Hobbs (1980) for outcrops in the northernmost part of the Lost River Range. The name was first applied to strata in the Lemhi Range by Tysdal (1996b) and Tysdal and Moye (1996). In the mapped area, the Lem Peak fault has cut out most of the Lawson Creek: it occurs only south of the fault. The maximum thickness of the Lawson Creek observed is about 300 m, on a ridge between the headwaters of Wright Creek on the north and Kadletz Creek on the south, in the May Mountain quadrangle (fig. 2). The lower part of the formation is fairly well exposed on the Wright-Kadletz ridge, directly south of the measured section within the Big Creek Formation (fig. 2). In general, strata of this area revealed interbeds of a variety of rocks—fine-grained siltite to coarse-grained orthoquartzite, well sorted to poorly sorted, metamorphosed to the lower greenschist facies. The rocks of this area serve as the basis for the following description.

The contact of the Lawson Creek is conformable and gradational with the underlying Swauger Formation. The contact was chosen where the thick beds of Swauger orthoquartzite give way to a Lawson Creek sequence that contains abundant beds of metasandstone and siltite, and orthoquartzite constitutes only a small percent of the rocks. The change takes place fairly abruptly in most places within the mapped area.

METASANDSTONE AND ORTHOQUARTZITE

Metasandstone is generally quartz rich but ranges from about equal parts feldspar and quartz to locally orthoquartzite; it commonly contains a fine-grained matrix that is chloritized. Beds range from 1 cm to 1.5 m thick. Orthoquartzite is gray, gray green, and blue green, is fine to coarse grained, and contains a high percent of well-rounded quartz grains, some with overgrowths. It is massive to planar laminated, in beds as thick as 1 m.

A few beds within the Lawson Creek are composed of light-gray fine-grained quartz-rich metasandstone that is finely laminated, contains dark-gray heavy minerals in laminae 1–2 grains thick, and locally is crosslaminated. Other metasandstone is poorly sorted, composed of well-rounded medium- to coarse-grained quartz, minor plagioclase, and medium- to coarse-grained silt, and 2–3 percent matrix. Some well-sorted fine-grained quartz-rich beds contain a recrystallized clay matrix that constitutes 10–15 percent of the rock.

Rusty-brown-weathering metasandstone beds or laminae occur intermittently throughout the exposures. Ripple crosslaminae are fairly common in the metasandstone beds. A few orthoquartzite and quartzose metasandstone beds display crosslaminae about 1 m thick. Rip-up clasts of argillite chips locally "float" within quartzite beds.

SILTITE

Medium- to dark-gray siltite and argillaceous siltite, interlayered with thin beds of metasandstone, form sequences as thick as 10 m between sequences of beds chiefly composed of metasandstone and orthoquartzite. The siltite sequences display alternate interlayering of the siltite and metasandstone beds, which range from 0.5 to 5 cm thick. The siltite is fine to coarse grained, and the interbedded metasandstone and orthoquartzite generally are fine grained. These strata range from planar laminated to ripple crosslaminated and display abundant flaser and lenticular bedding. Siltite beds generally contain a higher percent of feldspar than the metasandstone. Some strata of the sequence display fine- to medium-grained siltite that fills ripple troughs of the underlying metasandstone. The upper surface of the siltite layer is planar. Cut-and-fill structures are also present within the interbedded siltite and metasandstone sequences.

ORIGIN

The Lawson Creek Formation is interpreted as an intertidal sequence, displaying sedimentary structures typical of those on tidal flats. The flaser and lenticular bedding, and the sequences of interbedded fine- and coarse-grained rock, indicate deposition under alternately high and low energy conditions.

At the type section of the Lawson Creek Formation, near Lawson Creek in the Lost River Range (fig. 2), the contact with the underlying Swauger is covered (Hobbs, 1980, fig. 3). Above the covered interval is a 250 m thick sequence that Hobbs called the transition zone, which consists of metasandstone that he considered similar to that of the Swauger. My examination shows the transition strata to be stream deposits, perhaps part of a braid delta, in contrast to the marine Swauger orthoquartzite. Northwest from the type section, in a reference section near Shep Creek (fig. 2), Hobbs (1980) noted the absence of the transition unit, as well, and that rocks like those of the middle unit of the type section were deposited directly on the Swauger, with which they are conformable. The middle unit of the type section, and the section at Shep Creek, are interpreted by me as an intertidal sequence, as is the upper unit of the formation.

In the Lemhi Range, a nonmarine transition unit of stream deposits was not observed beneath the intertidal strata—its absence is not surprising, considering the local occurrence of the unit in the Lost River Range. The Lawson Creek strata of the Lemhi Range differ in lacking the upper unit described by Hobbs (1980). This unit mainly consists of thin-bedded siltite that contains abundant mudcracks, rip-up clasts, and other features suggestive of the upper intertidal zone of a tidal flat. Such a unit may be absent from the incomplete formation in the Lemhi Range due to faulting. The general variability of intertidal depositional environments in coastal areas may account for differences in the two ranges as well.

Intertidal strata of the Lost River Range are chiefly reddish brown to pale red purple, whereas those in the Lemhi Range are mainly pale green and light to dark gray. The color differences indicate oxidation states of the rocks and probably reflect conditions after the time of deposition of the sediments. Color is not necessarily a reliable criterion for correlation.

Intertidal strata assigned to the Lawson Creek Formation in the Lemhi Range are similar to strata described in the section on the Swauger Formation, from the upper part of the Swauger in the Allison Creek area. The two sequences could be confused with one another without extensive exposures. The sequence within the Swauger is thinner and is overlain by a thick sequence of orthoquartzite. As the depositional environment began to change from that of the Swauger to that of the Lawson Creek, intertonguing of strata took place. Some intertonguing of strata likely occurred only locally, thus is not regionally extensive. Hence, choosing the Swauger–Lawson Creek contact may be difficult in some areas where exposures are poor.

CONCLUSIONS

1. The Lemhi Group and overlying Middle Proterozoic formations of the mapped area lie on two structural blocks that are believed to be two thrust plates now juxtaposed by the Tertiary Lem Peak normal fault.

2. The Big Creek, Swauger, and Lawson Creek Formations are marine units that were deposited in tidally controlled environments.

3. The small area of Gunsight Formation in the northern part of the Lem Peak quadrangle is interpreted as a fluvial sequence in which siltite strata constitute a large part of the rocks and the channels make up a small part.

4. The Apple Creek Formation is composed of marine turbidites and possibly debris flow deposits. The sequence north of the Lem Peak fault is several times thicker than equivalent strata south of the fault. Three lithofacies occur north of the fault, one south of it.

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