The Livingston Formation in the Madison Range of Southwestern Montana

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CONTENTS

FIGURES

TABLES

The Livingston Formation in the Madison Range of Southwestern Montana

By R. G. Tysdal, D. J. Nichols, *and* G. R. Winkler

Abstract

The Livingston Formation in the Madison Range of southwestern Montana is a sequence of volcanic and volcaniclastic rocks that is subdivided into three mappable units which, in ascending order, are named informally the lower, middle, and upper members. The lower member is a composite unit composed of mudstone, siltstone, sandstone and conglomeratic sandstone, and minor tuff, olivine basalt, and volcanic conglomerate. The middle member is composed of somber-colored volcanic flows and flow breccias of dacitic to andesitic composition, with lesser tuff and basalt. The lower two-thirds of the upper member consists of well-rounded volcanic clasts in a volcaniclastic sandstone matrix; the upper third is chiefly sandstone with local lenses of conglomerate. This upper third is transitional into the overlying Sphinx Conglomerate, a synorogenic deposit present in the Madison Range.

The Livingston Formation of the Madison Range is of Cretaceous age and probably was deposited during the early to middle parts of the Campanian Stage. The age is based on a combination of megafaunal and palynological data from below and within the Livingston, K-Ar dates on tuff units from within the lower member, and K-Ar and $^{40}Ar/^{39}Ar$ dates on intrusive rocks that postdate deformation of the sequence.

INTRODUCTION

The name Livingston Formation originally was applied by Weed (1893) to a thick sequence of volcaniclastic sedimentary strata, including agglomerate, in the vicinity of Livingston, Montana. Peale (1896) broadened the area of application to include predominantly pyroclastic rocks preserved near Sphinx Mountain in the Madison Range; in Jefferson Canyon, about 110 km west of Livingston; and near Maudlow, about 70 km northwest of Livingston (fig. 1). Strata subsequently assigned to the Livingston Formation varied from one author to another until the 1960's when, during extensive mapping in the Livingston area, Roberts (1963, 1972) restricted rocks assigned to the unit, raised the unit to group status, and defined four new formations within the group (fig. 2). In this paper we describe the volcaniclastic and volcanic rocks of the Livingston of the Madison Range; interpret the general depositional environment of the facies; and date the sequence by a combination of paleontologic and radiometric dating, and the time of deformation.

Livingston rocks of the Sphinx Mountain area were first mapped and described by Peale (1896) in the Three Forks Folio. A larger scale map was published by Beck (1960), who recognized a tripartite division to the unit. Hadley (1969) mapped the Livingston strata northwest of Sphinx Mountain and described the three subunits in more detail (Hadley, 1980). In an unpublished Ph. D. dissertation, Hall (1961) mapped and briefly described rocks from two previously unrecognized areas of Livingston strata in the western part of the Gallatin Range (fig. 1), correlated them with the Livingston of the Madison Range, and speculated that intrusive rocks of Lone Mountain may have been a source for the volcanic and volcaniclastic rocks. The present study, an outgrowth of geologic mapping (Tysdal and Simons, 1985; Tysdal, 1986) for the Madison Range Wilderness Study Area, describes and interprets Livingston rocks of the Madison Range only. Livingston rocks described by Hall (1961) in the Gallatin Range appear to be similar in many respects, although Hall did not subdivide them.

The name Livingston was not used by Hadley (1969, 1980) for the sequence in the Madison Range. He believed the rocks correlated with the lower member of the Elkhorn Mountains Volcanics, the nearest outcrop of which is about 75 km to the northwest. We follow Peale (1896) and Beck (1960) and use the name Livingston, to preserve historical precedence and to retain the regional correlation inherent in this usage. We retain formational status for the sequence in the Madison Range, and the three mapped units are treated as informal members. The three members are restricted to such a small area (about 60 km^2) of the Madison Range that introduction of one or more formation names seems unwarranted. Correlative Livingston rocks of the Gallatin Range occupy an even smaller area and have not been subdivided.

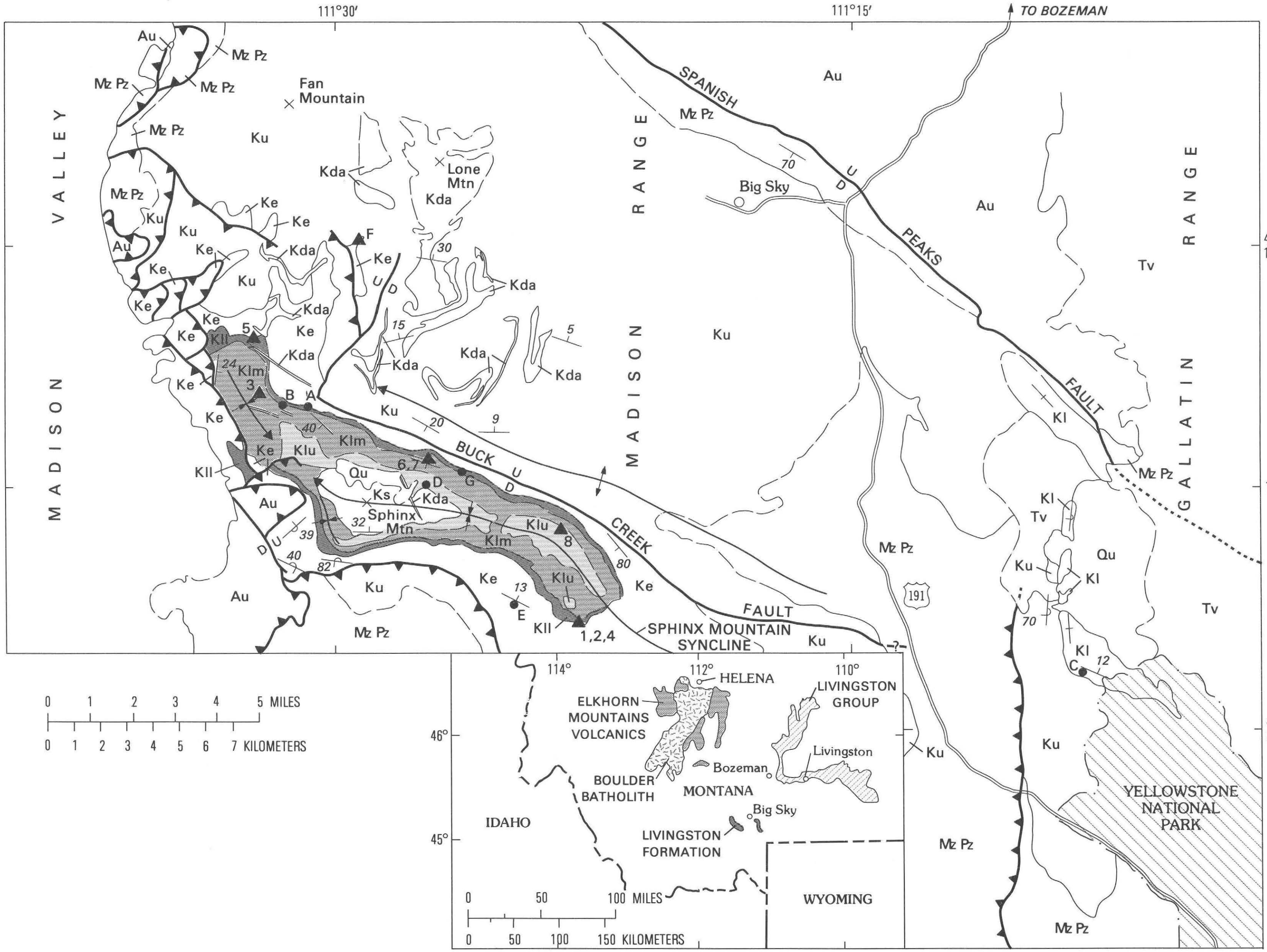

Figure 1 (above and facing page). Geologic map showing outcrop areas of Livingston Formation in the Madison and Gallatin Ranges, locations of paleontological collections (A–G) and sample sites of igneous rocks (1–8). Map compiled from Tysdal and Simons (1985), McMannis and Chadwick (1964), Hall (1961), and unpublished data.

EXPLANATION

Qu	Unconsolidated sedimentary rocks (Quaternary)
Tv	Volcanic rocks, undivided (Tertiary)
Kda	Dacite intrusive rocks (Upper Cretaceous)
Ks	Sphinx Conglomerate (Upper Cretaceous)
Klu	Livingston Group, upper member (Upper Cretaceous)
Klm	Livingston Group, middle member (Upper Cretaceous)
Kll	Livingston Group, lower member (Upper Cretaceous)
Kl	Livingston Group, undivided (Upper Cretaceous)
Ku	In Gallatin Range, Cretaceous rocks older than Livingston Group; in Madison Range, Cretaceous rocks older than Virgelle Sandstone, and unmapped areas of Cretaceous dacitic intrusive rocks (Upper Cretaceous)
Ke	(?)Everts Formation and Virgelle Sandstone, undivided (Upper Cretaceous)
MzPz	Sedimentary rocks, undivided (Mesozoic and Paleozoic)
Au	Metamorphic rocks, undivided (Archean)

Contact—Dashed where approximately located

U / D — Fault—D, downthrown side; U, upthrown side

Thrust fault—Teeth on upper plate

Anticline—Showing trace of axial plane and direction of plunge

Syncline—Showing trace of axial plane and direction of plunge

Bedding

40 — Inclined

70 — Overturned

●B — Fossil locality

▲3 — Igneous-rock locality

Petrologic study of volcanic material in the sedimentary rocks of the Livingston Group in the Livingston area indicated that much of it was derived from the Late Cretaceous Elkhorn Mountains Volcanics, associated with emplacement of the Boulder batholith (McMannis, 1955; Klepper and others, 1957; Roberts, 1963, 1972). Local volcanic source rocks occur near Maudlow (Skipp and McGrew, 1977); south of Big Timber, about 50 km east of Livingston (Weed, 1893; Parsons, 1942); and near Flathead Pass in the Bridger Range, about 75 km northwest of Livingston (Weed, 1893) (fig. 1). We suggest that most of the volcaniclastic strata and associated volcanic rocks of the Livingston in the Madison Range also were derived locally.

LIVINGSTON FORMATION

The Livingston Formation within the Madison Range is preserved only in a northwest-trending erosional remnant that forms an outcrop belt about 19 km long and as much as 5 km wide in the west-central part of the range (fig. 1). The formation is composed of three informal units, which Hadley (1980) named, in ascending order, the volcanic sandstone unit, volcanic breccia unit, and volcanic conglomerate unit. We have renamed these units the lower, middle, and upper members, respectively. The preserved sequence has a maximum thickness of about 1,000 m. Representative igneous rocks from the various members that make up the formation were analyzed chemically (table 1), and the data were used for classification according to the method of De la Roche and others (1980), as shown on figure 3.

The volcanic and volcaniclastic rocks of the outcrop belt in the Madison Range can be interpreted as both vent and alluvial facies, following criteria outlined by Parsons (1965, 1969) and Smedes and Prostka (1972) for rocks in and near Yellowstone National Park. A vent facies ideally is characterized by angular poorly sorted breccias, dike swarms, stocks, plugs, and (or) laccoliths. Away from an intrusive center, vent facies rocks intertongue with alluvial facies rocks, which are composed of water-laid volcaniclastic strata of conglomerate, sandstone, and siltstone as well as airfall tuff. Volcanic units become thin away from the vent area, whereas the sorting, rounding, and fineness of clasts in the sedimentary units increase away from the vent area.

Lower Member

The lower member ranges from about 60 to 250 m thick and is a heterogeneous assemblage of mudstone, siltstone, sandstone and conglomeratic sandstone, welded tuff, olivine basalt, and volcanic conglomerate. The member is an alluvial facies sequence in which the variety and thickness of sedimentary units increase to the southeast (fig. 4).

The most widespread, and thickest, unit in the lower member is a volcaniclastic sandstone that Hadley (1980) briefly described from exposures at the northwest end of the outcrop belt in the Madison Range. The unit is recognized along the entire length of the belt, is thickest in the southern exposures, and is composed chiefly of angular fractured crystals of basalt constituents cemented by chlorite. Some outcrops have an admixture of rounded grains of volcanic rock composed of felted plagioclase laths, and others contain pebbles and cobbles of basalt. Steep to shallow tabular and trough crossbeds are common. The sandstone locally is conglomeratic, much more so in the northwestern part of the belt than southeastward, with lenses as much as several meters thick of subangular to well-rounded pebbles of red, green, and dark-gray chert and volcanic rocks, including tuff. The

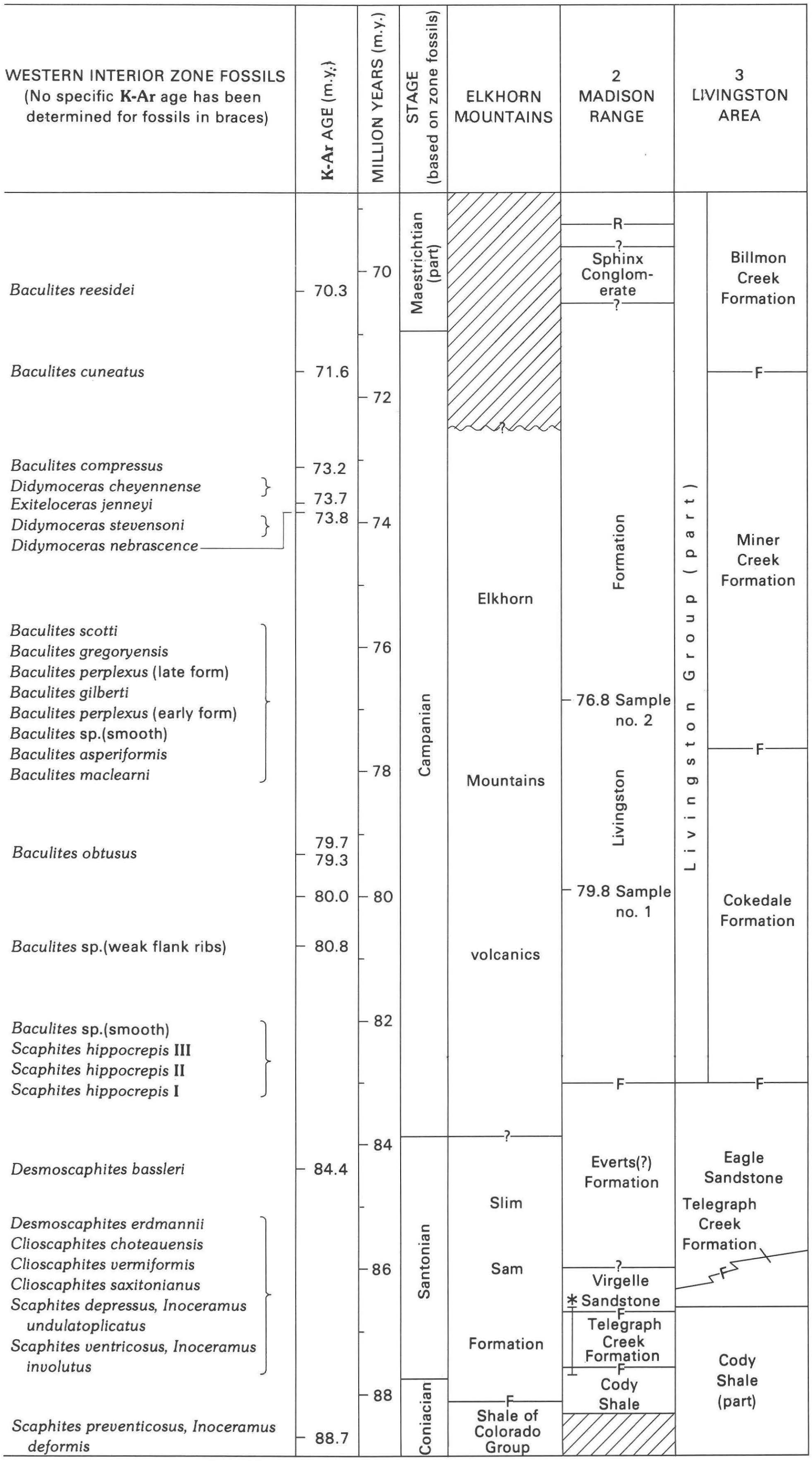
WESTERN INTERIOR ZONE FOSSILS (No specific K-Ar age has been determined for fossils in braces)
K-Ar AGE (m.y.)
MILLION YEARS (m.y.)
STAGE (based on zone fossils)
ELKHORN MOUNTAINS
2 MADISON RANGE
3 LIVINGSTON AREA
Baculites reesidei
70.3
Baculites cuneatus
71.6
Baculites compressus
73.2
Didymoceras cheyennense
73.7
Exiteloceras jenneyi
73.8
Didymoceras stevensoni
Didymoceras nebrascence
Baculites scotti
Baculites gregoryensis
Baculites perplexus (late form)
Baculites gilberti
Baculites perplexus (early form)
Baculites sp.(smooth)
Baculites asperiformis
Baculites maclearni
Baculites obtusus
79.7
79.3
80.0
Baculites sp.(weak flank ribs)
80.8
Baculites sp.(smooth)
Scaphites hippocrepis III
Scaphites hippocrepis II
Scaphites hippocrepis I
Desmoscaphites bassleri
84.4
Desmoscaphites erdmannii
Clioscaphites choteauensis
Clioscaphites vermiformis
Clioscaphites saxitonianus
Scaphites depressus, Inoceramus undulatoplicatus
Scaphites ventricosus, Inoceramus involutus
Scaphites preventicosus, Inoceramus deformis
88.7
70
72
74
76
78
80
82
84
86
88
Maestrichtian (part)
Campanian
Santonian
Coniacian
Elkhorn
Mountains
volcanics
Slim
Sam
Formation
Shale of Colorado Group
R
?
Sphinx Conglom-erate
?
Livingston Formation
76.8 Sample no. 2
79.8 Sample no. 1
F
Everts(?) Formation
?
Virgelle
* Sandstone
F
Telegraph Creek Formation
F
Cody Shale
Livingston Group (part)
Billmon Creek Formation
F
Miner Creek Formation
F
Cokedale Formation
F
Eagle Sandstone
Telegraph Creek Formation
F
Cody Shale (part)

Figure 2(facing page). Correlation chart showing relationships of the Livingston Formation in the Madison Range, with the type area of the Livingston Group in the Livingston area and the Elkhorn Mountains Volcanics in the Elkhorn Mountains southeast of Helena. Boundaries of the Upper Cretaceous stages, Western Interior fossil zones, and potassium-argon ages are adapted from Obradovich and Cobban (1975), except that the radiometric ages are recalculated for new ^{40}Ar decay constants (Steiger and Jager, 1977). Column 1 is modified from Robinson and others (1968), Gill and Cobban (1973), Smedes (1966), and Klepper and others (1957). Column 2 is from the present study. Column 3 is from Roberts (1972), as modified by Skipp and McGrew (1977). F—boundary dated with fossils, and correlates with zone fossils of leftmost column. R—boundary dated by K-Ar date, and correlates with million-year column. *At the one locality where *C. saxitoniatus* was found in the Virgelle Sandstone in the Madison Range, the fossil is associated with *S. depressus* (range zone indicated by vertical bar); hence, the two faunal zones overlap. This differs from findings in north-central Montana where *C. saxitoniatus* is wholly younger than *S. depressus* (Cobban, oral commun., 1984).

lenses commonly are trough crossbedded, with troughs as much as 2 m across. Interlayered in the lower member in the southeasternmost part of the outcrop belt are abundant beds of greenish- and dark-gray carbonaceous mudstone, bentonitic mudstone, and a few thin beds of bentonite and biotite-bearing tuff. Some mudstone contains discontinuous coaly lenses about 1 cm thick and as much as 1 m long.

The basal contact of the lower member generally is marked by an abrupt increase of volcanic grains, which makes the member much darker than the underlying strata. In a few places the lower member is demonstrably transitional downward through a few meters into the underlying strata, and the contact is chosen at the horizon where volcanic grains become the dominant constituent. In the zone of transition, the member is a mixture of rounded quartz grains associated with abundant rounded volcanic-rock fragments and angular broken grains of plagioclase and minor potassium feldspar, clinopyroxene, and biotite. The matrix is chloritized and contains minor

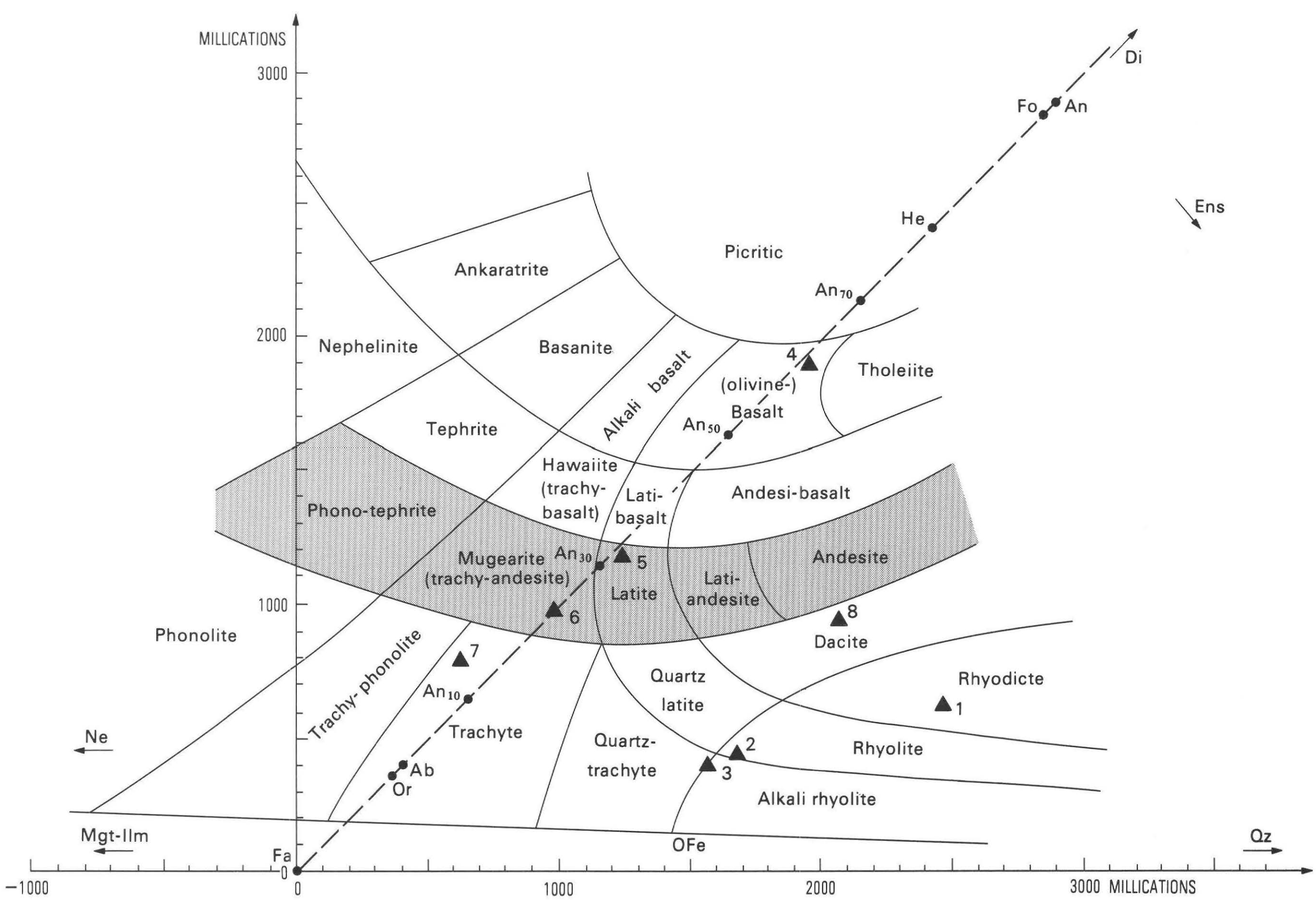

Figure 3. Grid for classification of volcanic igneous rocks (from De la Roche and others, 1980), showing plots of samples analyzed in table 1. Sample locality numbers are those of figure 1. Grid used with permission of Elsevier Scientific Publishing Company.

Table 1. Data on igneous rocks of the Livingston Formation in central part of Madison Range.

Sample locality no. (correlates with figs. 1 and 3)	Field No.	Location (lat N., long W.)	Rock name (Classification scheme of De la Roche and others, 1980)	Geologic occurrence	Chemical analysis (wt percent)										
					SiO_2	Al_2O_3	$FeTO_3$	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	LOI
1	80MWk237C	45°07′07″ N. 111°24′10″ W.	Rhyodacite	Gray welded tuff in lower member.	65.7	15	2.19	0.65	2.91	4.45	1.36	0.48	0.1	0.05	6.32
2	81MTz840E	45°07′07″ N. 111°24′10″ W.	Rhyolite	Brown welded tuff in lower member.	68	15.5	2.69	.49	.94	3.81	6.05	.49	<.05	.07	.51
3	82MTz1767	45°12′20″ N. 111°32′12″ W.	Alkali rhyolite	Brown welded tuff in middle member.	68.8	15.4	2.49	.55	.66	4.37	6.03	.53	.11	.03	.93
4	80MWk237A	45°07′07″ N. 111°24′10″ W.	Basalt	Flow in lower member.	47.1	7.93	9.43	20.4	6.53	1.14	2.51	.42	.52	.18	3.12
5	82MTz1756	45°13′07″ N. 111°32′22″ W.	Basalt porphyry	Intrudes lower member.	53.7	19.7	7.01	1.21	6.57	3.90	3.33	.85	.66	.24	2.17
6	80MWk218A	45°10′20″ N. 111°27′10″ W.	Trachyandesite	Flow in middle member	56.1	17.8	6.54	2.17	4.92	3.83	5.15	.88	.70	.10	1.23
7	81MTz854D	45°10′20″ N. 111°27′10″ W.	Trachyte	---- do ----	57.5	17.1	7.25	1.81	3.36	5.43	4.73	.65	.44	.23	.86
8	82MTz1686	45°09′00″ N. 111°23′32″ W.	Dacite	Autoclastic flow breccia in middle member.	62.9	16	5.99	1.73	4.96	3.86	2.71	.61	.26	.10	.87

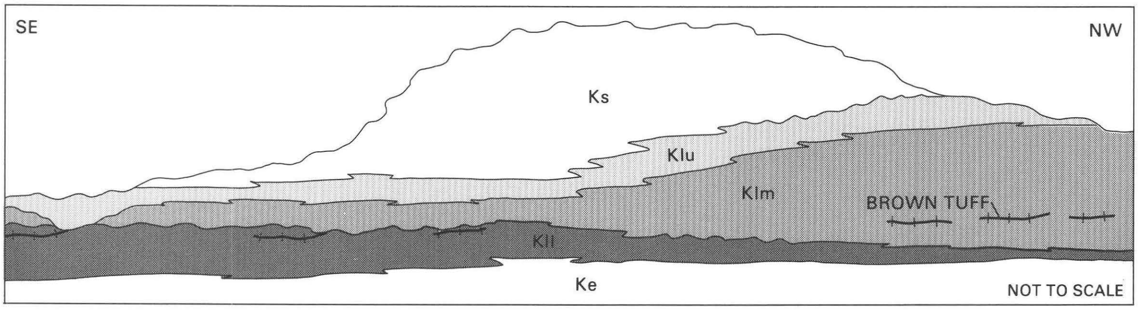

Figure 4. Schematic cross section showing general stratigraphic relationships of the Livingston Formation in the Madison Range outcrop belt. Wavy line indicates diastem, jagged line indicates intertonguing. Ks, Sphinx Conglomerate; Klu, Klm, and Kll are upper, middle, and lower members, respectively, of Livingston Formation; Ke(?), Everts(?) Formation.

calcite. The sandstone ranges from moderately to poorly sorted, although some strata contain abundant magnetite grains sorted into distinct layers. In one place the lower part of the member intertongues with beds and lenses, as much as 100 m thick, of light-gray, well-sorted, fine- to medium-grained, quartz-rich "salt and pepper" sandstone like that of the underlying strata. Calcite cement is common. Trough crossbeds are common and slump structures were observed in some outcrops. Such units probably represent stream-channel deposits.

Basalt is a widespread rock type of the lower member, with flows ranging from about 8 m to as much as 60 m thick. The basalt contains olivine phenocrysts; the matrix is composed chiefly of plagioclase and lesser clinopyroxene and magnetite. Both the phenocrysts and matrix are altered, containing widespread chlorite and lesser calcite. Some flows are vesicular, with radiating fibrous calcite filling the vesicles. At least one flow has a rubbly breccia texture. Within the lower member, basalt flows are thickest toward the southeastern end of the outcrop belt in the Madison Range (fig. 4). The basalt flows everywhere overlie the basaltic volcaniclastic sandstone unit of the lower member. No basalt flows underlie the sandstone, which indicates the sands were eroded from basalt flows outside the present outcrop area. In the northernmost part of the outcrop belt, no basalt was found by us or Hadley (1980) in the lower member, but basalt does occur within the overlying middle member. It is unknown if this latter basalt is time correlative with that of the lower member.

Welded tuff units are common in the upper part of the lower member. The two prominent ones are a gray tuff and a stratigraphically higher brown tuff. The gray tuff is only a few meters thick and is 60 to 70 percent welded glass shards, with phenocrysts of plagioclase (15 to 20 percent), and lesser biotite (1 to 8 percent), clinopyroxene (1 to 5 percent), hornblende (1 to 2 percent), and opaques (2 to 3 percent). The glass in one sample from near Lizard Lakes (fig. 1, loc. 1) shows almost no devitrification and the phenocrysts are not altered.

The brown welded tuff is the most abundant of the tuff units and is as much as 100 m thick. It is composed of about 50 percent glass shards, most of which are devitrified; plagioclase phenocrysts (25 percent); biotite (5 percent); quartz (5 percent); opaques (<5 percent); and pumice fragments (15 percent). The pumice fragments and glass shards are stretched and flattened, forming a flow texture in which shards are molded against the phenocrysts and pumice fragments.

The brown tuff, although the thickest tuff unit, is not present in all of the observed outcrops. It overlies different rock units at different places, and its thickness varies from place to place. The tuff was deposited on a surface that is a diastem, but its abrupt changes in thickness and discontinuous nature, including absence from some sections, suggests that its upper surface also is a diastem. This is definitely the case at several localities, because the tuff is overlain by different types of nonmarine sedimentary rock units.

A similar brown welded tuff is present within the overlying middle member in the northwestern part of the outcrop belt (fig. 4). Its geologic setting is discussed in the next section, "Middle member," but its significance is considered here. Table 2 compares selected trace elements of brown welded tuff from the lower member (fig. 1, loc. 2) with brown tuff from the middle member (fig. 1, loc. 3), and compares both with the gray tuff. The two brown tuffs have similar concentrations of the listed elements, but differ significantly from those of the gray tuff. These same relations exist for the major elements, as shown in table 1. These data, combined with the identical appearance of the brown tuffs, and their similar thickness, suggest they represent the same volcanic event. Hence, they constitute a time line, and show that the middle unit at the northwestern end of the belt in the Madison Range was being formed at the same time as part of the fluvial strata of the lower unit at the southeastern end of the belt (fig. 4).

Volumetrically minor tuff units higher in the upper part of the lower member differ from the brown and

Table 2. Kevex X-ray analyses for selected trace elements of welded tuffs from the Livingston Formation.

[Detection limit for each element is shown above elemental abbreviation. Values in parts per million]

Sample locality no.	Description	6 Rb	5 Sr	4 Y	3 Zr	3 Nb	3 Mo
1	Gray tuff (lower member).	83	802	27	264	11	0
2	Brown tuff (lower member).	141	249	26	278	13	7
3	Brown tuff (middle member).	150	236	22	258	10	3

gray tuffs by being 75–85 percent glass shards, largely devitrified, with 5–10 percent plagioclase phenocrysts, and fewer rock fragments. Mafic minerals make up less than 1 percent of the constituents. In addition, these tuffs are only slightly flattened and distorted; flow structures are not common. The shards are sharply angular and include local unbroken glass-bubble walls and abundant Y-shaped shards. The tuffs are commonly tan, green, or light gray, only a meter or two thick, and are discontinuous.

In one place near the southeasternmost part of the outcrop belt is a 30-m-thick lahar deposit of breccia and conglomerate (fig. 5). The lahar is an unsorted and unstratified deposit consisting of subangular to rounded basaltic pebbles, cobbles, and boulders up to 0.5 m in diameter set in a fragmental volcaniclastic sandstone matrix. The clasts make up about 60 to 70 percent of the deposit. Some of the clasts are of a porphyritic basalt of a type known only from sills that intrude the base of the lower member and the top of the underlying strata at the northwesternmost part of the outcrop belt, suggesting a source area northwest of the preserved deposit. The lahar is believed to represent a stream-valley deposit which, like present-day lahars, typically is preserved on a valley floor some distance from its source area (Crandell, 1971, p. 4; Fisher and Schmincke, 1984, p. 297).

In the Madison Range, the lower member is largely an alluvial facies deposit in which the variety and thickness of sedimentary units increase to the southeast (fig. 4). The basal basaltic volcaniclastic sandstone, the only unit of the lower member that occurs throughout the outcrop belt, shows a southeastward thickening that coincides with a decrease in the abundance and thickness of pebble conglomerate lenses. The "maturity" of the sandstone itself shows only a marginal increase to the southeast, but interlayered mudstone beds are present at the southeast and not at the northwest. The general overall pattern, therefore, shows a southeastward decrease in grain (clast) size and an increase in sorting.

According to the vent facies/alluvial facies model presented earlier, fossil trees and other plant material are common in the alluvial facies, but not in the vent facies; this relationship reflects erosion of vegetation from the flanks of a vent area and deposition in adjacent lowlands, or vegetation in the lowlands to start with (Smedes and Prostka, 1972). In the Madison outcrop belt, large fragments of palm tree trunks, as well as particulate plant debris, are common in the volcaniclastic sandstone of the lower member. Leaf collections from the member have been made by Peale (1896) and Hall (1961).

The conglomeratic lahar deposit present in the lower member at the southeastern end of the outcrop belt also fits the expected pattern. Lahars typically occur on valley floors some distance from their source (Crandell, 1971, p. 4); thus preservation of isolated bodies is to be expected, representing deposits in topographic lows at the time interval of deposition, and not found closer toward the vent area.

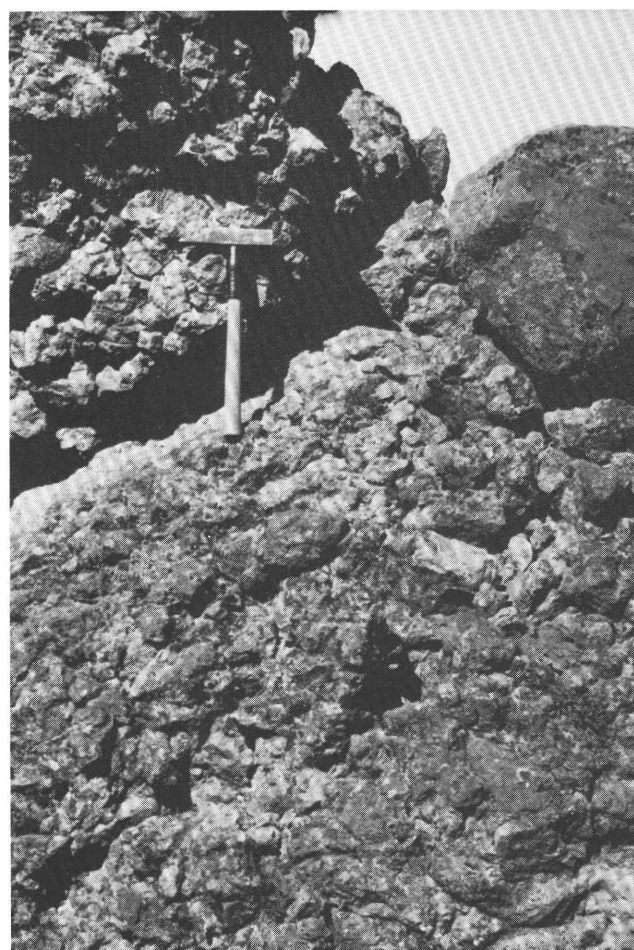

Figure 5. Laharic breccia in the lower member of the Livingston Formation. Hammer for scale; handle is about 35 cm long.

The sequence of units in the lower member differs from place to place within the outcrop belt of the Madison Range. Nevertheless, there is an overall pattern to the sequence. The basaltic volcaniclastic sandstone makes up the basal part of the member, and is directly overlain by basalt in most outcrops. The brown welded tuff is consistently upsection from the basalt flows. Not all sections contain the brown welded tuff, however. In at least five of nine observed sections in the southeastern half of the belt, basalt is directly overlain by flow and flow breccia of the middle member of the sequence. In the other sections, strata of siltstone, sandstone and conglomeratic sandstone, and welded tuff occur in between.

Middle Member

The middle member of the Livingston Formation in the Madison Range is composed chiefly of purple to mauve volcanic flow breccia of dacite to andesite composition and lesser flow breccia of trachyte to trachyandesite composition. The volcanic breccia unit is thickest in the northwestern part of the outcrop belt where it is estimated to be 300 to 400 m thick (Hadley, 1980, p. 80) (fig. 4). Hadley (1980) described these rocks as several types of clinopyroxene, hornblende, or biotite-bearing andesite breccia firmly cemented in a matrix of finer particles of the same material. He noted units 15 m or more thick, showing no sorting or bedding, with interbeds of finer grained tuff-breccia and coarse volcaniclastic sandstone. In some places within the breccia unit, thick bodies of slightly brecciated pyroxene andesite may represent lava flows.

Brown biotite-bearing welded tuff, correlated with that of the lower member, was observed by us in three places in the lower middle part of the middle member in the northwestern part of the outcrop belt. At one of the localities, the tuff is several meters thick and is overlain and underlain by purple flow breccia. The upper breccia is overlain by a sequence about 100 m thick of deeply weathered olivine basalt.

The trachyte to trachyandesite flow occurs on the north side of the central part of the outcrop belt, near locality 7. This flow is as much as 50 m thick, and much of it shows a flow alinement of elongate zoned plagioclase phenocrysts. The upper part is a flow breccia, in which the zoned plagioclase phenocrysts and rock fragments are more nearly equidimensional and are not alined. Some of the clasts are as much as 20 cm across.

The middle member of the formation represents the ''zenith'' of volcanic activity for rocks preserved in the Madison Range outcrop belt. The breccia of the middle member is thickest and most varied at the northwestern end of the belt, and is represented by only a single autobreccia flow at the southeastern end of the belt. Concentration of the variety and thickness of extrusive rocks at the northwestern end of the belt, as well as the occurrence there of porphyritic basalt sills within the lower member and the underlying Cretaceous strata, suggests that the northwestern end may be a vent area, or at least is closer to a vent area than rocks at the southeastern end of the belt.

Upper Member

The upper member of the Livingston Formation has a maximum thickness of about 200 m. The lower and middle parts of the member consist of well-rounded clasts of volcanic rocks in a volcaniclastic sandstone matrix. The clasts commonly range from 10 to 50 cm in diameter but some are as large as 150 cm (fig. 6). They are representative of the volcanic rocks present in the lower two members of the formation, particularly the reddish-purple flow breccia of the middle member. Other specifically identified clasts include olivine basalt, minor biotite-bearing welded tuff, and a few igneous clasts for which no comparable outcrop is known. The matrix is coarse-grained sandstone of angular lithic fragments of volcanic rocks—chiefly plagioclase, with lesser clinopyroxene, potassium feldspar, hornblende, biotite, quartz, magnetite, and volcanic-rock fragments. The rocks are poorly cemented by calcite, hematite, and (or) chlorite.

Contact of the middle and upper members is sharp; it is a diastem in some places but clearly is transitional

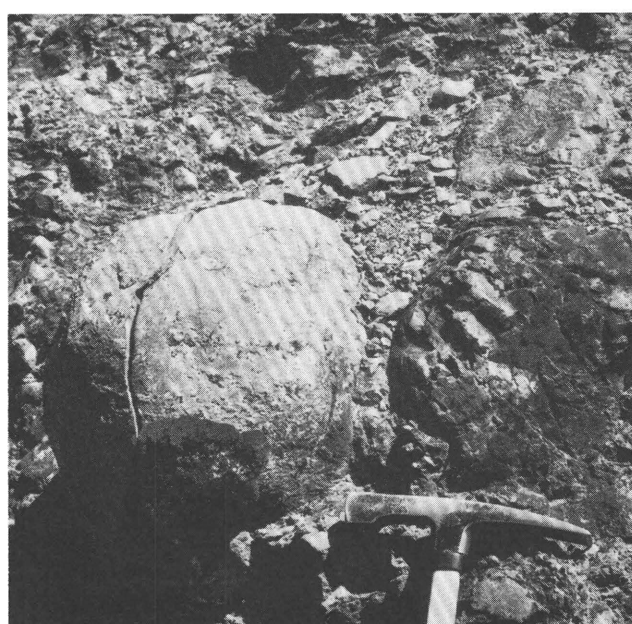

Figure 6. Rounded volcanic boulder in upper member of the Livingston Formation. Head of hammer is about 20 cm long.

in others. South of locality 7 (fig. 1), for example, sandstone of the upper member is interlayered with flow breccia in the uppermost part of the middle member. The change from breccia to sandstone is subtle because composition of the two types of rocks is the same. The top of the highest flow was chosen as the contact of the two members.

Many of the cobbles and boulders in the lower part of the upper member are isolated within a sandstone matrix and do not touch one another. The strata are probably lahars, flood deposits, laid down by a rapidly moving slurry of boulders and finer material, similar to modern-day lahars described by Crandell (1971, p. 58–60) for the Mount Rainier, Washington, area and by Waldron (1967) in Costa Rica. Other conglomerates have a much lower matrix percent but may be of the same origin.

The upper third of the upper member is chiefly sandstone, with local units of boulder conglomerate, abundant lenses of pebble conglomerate, and volumetrically minor mudstone. Conglomerate lenses are a few meters to several tens of meters wide, and range from a few centimeters to a few meters thick. Many show steeply inclined crossbeds and crosscutting erosional features characterisic of anastomosing channels.

Upsection, the conglomerate lenses of the upper third of the upper member, in addition to volcanic clasts, contain increasing quantities of clasts of sedimentary rocks recycled from Mesozoic strata. Some of the clasts are from specifically recognizable units such as the gastropod limestone from the top of the Lower Cretaceous Kootenai Formation, oolitic limestone from the Middle and Upper Jurassic Ellis Group, and ochre mudstone from the Upper Jurassic Morrison Formation as well as sandstone and chert from formations not specifically identified. The calcareous cement of the member also increases in amount upsection.

Along the southeastern limit of the outcrop area of the Sphinx Conglomerate (fig. 1), where the section is fairly well exposed, the upper part of the upper member of the Livingston Formation contains maroon-red mudstone, red and green mudstone, gray mudstone, and minor interbedded sandstone. These strata are overlain by pale-green, medium- to coarse-grained, pebbly sandstone that is transitional through about 30 m into the Sphinx Conglomerate. All of these strata described in the first part of this paragraph occur higher stratigraphically than the conglomerate layers and lenses, and are 2 or 3 m to several meters thick. The contact with the overlying Sphinx Conglomerate is transitional. The contact is placed at the base of the first occurrence of a conglomerate bed, largely composed of limestone clasts, cemented with reddish-orange hematitic muddy sandstone. Conglomerate lenses downsection from the red and green mudstone lack the reddish matrix of the Sphinx Conglomerate.

Previous workers (Peale, 1896; Beck, 1960; Hall, 1961; and Hadley, 1980) concluded that the strata of the Livingston Group lay unconformably beneath the Sphinx Conglomerate. Beck (1960), however, observed that near the eastern and northern part of Sphinx Mountain the contact "appears to be conformable," but noted angular discordance along the west side of the mountain. We follow Beck (1960) in concluding conformity of strata on the northeast side, as well as everywhere else except on the west side. There, the Sphinx Conglomerate lies directly on volcanic rocks of the middle member of the Livingston. The contact on the west may be an unconformity, but the possibility exists that it is a fault. Evidence for a structural interpretation was presented by Tysdal and others (1986).

A series of turbidite beds overlies breccia of the middle member near the southeastern corner of the outcrop belt of the Madison Range and forms a localized unit at the base of the upper member. In a northwest-southeast exposure along the face of a ledge, these strata occupy a V-shaped cut about 0.5 km wide that was eroded into the middle and lower members. The erosional depression probably was a pond or small lake. The turbidites were formed by the discharge of a sediment-laden stream, or streams, into the lake. The turbidite sequence is about 30 m thick, and grades upward from clay and silt-size particles in the lower beds to sand-size materials in the upper beds. The upper half of the sequence contains some irregularly shaped clasts of ripped up turbidite layers like those lower in the sequence. Erosion scours are present at several intervals, immediately overlain by pebbly coarse-grained sandstone, rip-up clasts, and channel crossbeds; some layers show water escape structures. The uppermost layers of the sequence are very coarse grained sandstone with large-scale crossbeds and are stream channel deposits.

Rocks in the lower half of the sequence are composed of clay to silt-size particles in turbidite layers a few millimeters to 1 or 2 cm thick; some layers are varve-like. The strata have an overall color of grayish-pink to tan. Thin sections of the coarser grained turbidite sequence show a composition of detrital volcanic debris. The grains are angular, broken fragments, chiefly plagioclase, with lesser potassium feldspar, clinopyroxene, biotite, hornblende, volcanic-rock fragments, and minor quartz. The matrix and topmost part of turbidite layers are clay-size material that was not analyzed. Opaque grains (for example, magnetite) make up as much as 10 percent of some rocks.

The upper member of the Livingston in general shows a southeastward and upward decrease in the number and thickness of conglomerate layers; clast size also decreases southeastward and upward (fig. 4). Limited measurement of paleocurrent structures indicates a southeastward transport direction. Following the concept of vent facies versus alluvial facies outlined previously, a vertical section near Sphinx Mountain indicates that the upper part of the member records deposition farther from the source area than does the lower conglomerate part of the member. However, the section may simply reflect an upward and southeastward decrease in the vigorousness of the depositional processes, and distance from the source need not have changed. Deposition of the upper member would then have coincided with a waning of volcanic activity in the vent area.

Age

Livingston Formation rocks of the Madison Range were assigned a Cretaceous age by Peale (1896) on the basis of a megafossil flora collected by him (Peale, *in* Knowlton, 1893, p. 44, 45) from strata between the Middle and North Forks of Bear Creek (fig. 1, approx. loc. A). It is not clear, however, whether the collection was from the lower member or from the upper part of the underlying Everts(?) Formation. A leaf collection from Livingston strata in "sec. 30?, T. 7 S., R. 2 E." (fig. 1, approx. loc. B) was assigned a Paleocene age by Erling Dorf (Hall, 1961, p. 81); and another flora (fig. 1, approx. loc. C) was assigned a "late upper Cretaceous" age by R. W. Brown (Hall, 1961, p. 81, 82). Freshwater gastropods and pelecypods collected by Beck (1960, p. 132) (fig. 1, approx. loc. D) are not age diagnostic.

Our studies show that the maximum age of the Livingston strata is Campanian and that the minimum age is no younger than about mid-Maestrichtian. The age assignment was determined through (1) palynological dating of strata below and within the Livingston, (2) radiometric dating of welded tuffs within the Livingston, and (3) radiometric dating of dacite laccolithic rocks that Tysdal and others (1986) have shown to postdate deformation of the Livingston.

The palynological sample from locality E (fig. 1; USGS paleobotany loc. no. D6285) is from the upper 100 m of the strata that conformably underlie the Livingston rocks. The stratigraphic position of the sample could not be determined more precisely because of limited outcrops and the more than 1-km separation of the sample locality from the nearest Livingston outcrops. The sample was obtained from a dark-gray carbonaceous mudstone that underlies a unit of trough crossbedded "salt and pepper" sandstone. The sample from locality E yielded the following palynomorphs, some of which are shown in figure 7:

Appendicisporites sp.
Araucariacites sp.
Callialasporites sp.
Cicatricosisporites sp. cf. *C. australiensis*
Cicatricosisporites sp.
Complexiopollis? sp.
Cupuliferoidaepollenites sp.
Cyathidites minor
Distaltriangulisporites sp. C
Echinatisporis varispinosus
Eucommiidites minor
Foraminisporis wonthaggiensis
Gleicheniidites senonicus
Hazaria sp.
Laevigatosporites sp.
Nyssapollenites sp.
Osmundacidites wellmanii
Proteacidites retusus
Pseudoplicapollis newmanii
Taxodiaceaepollenites hiatus
Triatriopollenites granulatus
Zlivisporis novomexicanum
"Sporites type 1"
isoetalean microspores
tricolpate pollen, unidentified

The assemblage is indicative of latest Santonian or earliest Campanian age. Key forms in the assemblage are *Distaltriangulisporites* sp. C and *Pseudoplicapollis newmanii*, which on the basis of previously published records (Nichols and others, 1982, pl. 1) were not known to occur together. The previously known range of *Distaltriangulisporites* sp. C is limited to about the upper two-thirds of the Santonian, and *Pseudoplicapollis newmanii* is believed to have appeared first in the earliest Campanian. The co-occurrence of these species suggests an age at or near the Santonian-Campanian boundary for rocks just below the Livingston Formation. An independent evaluation of the maximum age of the assemblage is provided by the early Santonian ammonite *Scaphites depressus*. A specimen of this species (identified by W. A. Cobban, written commun., 1981) was collected by us from the base of the Virgelle Sandstone (fig. 1, loc. F), about 400 m stratigraphically below the palynomorph assemblage of locality E.

The palynological sample of locality G is from a brown carbonaceous mudstone in the lower member of the Livingston from a locality in the east-central part of the outcrop area (fig. 1; USGS paleobotany loc. D6368). It was collected about 50 m above the base of the member and yielded the following palynomorphs, some of which are shown in figure 7:

Appendicisporites sp.
Aquilapollenites sp.
Cicatricosisporites sp.
Cupuliferoidaepollenites sp.
Cyathidites minor
Echinatisporis varispinosus
Foraminisporis wonthaggiensis
Gleicheniidites senonicus

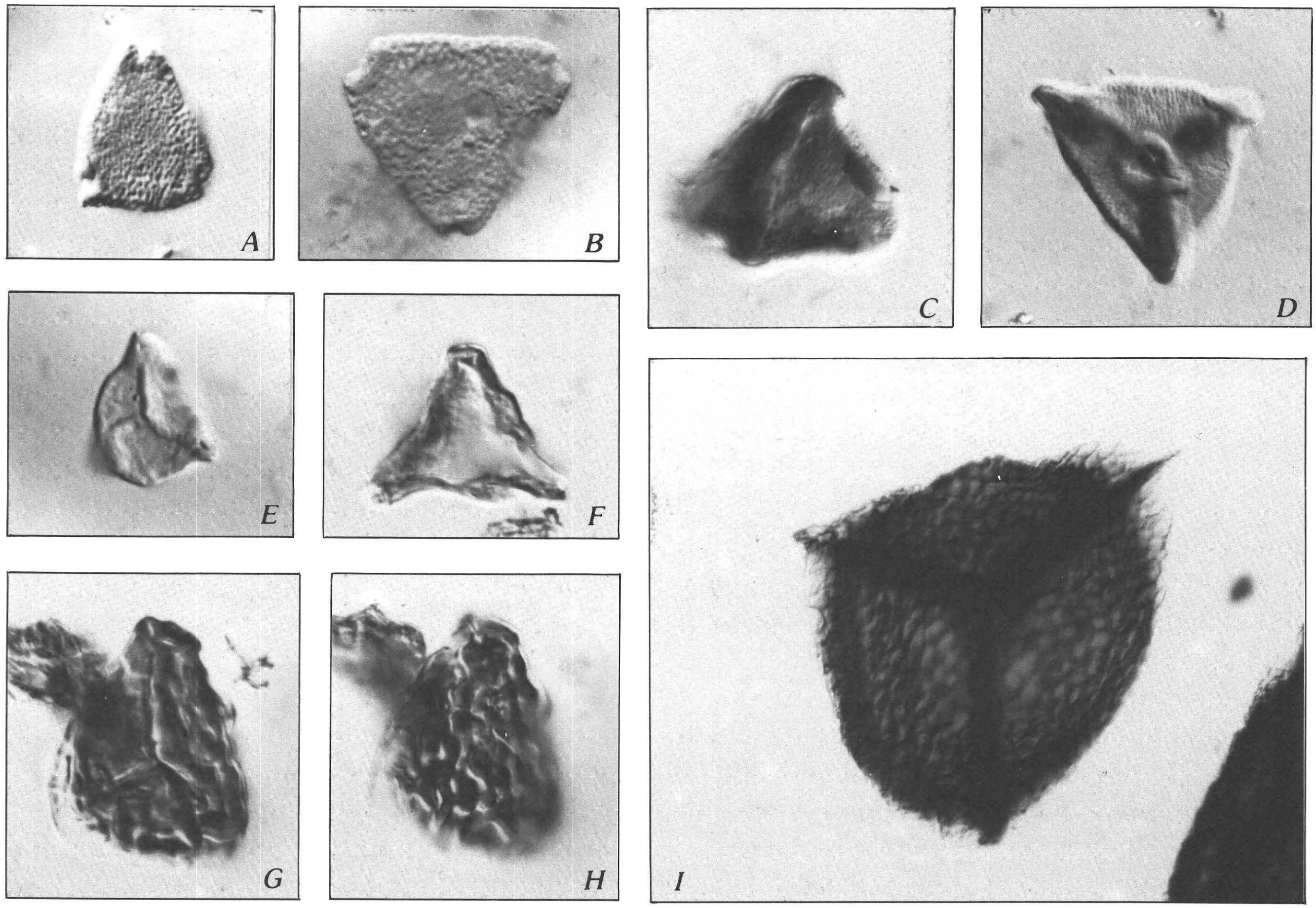

Figure 7. Stratigraphically significant pollen and spores from the Livingston Formation of the Madison Range and underlying beds. a, b - *Proteacidites* spp.; c - *Aquilapollenites* sp. (equatorial view); d - *Aquilapollenites* sp. (polar view); e - *Pseudoplicapollis newmanii*; f - *Complexiopollis*? sp.; g, h - *Distaltriangulisporites* sp. C, (two levels of focus on the same specimen); i - *Minerisporites pseudorichardsonii*. Specimens in a-d and i are from the Livingston Formation. All specimens enlarged 1000X except i, 1200X.

Hazaria sp.
Laevigatosporites sp.
Microreticulatisporites sp.
Minerisporites pseudorichardsonii
Pityosporites sp.
Proteacidites retusus
Proteacidites spp.
Pseudoplicapollis newmanii
Schizeaeoisporites sp.
Taxodiaceaepollenites hiatus
Triatriopollenites granulatus
Zlivisporis novomexicanum
isoetalean microspores
tricolpate pollen, unidentified
trilete spores, unidentified

The assemblage includes species characteristic of early Campanian age. The key species are *Pseudoplicapollis newmanii*, a form that appeared in the earliest Campanian and for which the earliest Campanian palynomorph biozone is named (Nichols and others, 1982), and *Aquilapollenites* sp., a previously undescribed form. The species of *Aquilapollenites* present has not been reported from middle or late Campanian palynomorph biozones, and none of the other species of palynomorphs that characterize the middle or late Campanian are present in the assemblage from sample locality G. The megaspore *Minerisporites pseudorichardsonii* has been reported previously from the Santonian in Wyoming and the lower Campanian in Montana (Tschudy, 1976). Thus the palynological evidence indicates that the lower member of the Livingston is early Campanian in age, and it suggests that the unit dates from near the boundary of the *P. newmanii* and *A. senonicus* biozones (estimated absolute age about 81 m.y.).

Two potassium-argon dates (table 3) on biotite were obtained from previously described welded tuff units within the lower member of the Livingston. Both samples are from the southeastern corner of the outcrop belt (fig. 1). The sample of locality 1, from the gray welded tuff, yielded an age of 79.8 ± 2.9 m.y. The sample of locality

2, from the stratigraphically higher brown welded tuff, yielded an age of 76.8±2.5 m.y. Using the correlation table of Obradovich and Cobban (1975), as modified to reflect new decay constants for ^{40}K (Steiger and Jager, 1977), the sample from locality 1 clearly is of early to middle Campanian age; the sample from locality 2 is middle Campanian.

In summary of the foregoing data, we consider the lower member of the Livingston in the Madison Range to be of early to middle Campanian in age. Palynology indicates the member is early Campanian, and radiometric dating indicates an early to middle Campanian age. The radiometric dates are from welded tuffs within the upper part of the lower member and are higher stratigraphically than the palynological sample.

The minimum age of the Livingston Formation in the Madison Range is uncertain, but could be as young as Maestrichtian. No age determinations were made for rocks of the middle and upper members of the Livingston or for the overlying Sphinx Conglomerate, but a minimum age of Maestrichtian for both sequences was determined via timing of deformation relative to intrusion of laccolithic rocks centered at Lone Mountain (fig. 1) north of the Livingston outcrop belt. Both the Livingston and Sphinx strata occur within the Sphinx Mountain syncline, a northwest-trending fold that formed after deposition of the two units. Tysdal (1986) and Tysdal and others (1986) showed that the western end of the fold was subsequently deformed during eastward-directed thrusting of the Hilgard fault system, a series of north-trending faults and folds along the western side of the southern two-thirds of the range. North of the Sphinx Mountain syncline, dacitic laccolithic rocks and dikes intruded structures of the Hilgard system. Several of the dikes extend as far south as the Livingston outcrop belt where they cut the Livingston, and one cuts the Sphinx Conglomerate as well. None of the dikes were satisfactory for dating, but because the laccolithic rocks also cut the Hilgard fault zone, they are used to provide a minimum age for the Livingston.

Radiometric dating of hornblende dacite of the laccolithic rocks was reported by Tysdal and others (1986). K-Ar determinations on three hornblende separates yielded ages of 72.7±1.6 m.y., 72.7±4.6 m.y., and 68.3±4.2 m.y. $^{40}Ar/^{39}Ar$ determinations on the separates that gave the latter two ages showed the hornblende release spectra were disturbed; one separate yielded ages of 69 to 85 m.y., and the other 67 to 71 m.y. The 85 m.y. age was discounted because it is greater than the known age of some of the deformed strata, and ages slightly older than the minimum 68–69 m.y. were probably caused by excess radiogenic argon. Hornblende from a dike gave a K-Ar age of 116 m.y., an age that is older than the Everts(?) Formation that the dike intruded, and older than the age of the entire Upper Cretaceous section.

Table 3. K-Ar ages and analytical data of samples from lower member of Livingston Formation

[U.S. Geological Survey analysts: Sample 1 - R. F. Marvin, H. H. Mehnert, K. Futa; sample 2 - R. J. Miller]

Sample locality no.	Analyzed minerals	K_2O (percent)	^{40}Ar (moles/ g×10^{-10})	^{40}Ar / total ^{40}Ar	Age (m.y.) ± 2
1	Biotite	6.865	8.066	.91	79.8±2.9
2	--- do ---	6.60	7.456	.84	76.8±2.5

Tysdal and others (1986) concluded that the age of emplacement for the laccolithic dike rocks was about 68–69 m.y. Hence, the youngest Livingston strata of the Madison Range can be no younger than about mid-Maestrichtian.

Regional Correlation

Livingston rocks in the Madison Range originally were considered by Peale (1896) to be an outlier of the Livingston sequence that is preserved largely in the Livingston area. Hadley (1980) rejected this concept and considered the Madison Range strata to be a remnant of the Elkhorn Mountains Volcanics because of the apparent similarity of the Livingston in the Madison Range and the lower member of the Elkhorn Mountains Volcanics. The 79.8±2.9 m.y. date obtained for the lower welded tuff of the lower member of the Livingston is coincident with the 79.8 m.y. date (recalculated from 78 m.y., using new ^{40}Ar decay constants, Steiger and Jager, 1977) cited by Robinson and others (1968), Tilling and others (1968), and Tilling (1974) for the climax of major volcanism of the Elkhorn Mountains Volcanics. The time span of the latter volcanism is not so firmly agreed upon, however, with the estimated span (using recalculated ^{40}K decay constants) ranging from about 84 to 70 m.y. ago (Skipp and McGrew, 1977; Roberts, 1972; Robinson and others, 1968; Klepper and others, 1957; Smedes, 1966). Even though the ages of the three sequences of rocks are correlative, we believe that a closer source is probable for most of the Livingston rocks of the Madison and the Gallatin Ranges.

The Elkhorn Mountains Volcanics and once contiguous correlative rock units may have covered as much as 26,000 km² of southwestern Montana during the Late Cretaceous (Smedes, 1966, p. 21). Volcanic and volcaniclastic sequences that at one time may have formed a part of the assemblage, but that now are isolated from the present area of concentration of the Elkhorn Mountains Volcanics (inset map of fig. 1), generally are known by other names. This came about because of independent study in different areas, unique aspects of different rock sequences, and a lack of dates for some units, but also because local source areas exist for some units. Hence, even though the volcanic and volcaniclastic rocks of the Madison Range are timeequivalents of the Elkhorn Mountains Volcanics, and once may have been contiguous with them (as proposed by Hadley, 1980), another, closer source may be just as probable.

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