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Facies analysis of the volcaniclastic Two Medicine Formation Wolf Creek Montana

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Facies Analysis of the Volcaniclastic Two Medicine Formation, Wolf Creek, Montana

By

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Director: Marc S. Hendrix

The Campanian Two Medicine Formation is a sedimentary and volcanic sequence deposited in the northern Rocky Mountain Foreland Basin. The Two Medicine Formation has traditionally been divided into two facies. The eastern facies consists of 594 meters of sedimentary and volcaniclastic rocks of continental origin. The western facies is approximately 1,372 meters thick, and is divided into a lower sedimentary member and an upper volcanic member (often referred to as the Big Skunk) (Schmidt 1972). Facies analysis of the volcaniclastic strata of the lower, western facies exposed near Wolf Creek Montana suggest an volcaniclastic apron depositional environment. This analysis is based on sandstones deposited by high-sediment-load sheet flood and debris flow processes, and on the mudstones and erosive surfaces which typically cap them.

Petrographic analysis of rock samples in thinsection indicates an undissected arc sandstone provenance which was rich in augite, quartz-poor, and contained uncommon hornblende. The Elkhorn Mountain Volcanics, which are rich in hornblende, augite and quartz, have been suggested as the source of these volcanic rocks by previous workers. The nearby Adel Volcanics, in which augite also is a significant phenocryst, may imply an alternate volcanic source. The Adel Mountain Volcanics, which have been previously identified as Paleocene, have more recently been dated as Campanian (Sheriff and Gunderson, 1994). The Adel Mountain Volcanics and the volcaniclastic member of the Two Medicine may, therefore, represent equivalent strata, produced from the same Campanian volcanic source. The small amount of hornblende may represent inter-eruption background sedimentation from the more distant Elkhorn Mountain Volcanics.

If they are indeed equivalent strata, the Two Medicine and the Adel Mountain Volcanics would likely have been in close proximity, while the sparsely represented Elkhorn Mountain Volcanics could have been more distant. This supposition is supported by the palinspastic map by Price and Sears (1997) which places the Two Medicine Formation and the Adel Mountain Volcanics within the footwall of the Eldorado Thrust, and the Elkhorn Mountain Volcanics within the hanging wall of the thrust.

Acknowledgements

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My research was conducted on the Clonninger Ranch: thanks to Jim and Gail Clonninger for allowing access to this stunningly beautiful exposure.

The words of encouragement from Dr. Steve Sheriff were extremely important and encouraging for me over the past few years.

Thank you to Funhouse members past and present, for nothing less than my survival in Missoula, MT; particularly, Derek Sjostrom, Darren Brost, Sonia Nagorski, Joshua Distler, Buddy von Buddy, Dave Nyquest, Stevehelgen (R.I.P.), and Pat Collins.

The support of my family has never wavered. Thanks, Mom, Dad, Eric and Andy.

Thank you to my guiding light, Casey Evans.

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Introduction:

The Two Medicine Formation is the proximal part of a non-marine clastic wedge that was deposited in a foreland basin adjacent to the active Rocky Mountain thrust belt in Montana (Viele and Harris, 1965) (Figure 1). Sediments comprising the formation were derived from exposed, deformed sedimentary rocks and contemporaneously erupted volcanics. The Two Medicine Formation is currently of interest because, along with the correlative Golden Spike Formation to the southwest, it is the oldest formation which was synorogenically deposited across the modern day Purcell Anticlinorium. Analysis of the depositional record of material shed off of the rising anticlinorium should help constrain the sedimentological and structural history of western Montana during the Cretaceous.

During the summer of 1996, I conducted an outcrop-based, sedimentological study of the Two Medicine Formation, near Wolf Creek, Montana. Several sections were measured through the interbedded volcanic and volcaniclastic rocks (previously identified and mapped by Schmidt (1972a)), in an attempt to characterize the sedimentological history and provenance of the rocks within the study area. Using mainly facies analysis and thinsection petrology, I sought to constrain the depositional styles and potential source areas of the rocks of the southern Two Medicine Formation.

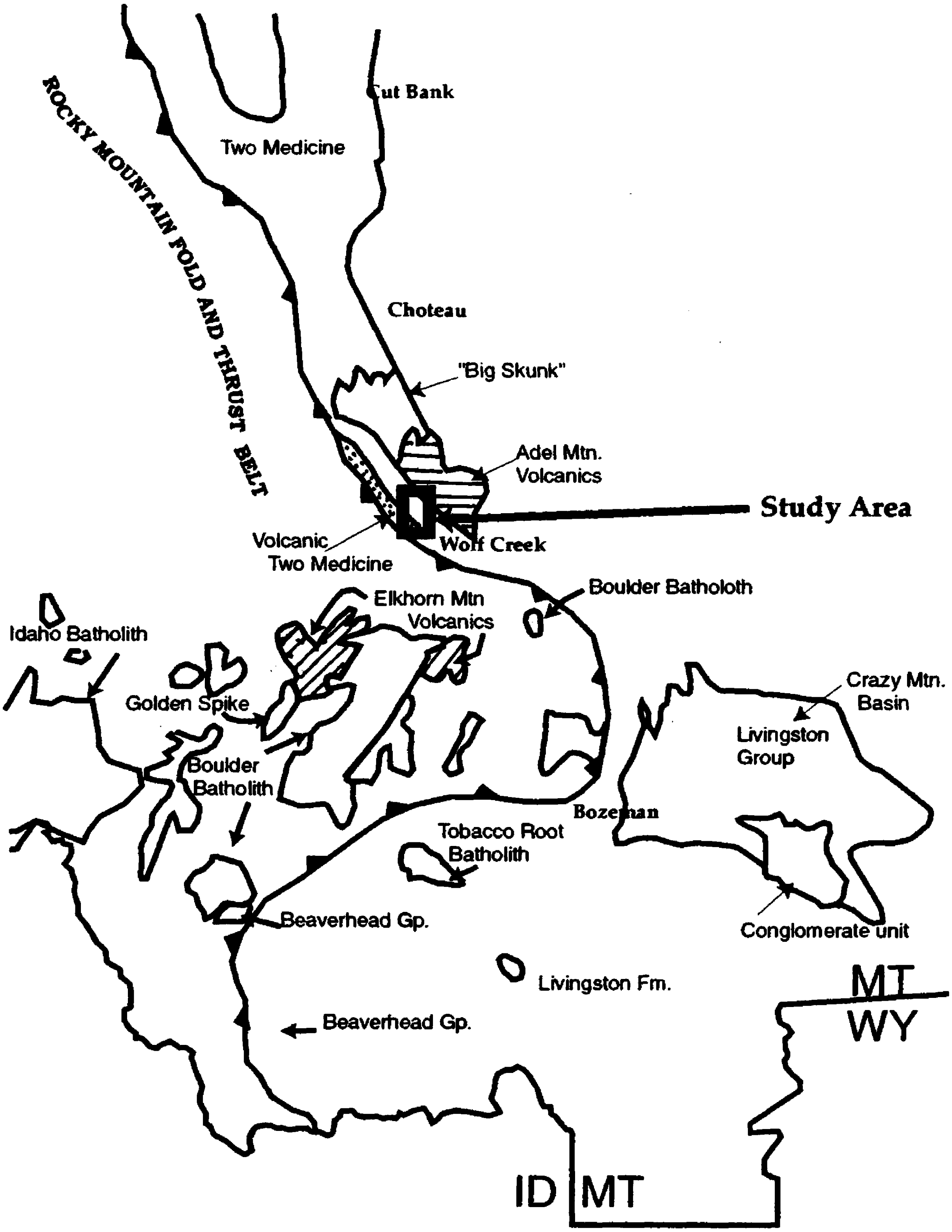

Fig. 1. Significant volcanic, volcaniclastic and sedimentary rocks in Western Montana, including the Two Medicine Fm., Adel Mountain Volcanics, and Elkhorn Volcanics

Background: The Rocky Mountain Foreland Basin

The Mesozoic Sevier thrust belt in western North America is continuous from the southwestern United States to northwestern Canada (where it is referred to as the Columbian belt). It created a compressional, retroarc type basin, and generally consists of thin-skinned thrust plates that underwent eastward tectonic transport (Armstrong, 1968, Price and Mountjoy, 1970). Thrusting began in Middle to late Jurassic time as interpreted from the earliest arrival of western derived deposits within the foreland basin (Armstrong and Oriel 1965; Monger and Price 1979) The beginning of thrusting appears to have been diachronous in the vicinity of the Montana-Canada border. Gillespie and Heller (1995) suggested that evidence of rapid asymmetric subsidence associated with the thrust belt indicates that thrusting in southern Canada began as much as 40 Ma earlier (Late Jurassic) than in Montana (Early Cretaceous).

During this time, the subsidence in the foreland basin decreased southward to a negligable amount ~250 km south of Canada. (Gillespie and Heller 1995). This is consistent with Harrison et al.(1980) who suggested that displacement on major thrusts in southern Canada dies out southward into northern Montana. Similarly, Price and Sears (1997) suggested that the Rocky Mountains of northwestern Montana and adjacent Alberta formed in front of a major thrust plate that overrode the foreland basin by rotating clockwise 25-30 degrees about a pole, located near Helena, Montana (Figure 2).

The Jurassic island arc system outboard of the North American continent evolved into an Andean system following collision of the arc and re-establishment atop continental crust (Dickinson 1975). The main phase of rapid subsidence occurred during the

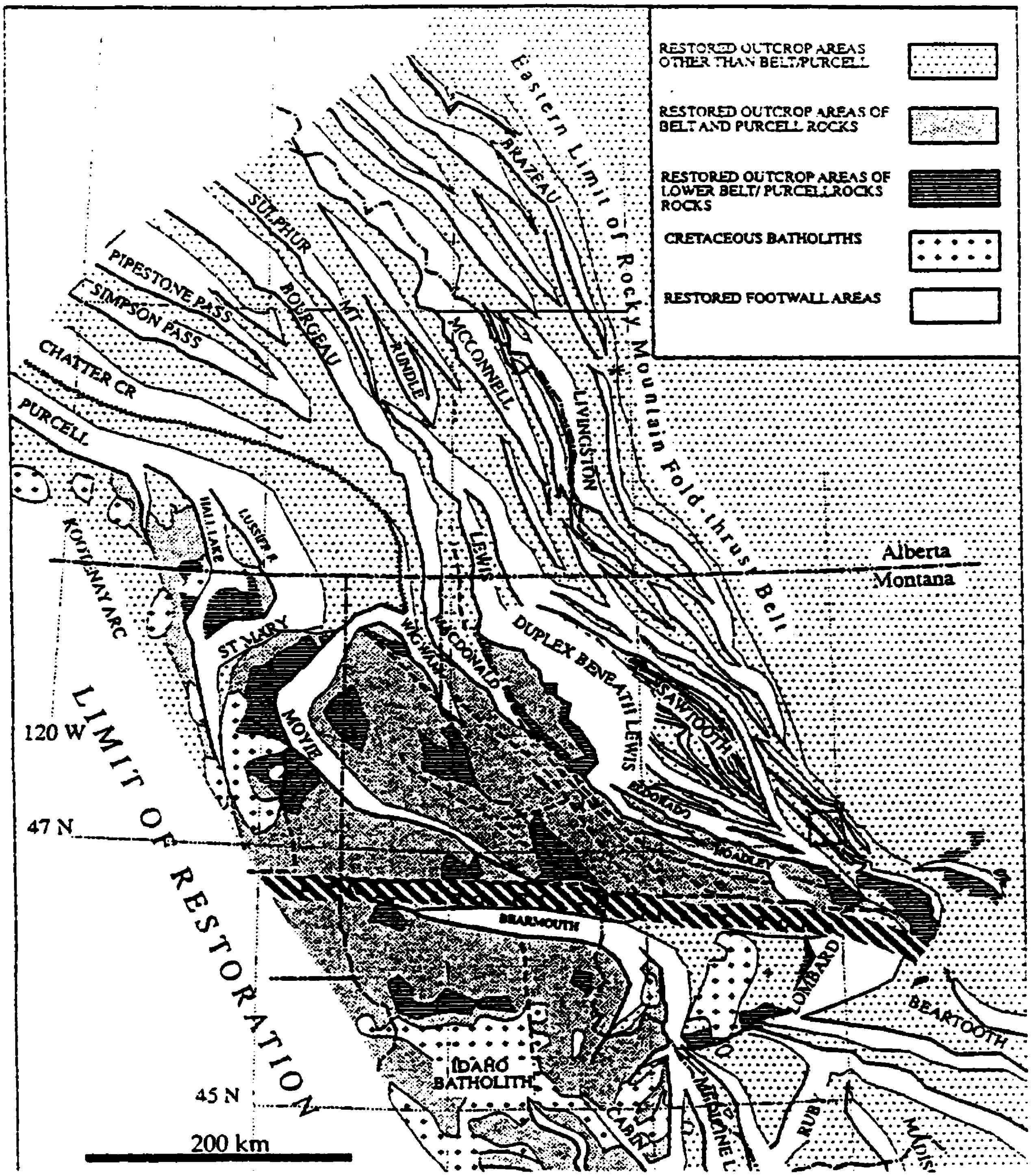

Fig. 2: Palinspastic map (Price and Sears 1997) showing decreasing magnitude of thrusting to the south

Santonian, during a phase of increased orthogonal convergence between North America and the Farallon Plate. A fold and thrust orogen was thereby initiated across the back-arc region, causing widespread foreland basin deposits partially due to a topographically elevated hinterland (Peterson, 1986). Wedge top deposition (DeCelles and Giles, 1996; DeCelles and Currie, 1996) composed a large and important portion of sedimentation in the area (Lageson, 1994). Subsequently, in the Late Cretaceous, shallowing of the Farallon plate caused isostatic broadening of the foreland basin, followed immediately by wholesale disruption of the basin by intraforeland uplifts (Peterson, 1986).

In the Cretaceous, the retro-arc foreland basin reached its largest extent and most rapid rate of subsidence in Montana; simultaneouly, the Cretaceous Western Interior Seaway was created as a result of both load-induced subsidence and tectono-eustatic sea level fluctuations. Unroofing of the Cordillera to the west provided the bulk of sedimentation into the seaway (Peterson, 1986).

One significant result of the disruption of the basin was the creation of the Purcell Anticlinorium in western Montana.This uplift was regionally unroofed to Middle Proterozoic levels, and was the source of a vast amount of material shed into the foreland basin. The first synorogenic units shed due to the unroofing of the Purcell Anticlinorium were the correlative, Campanian Two Medicine and Golden Spike Formations. (Fig. 3)

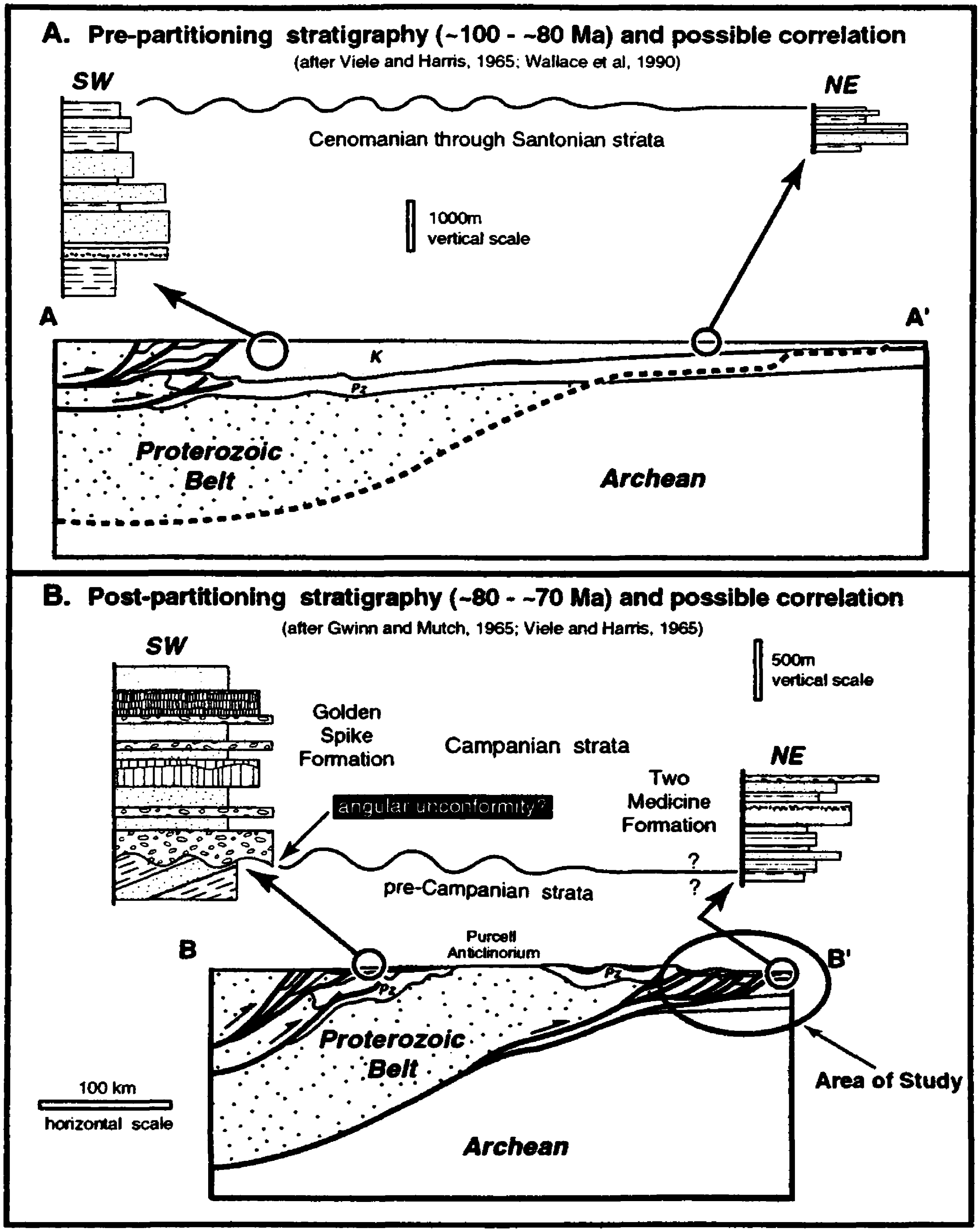

Figure 3: Model for formation of Purcell anticlinorium and Lewis and Clark line and possible evolution of stratigraphy north and south of the anticlinorium.

Overview: The Two Medicine Formation

Weimer (1960) showed that Cretaceous strata in western Montana underwent a crude upward coarsening and a facies transition from marine mudstone and limestone (deposited in the Cretaceous Interior Seaway) to nonmarine sandstone and conglomerate.

Within this Cretaceous facies transition, the Two Medicine Formation was deposited. The Two Medicine Formation is a Campanian age eastward-thinning, non-marine clastic tongue that accumulated along the western shore of the Western Interior foreland basin during two major regressive-transgressive cycles of the Cretaceous Interior Seaway (Rogers 1994). It overlies the sandy, wave-dominated delta/barrier island system of the Virgelle sandstone (Larson 1986), and is abruptly overlain by the marine Bearpaw shale (Lorenz 1980). Deposition of the Two Medicine began with the Telegraph Creek-Eagle regression, and continued until maximum transgression of the Bearpaw Sea (Gill and Cobban 1973).

The Two Medicine Formation consists of approximately 600-650m of nonmarine, alluvial sandstones and mudstones deposited between the rising Cordillera to the west, and the coastal plain to the east (Gavin 1985). Paleocurrent indicators and petrology have been interpreted to indicate derivation from the Elkhorn volcanics to the south-southwest, and perhaps from smaller volcanic centers to the west (Lorenz 1980). Two generalized facies are recognized in this sequence: a lower, delta plain/estuarine facies, and an upper, fluvial channel and floodplain facies. The lower facies consists of bedded carbonaceous mudstones with discontinuous coals (Lorenz 1980) and sand bodies which have been interpreted as anastomosing stream deposits (Gavin 1985). The upper subfacies consists of sandstone lenses in grey (and, uncommonly, red) mudstones, lacustrine clastic sequences and carbonates (Gavin 1985). Both facies contain rare conglomerates and nodular sandy limestones and are characterized by abrupt lateral facies changes indicative of frequent changes in the locus of deposition.

These facies interfinger to the east with marine shales of the Clagget and Bearpaw shales (Rogers et al. 1993). Post-Cretaceous erosion over the Sweetgrass Arch (Lorenz 1982) now separates the Two Medicine from its correlatives to the east. Further south, near Wolf Creek, Montana, the Bearpaw shale was not deposited, and the transgression is probably represented by oyster-bearing, brackish water facies transition, approximately 43m above above the top of the Two Medicine Formation. (Rogers et al. 1993)

Northern Exposure of the Two Medicine Formation

In central and northern Montana, Rogers (1994) suggested two discontinuities within the Two Medicine Formation. The lower is an areally extensive (20 km along strike) sequence boundary 70-100 m above the base of the Two Medicine, indicating a widespread subaereal erosion surface. The sheet deposits which host the discontinuity are dominated by medium- to large-scale wedge-planar and trough cross-stratification. Rogers (1994) interpreted these deposits as a fluvial succession of nonmarine claystones, siltstones and sandstones. His evidence suggesting a widespread subaerial erosion surface includes moderate relief (1-5 m), pervasive oxidation, and a persistent clay-pebble caliche lag. This sequence boundary coincides with a proposed fall in sea level at 80 Ma. This information was supported by an 40Ar/39Ar date of 80 Ma from a bentonite bed ~8m above the unconformity, which coincides with a sea level drop.

The lower discontinuity is overlain by ~30m of carbonaceous claystones, siltstones and lignites near the Two Medicine River. Near Cut Bank it is overlain by shoreface sandstones characterized by swaley bedding, marine trace fossils *Cylindrichnus* and *Terebellina*, and localized lags of oyster debris and flattened siderite pebbles. These paralic arid shallow-marine facies are interpreted as a transgressive system tract (Rogers et al 1993). Within this tract is a zone of bentonites which may correspond to the regionally pervasive Ardmore bentonite.

A second sequence boundary exists ~270 m above the lower discontinuity. It shows no erosional truncation, but is marked by an abrupt shift from fluvial and flood-plain deposits to lacustrine carbonate facies. Below this upper discontinuity lie trough cross-bedded and ripple laminated fluvial sandstones and paleosols characterized by small root traces, red and purple hues, slickensides, and abundant caliche. A ~15m thick carbonate rich interval overlies the upper discontinuity. It consists of thin, interbedded carbonate, intercalated with darker grey and grey-green noncarbonate shale. Additionally, at the top of the interval, it contains siliciclastic lacustrine facies of interbedded siltstone, and fine sandstone beds characterized by burrow traces and ripple stratification. According to Rodgers (1994) these facies may indicate tectonic loading within the Cordilleran orogen, with resultant subsidence and the addition of accommodation space within the foreland basin.

Southern Exposure of the Two Medicine Formation

The southern Two Medicine Formation is exposed in central Montana, near the town of Wolf Creek. Two facies of the Two Medicine were mapped by Schmidt (1972). By his definitions, the western facies is 1456 meters (4775 ft) thick, and consists of both volcanic rocks and volcaniclastic sedimentary rocks (Figure 4). The eastern facies is considerably thinner (594 meters (1950 ft)) and consists of predominantly sedimentary rocks with nonvolcanic clasts (Figure 4).

Viele and Harris (1965) assigned the name Two Medicine Formation to the sedimentary member and the name Big Skunk to the volcanic member. Schmidt (1978) pointed out that this classification tends to obscure the fact that the volcanic rocks are stratigraphically equivalent to the upper part of the Two Medicine, which is sedimentary. The volcanic member of the Two Medicine Formation, of which the study area of this project consists, is an interlayered assemblage of clastic volcanic rocks and lava flows.

Schmidt (1972) mapped a large number of thrust faults to the northeast of the study area, separating the Late Cretaceous Two Medicine from the (ostensibly) Paleocene Adel Mountain Volcanics (Figure 1). Schmidt (1972) considered the Adel Mountain Volcanics to be Paleocene based on mapped relations showing the Adel Mountain Volcanics unconformably overlying the Cretaceous St. Mary's River Formation) and lithologic similarities between the Adel Mountain Volcanics and volcanics of the Eocene Absaroka Range and Highwood and Bearpaw Mountains. Interestingly, he felt that the Adel Mountain Volcanics were early Tertiary rocks, despite the occurrence of two Late Cretaceous fossil plants (*Viburnum montanum* and *Plantophyllum*) (Schmidt 1978).

a.

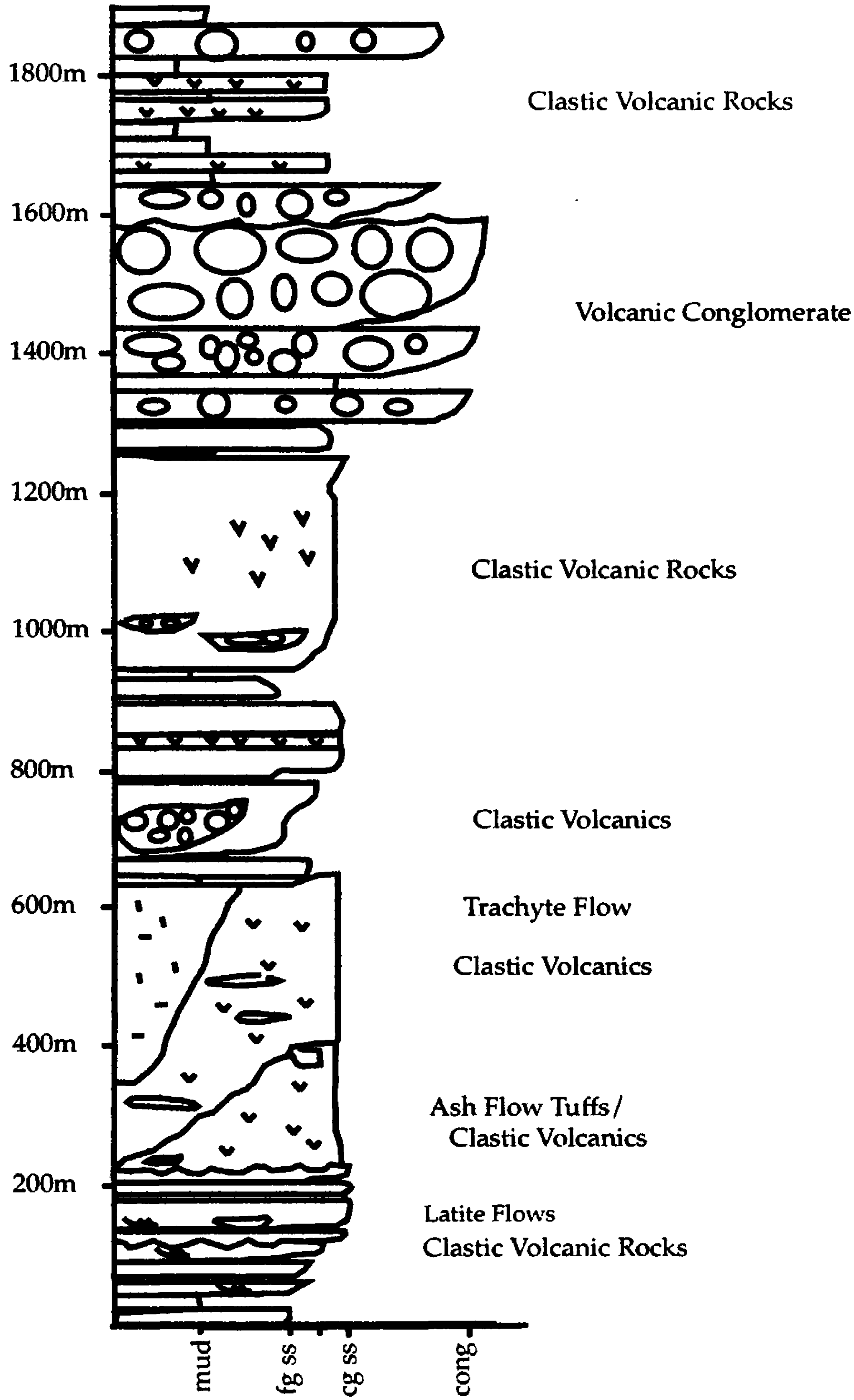

Fig. 4(a). Two Medicine Fm, western facies type column as described by Schmidt (1978); schematic type column created by, and used with kind permission of, Angela Smith, Montana State University

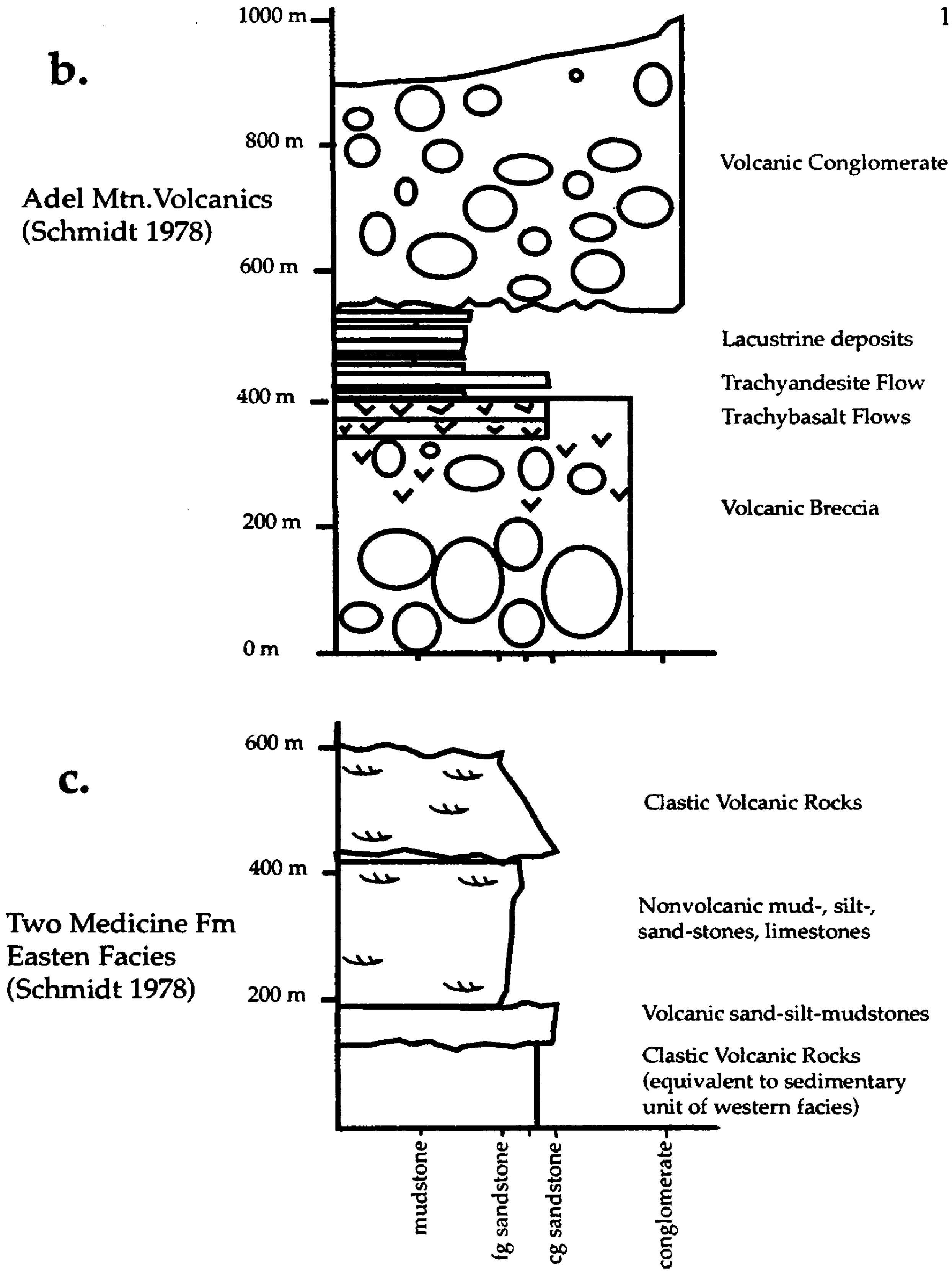

Fig. 4. Adel Mtn. Volcanics (b) and Two Medicine Fm (c) Type Columns as described by Schmidt (1978); schematic type column created by, and used with kind permission of, Angela Smith, Montana State University

More recent K-Ar dates from Sheriff and Gunderson (1990) (81.1 ±3.5 Ma (whole rock) and 71.2±2.7 Ma (biotite)) are similar to Two Medicine bentonite and tuff 40Ar/39Ar dates of approximately 80 Ma and 74 Ma (Rogers et al, 1993). Rogers' bentonites are 100m above the base of, and 10m from the top of the formation, respectively. These data suggest that the age of the Adel Mountain Volcanics is correlative to that of the Two Medicine. Furthermore, it has been suggested (J. Schmidt, personal communication, 1997) that the Adel Mountain Volcanics as mapped by R.G. Schmidt (1972a) (Figure 4) are actually the upper portion of the eastern facies of the Two Medicine. As described below, this idea is partially supported by petrology of rocks in the present study area.

Study Area: Lithologic Descriptions

The Two Medicine Formation is exposed in stream drainages and local roadcuts from the town of Wolf Creek, Montana (Fig. 5) to the Montana-Canada border. This study area contains approximately 750 feet of vertical stratigraphic section in the southern part of the western facies, exposed on a cliffside on and adjacent to the Clonninger Ranch, approximately 2 miles northwest of the town of Wolf Creek. Six vertical and two horizontal sections of the strata which Schmidt (1972) mapped as Ktvd (Fig. 6) were measured during the 1996 field season (see Appendix A).

Two Medicine strata exposed in the cliffside are composed of vertically stacked, nearly monolithologic, tabular sheets of volcaniclastic sandstone. Four distinct general rock types were observed: (1) coarse volcaniclastic sandstone, (2) sandy volcaniclastic mudstone, (3)coarse volcaniclastic conglomerate, and (4) volcanic ash/flow. These rocks occur in distinct, centimeter- to meter-scale sedimentary beds alternating between mudstone and coarse grained sandstone which either grade vertically into each other or are separated by a sharp contact. They are characterized by green, grey, red and purple hues, slickensides, and occasional soil horizons and root traces. Three separate ash beds are interstratified with the volcanic and conglomeratic strata.

Coarse Sandstone Facies

The coarse sandstone (from 0.8-3mm matrix grain size) appears in blue-green/grey beds (5B to 5BG to 10G and 4-6 / 1-3 (GSA Rock Color Chart, 1991)) at the base of the section. It subtly grades to green-grey towards the top of the section (5GY to 5G and 4-

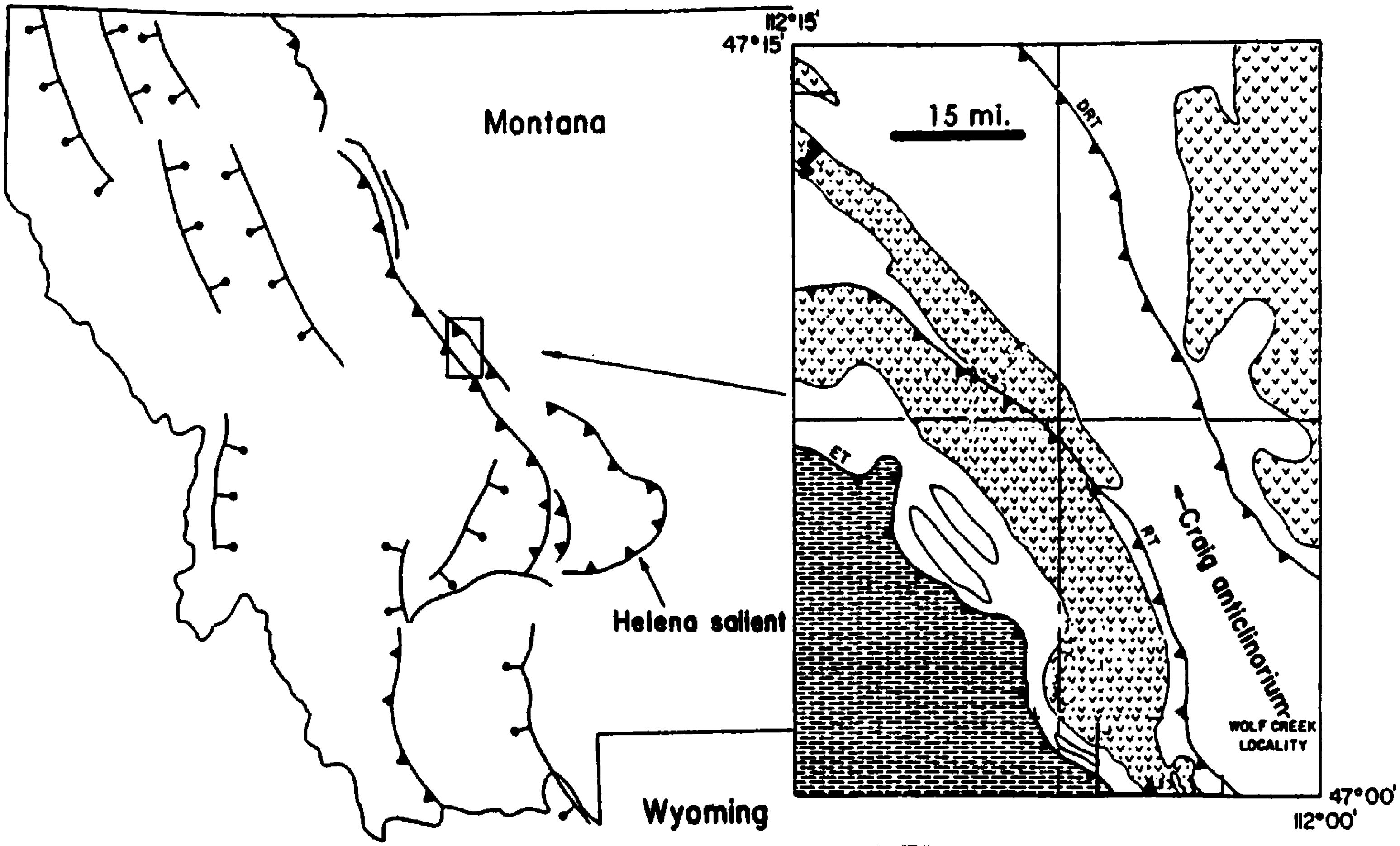

Fig. 5: Generalized geological map of the Wolf Creek area, location of the study area, and major structural features of western Montana (from Jolly and Sheriff, 1992)

Fig. 6: Six transects superimposed on southwest corner of geologic map of the Wolf Creek Quadrangle, Lewis and Clark County (Schmidt, 1972)

6/1-3; and N4-5). The sandstone facies features beds of layered, alternating coarse- and fine-grained sediment, which fill shallow scour surfaces with usually less than 0.1 m of relief. Within coarse sandstone beds are occasional bands of evenly distributed pebbles (approximately 70-90% matrix). The pebbles, which are 5-20mm in diameter are coarse volcaniclastic, volcanic and very fine grained volcaniclastic.

Typically, the base of an individual coarse sandstone layer is coarse gravel (3-5mm) and contains large, elongate, fine grained sandstone clasts (≤50 cm X 5 cm), identical to the very fine sandstone described below. Similar layers of elongate red sandstone clasts also locally lie significantly above the basal gravel, within the coarse sandstone. Small gravel-filled channels occur commonly at the base of, and less commonly within, the coarse beds.

The typical sandstone fines up abruptly from the basal gravel, then more gradually, until the top of the bed. It then grades into the very fine, typically red, sandstone described below, which is itself overlain by a sharp contact and another basal gravel. Less commonly, the sandstone begins to fine, then coarsens again to medium/coarse, before the appearance of the overlying basal gravel.

Pervasive fracturing and spheroidal weathering is evident, and may have destroyed most original sedimentary features, but several dune cross sets and ripple are locally present. The coarse sandstone facies uncommonly features rootcasts and wood fragments which are characterized by bright green colors, presumably due to oxidation. One group of large tree fragments ≥25cm in diameter was located within a coarse sandstone bed (see Appendix A, section 3, 140')

These sands are often constrained by basal erosion surfaces in beds which are commonly laterally tracable in sheets for up to 800 feet along strike, forming significant ledges. They can also be isolated layers which pinch out over tens of feet leaving the red mudstone background sediment (see Appendix B-a). In nearly all cases, the exact lateral terminus of each bed is difficult to locate.

Sandy Mudstone Facies

The sandy mudstone facies occurs in laterally extensive beds which are 0.01-1m thick and which typically cap coarser sandstone layers. Outcrop examples are red-purple, weathering to grey. The field-sample color varies from 5YR to 5RP and from 2-4 / 1-2 on the Mundt Color Chart, and weathered samples often are N4 grey. The facies is usually poorly-sorted on the handsample scale, though locally the top of a mudstone bed may be very-well-sorted. Pebbly zones are regularly present, and are either located in small channel-shaped lenses at the top of fine-grained beds, or evenly and sparsely (<5%) distributed within the bed. The top of each bed is commonly characterized by soft sediment deformation with up to 10cm of relief, or by small, irregularly shaped channels typically 2-3 cm deep (but up to 15 cm).The mudstone contains rootcasts and paleosols (see Appendix A).

Conglomerate Facies

The conglomerate facies is predominantly supported by a coarse-to-gravelly volcaniclastic matrix similar to the coarse sandstone facies. It appears across the entire cliffside, and is characterized by lateral change (see Appendix B(b)). Specifically, in places it is one thick, layered, volcaniclast-rich deposit, which fines up (e.g. Appendix A: Transect A, Transect F), while in other places (e.g. Appendix A: Transect D, Transect E) it shows two distinct layers, separated by a finer sandstone layer. When this is the case, the lower layer is generally coarser than the upper layer. Otherwise grading is all but absent.

Clasts are composed of black volcanic pebbles (which feature abundant feldspar laths), and pebbles and cobbles of sandstone and mudstone similar to the volcaniclastic material described above. The maximum clast diameter observed is 70 cm.

Volcanic Flow/Ash Bed Facies

The lower volcanic layer is a buff microcrystalline ash with a fine glassy matrix, which powders easily. It is 0.5 - >1.5m feet thick. Thicker exposures display both soft, friable tuff and hard crystalline tuff, in accordance with Schmidt's (1978) descriptions of tuff in the area. Capping the study section is a grey rhyolitic flow (weathering a pink buff), which, based on thinsection analysis, contains approximately 55% plagioclase (some of which is altered), 40% volcanic glass, 4% augite, and 1% opaques.

Study Area: Facies Interpretation

Historically, the southern Two Medicine has been described as alluvial facies (Gwinn and Mutch, 1965, Viele and Harris 1966, Lorenz 1984, Rogers 1994). Not surprisingly, the section studied near Wolf Creek fits the type profile of an alluvial fan (as described by Nilsen (1982)) in several ways. The section shows evidence of high-energy flows (e.g. the very coarse unsorted conglomerate). Coarser channel material and debris flows are poorly sorted. The sedimentary structures are limited to some planar stratification, and uncommon small-scale cross-bedding and ripples. There is little internal stratification of sandy deposits; they feature no fossil evidence, save a few small plant fragments, and significant soil profiles exist. However, in volcanic settings these criteria are not adequately indicative of an alluvial fan origin, as identical facies may extend many tens of kilometers across low-gradient alluvial-plain surfaces (Smith 1991).

Similar sedimentary sequences have been interpreted as having been deposited on extremely distal parts of a volcaniclastic alluvial fan: more specifically, on the alluvial apron. For example, deposits analogous to those in Wolf Creek (i.e. sheet sandstones, dominating conglomerates, tabular beds with non-scoured bases, some lenticular deposits) have been found at the margins of modern-day volcaniclastic fans in New Zealand (Palmer et al. 1993).

More significantly, lithologies similar to those found in the Wolf Creek study area have been interpreted as being volcaniclastic apron deposits by Smith (1991), who described in detail the typical facies sequences in continental volcaniclastic sediments. He used the term “apron” (1987 a; 1987b) to emphasize that, although sediments were dominated by debris-flows and flood deposits, the depositional morphologies were relatively low-gradient alluvial plains, with parallel or contributory drainage networks. This is in contrast to clastic alluvial fans, which develop because of transition from confined, channelized flow to sheet flow.

Smith (1991) described two fundamental conditions of sedimentation: syneruption and inter-eruption periods. The syneruption period results in geologically instantaneous production of large volumes of volcaniclastic sediment, and enhanced, variable runoff, leading to sedimentation by high-sediment-load flood and debris flow processes. The inter-eruption periods are typically much longer than the syneruption periods, sediment delivery is greatly diminished and streamflow processes are dominant (Fig. 7-a).

These characteristics suggest that the laterally extensive sandstone-facies beds which compose the bulk of the Wolf Creek area section are of the syneruption period category. Inter-eruption periods are represented in the column as the paleosols and erosive surfaces which typically cap the sandstones. The red mudstone facies is probably "background" sediment that may have its origin in the Elkhorn Mountain Volcanics, based on the appearance of hornblende crystals. The local hornblende is still visible in sandstone thinsection, suggesting that the large volumes of syneruption deposits dilute this background sediment.

The stratified, semi-discontinuous conglomerate facies does not appear to have been deposited in channel systems, as is typical of inter-eruption facies conglomerates. Rather, I suggest that this facies was deposited under turbulent conditions in hyper-concentrated, semi-viscous, lobate, discontinuous layers, perhaps in a large debris flow

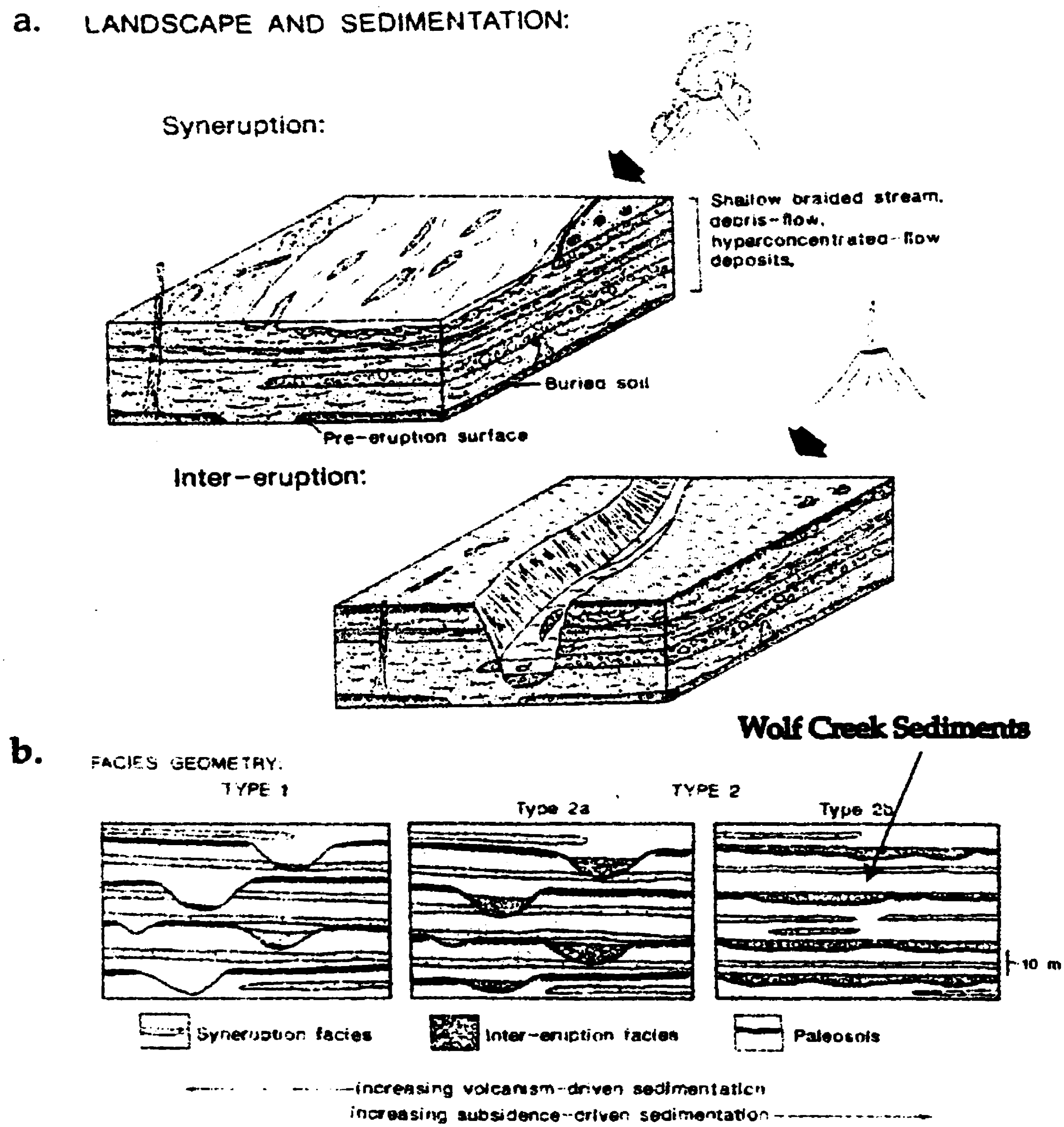

Fig. 7. a)Schematic representation of geomorphic, sedimentologic, and stratigraphic, characteristics of syneruption and inter-eruption condition. b) Two dimensional facies geometries in volcaniclastic apron sequences. Syneruption sheets are bounded by erosion surfaces and paleosols. Studied Wolf Creek sediments are type 2-b (from Smith 1991)

series, within a syneruption period. It may represent multiple, overlapping lahars: rapidly flowing, supersaturated mixtures of rock debris and water (Smith and Fritz, 1989) deposited during a syneruption period (Appendix Bb).

I interpret the Wolf Creek strata to be analogous to the "Type 2-b" volcaniclastic facies geometry of Smith (1991) (Figure 7-b). Based on limited lateral continuity of individual flows of inter-eruption conglomerates, and on subdued stream incision, Type 2-b characterizes higher subsidence rates and/or lower eruption frequencies. Since soil horizons are uncommon throughout the Wolf Creek area strata, it is likely that eruption frequency was, in general, rapid enough to inhibit much pedogenesis. Therefore, it is plausible that the 2-b type facies are a result of high subsidence rates, due to thrusting within the Sevier Belt during the Late Cretaceous.

Study Area: Thinsection Petrology

The volcanogenic mudstone and sandstone from the study contain mainly porphyritic and aphanitic volcanic-lithic fragments. Phenocrysts and microlites are typically plagioclase, augite, and hornblende, often within a fine-grained, plagioclase or K-feldspar rich matrix. (See Appendix D)

Fine-grained mudstone typically contains mainly plagioclase and hornblende microlites in a very-fine volcanic detrital matrix (Appendix D, Photo 3), whereas the coarser sandstones and gravels contain augite grains, and augite phenocrysts in a very fine-grained, K-feldspar crystal matrix, as well as plagioclase and a small component of hornblende. (Appendix D, Photos 2,4,5)

(see point count data: Appendix C)

Discussion of petrology

According to the classification scheme of Dickinson et al. (1985), a plot of these sandstones on quartz-feldspar-lithic ternary diagrams demonstrates a undissected arc origin, based on petrologies rich in volcaniclastic lithic fragments and feldspars (Figure 8). Similarly, Vandervoort (1988) reported volcarenite ratios (i.e. Lv=90; F=10) from the Two Medicine Formation. These data correspond with those reported by others (Viele and Harris 1965, Schmidt 1966, Lorenz and Gavin 1984) who attributed the volcanic-rich alluvial facies in southern Two Medicine exposures to the Elkhorn Mountain Volcanics. This provenance relation potentially explains the existence of augite, hornblende and zoned plagioclase in thinsection, all of which are found in the Elkhorn Volcanics (Smedes, 1966; Satoskar 1971).

The association of Two Medicine volcaniclastic sediment to an Elkhorn Mountain Volcanic source does not, however, explain the lack of quartz in thinsection or the coarser sandstones. Quartz is very common in the Elkhorn Mountain Volcanics (Smedes, 1966; Satoskar 1971), and would be an expected phenocryst in any resultant volcaniclastic deposit.

The main phenocryst in the nearby Adel Volcanic field is augite, commonly within a K-feldspar rich volcanic matrix (Beall, 1973, Lyons 1942, Lyons 1944). Initially, Schmidt (1972a, 1972b, 1972c) interpreted the Adel Mountain Volcanic Field to stratigraphically overlie the Two Medicine Formation. Specifically, he stated that the Adel Mountain Volcanics unconformably overlie the Cretaceous St. Mary's River Formation (Figure 9). Correlation problems, however, have been difficult due to the paucity of datable

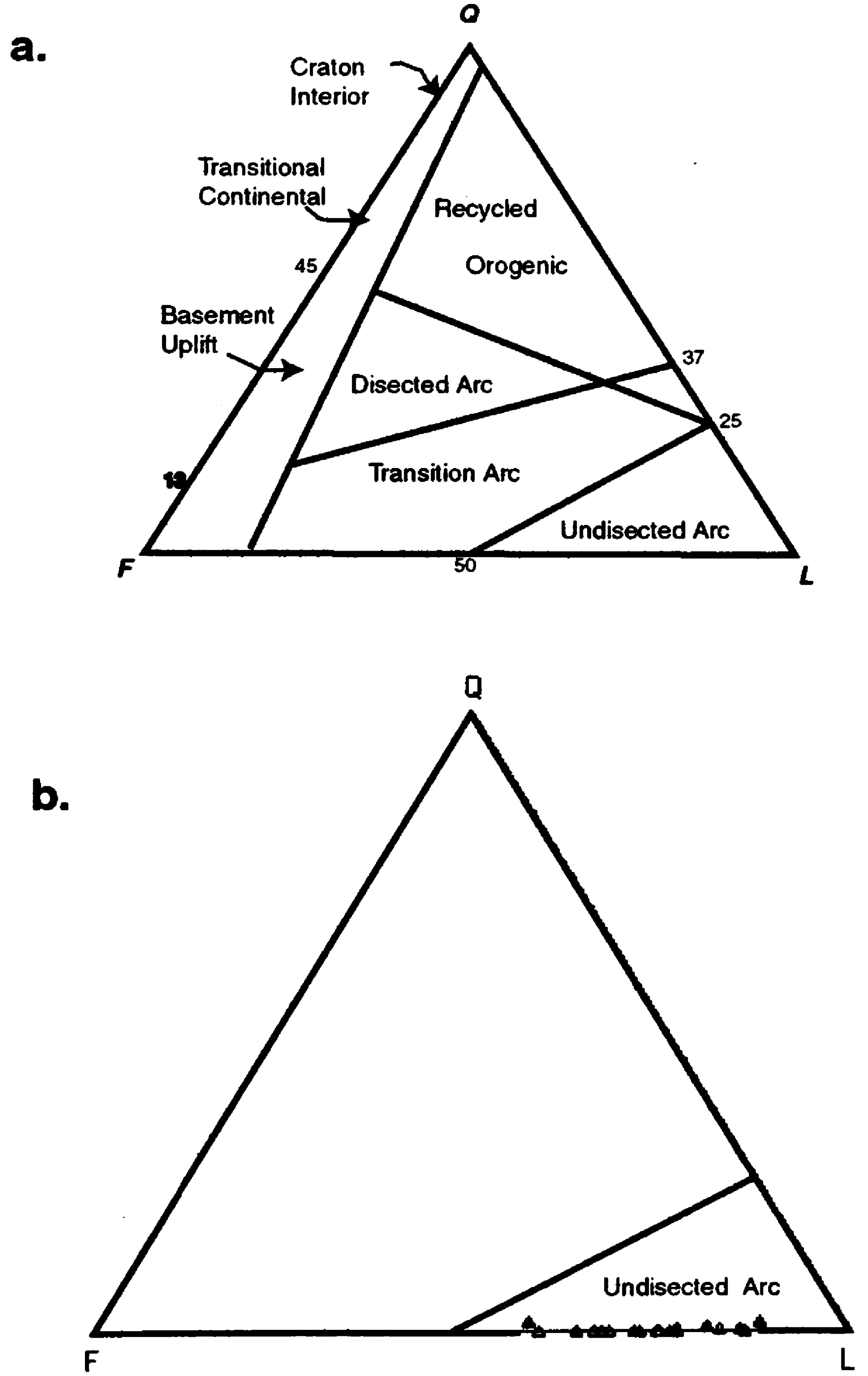

Fig.8. (a) General Quartz-Feldspar-Lithic provenance ternary diagram (after Dickinson 1985) and (b) Quartz-Feldspar-Lithic ternary plot of sanstones from the Wolf Creek Study Area

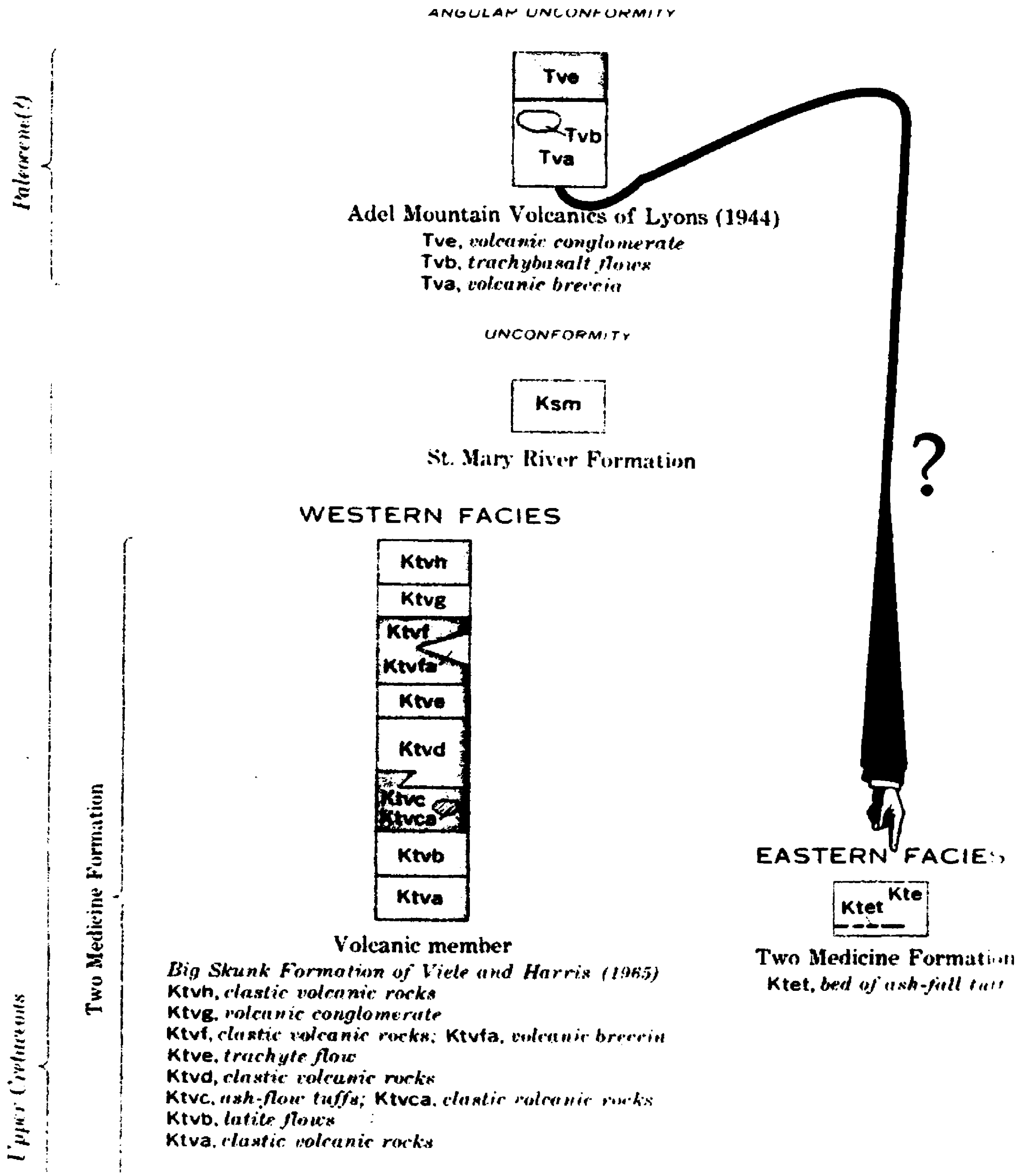

Fig. 9. Stratigraphic Column of Two Medicine and Adel Mountain Volcanics, showing possible relationship if Adel Mountain Volcanics to Two Medicine Formation, eastern facies. (from Schmidt, 1972a)

material in non-marine facies (Dyman, 1990).

The more recent dates of the Adel Mountain Volcanics and the Two Medicine from Sheriff and Gunderson (1990) (see above) indicate that the Two Medicine and the Adel Mountain Volcanic Field, as well as the Elkhorn Volcanics, may have been coeval. These two volcanic fields are major potential nearby sources which contain augite and hornblende phenocrysts, respectively, suggesting that they may have both contributed to the volcaniclastic sediment of the southern, western facies of the Two Medicine Formation.

One sample was acquired from the "Tva" volcaniclastic breccia facies of the Adel Mountain Volcanics, as mapped by Schmidt (1972a). Point count data is plotted along with that of the Wolf Creek Study Area rocks (Figure 10-a,b). On a standard Q-F-Lv ternary diagram, the Adel Mountain Volcanics sample plots within the cluster of Campanian Two Medicine sediments. On a ternary diagram with feldspar, lithic-volcanic and augite axes, the Adel Mountain sample plots close to the Two Medicine samples, but with a higher augite ratio. The elevated augite percentage may be expected, since the Adel Mountain Volcanics exposures less diluted, so to speak, by sedimentation from additional sources. This admittedly limited point-count data, therefore, supports the suggestion that the Adel Mountain Volcanics are lithologically similar to the upper Two Medicine Formation. A comparison of Two Medicine and Adel Mountain sandstones in thinsection can be made in Appendix D (Photos 5 and 6).

Significantly, the palinspastic map created by Price and Sears (1997) shows at least 40km of thrusting displacement in the area immediately to the west (Figure 11). If the post-Cretaceous thrusting (most significantly, the Lombard-Eldorado thrust) is

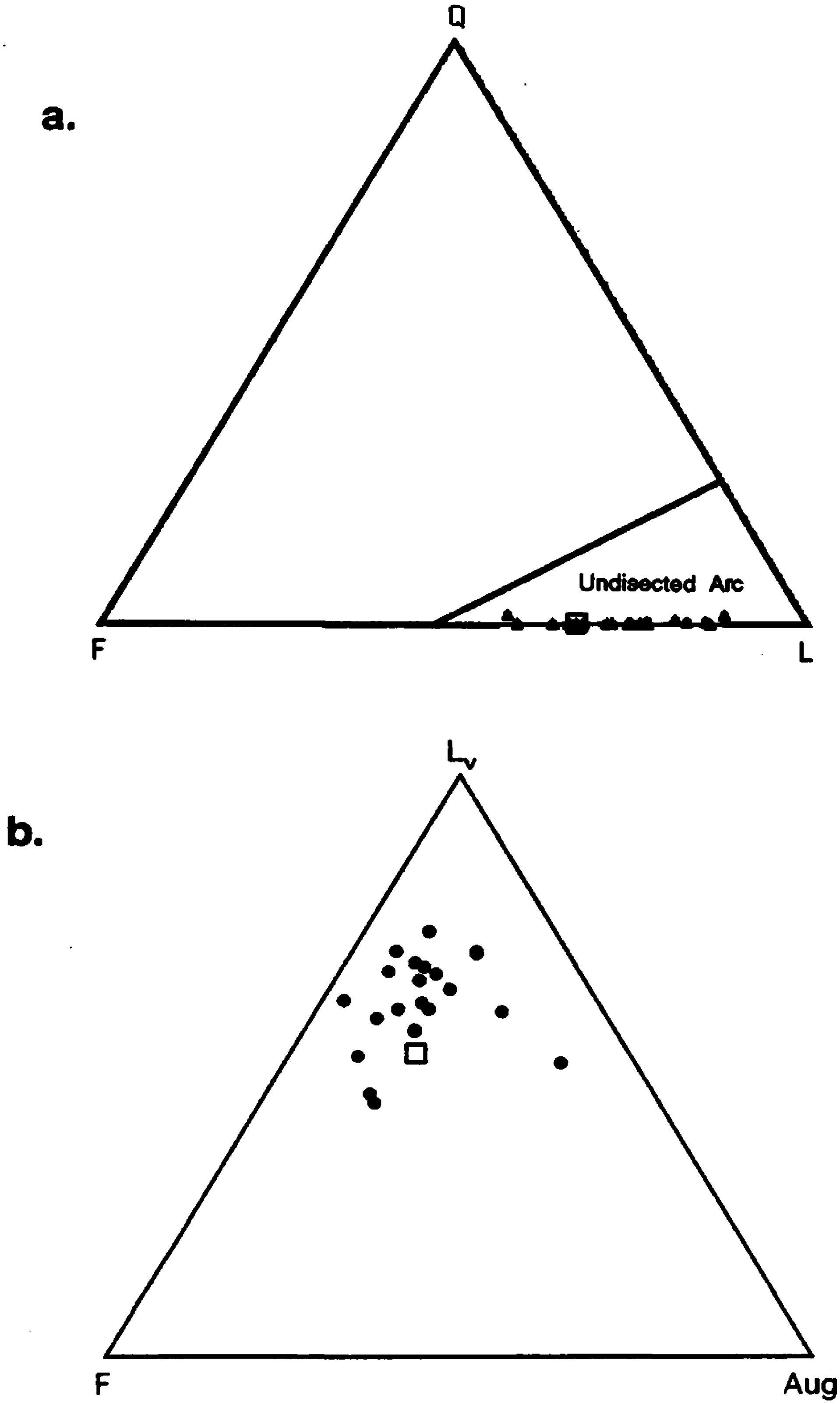

Figure 10: (a) Quartz-Feldspar-Lithic ternary plot of sanstones from the Wolf Creek Study Area,including Adel Mountain Volcanic Sample (open square); (b) Lithic-Volcanic-Feldspar-Augite ternary plot, including Adel Mountain Volcanic Sample (open square)

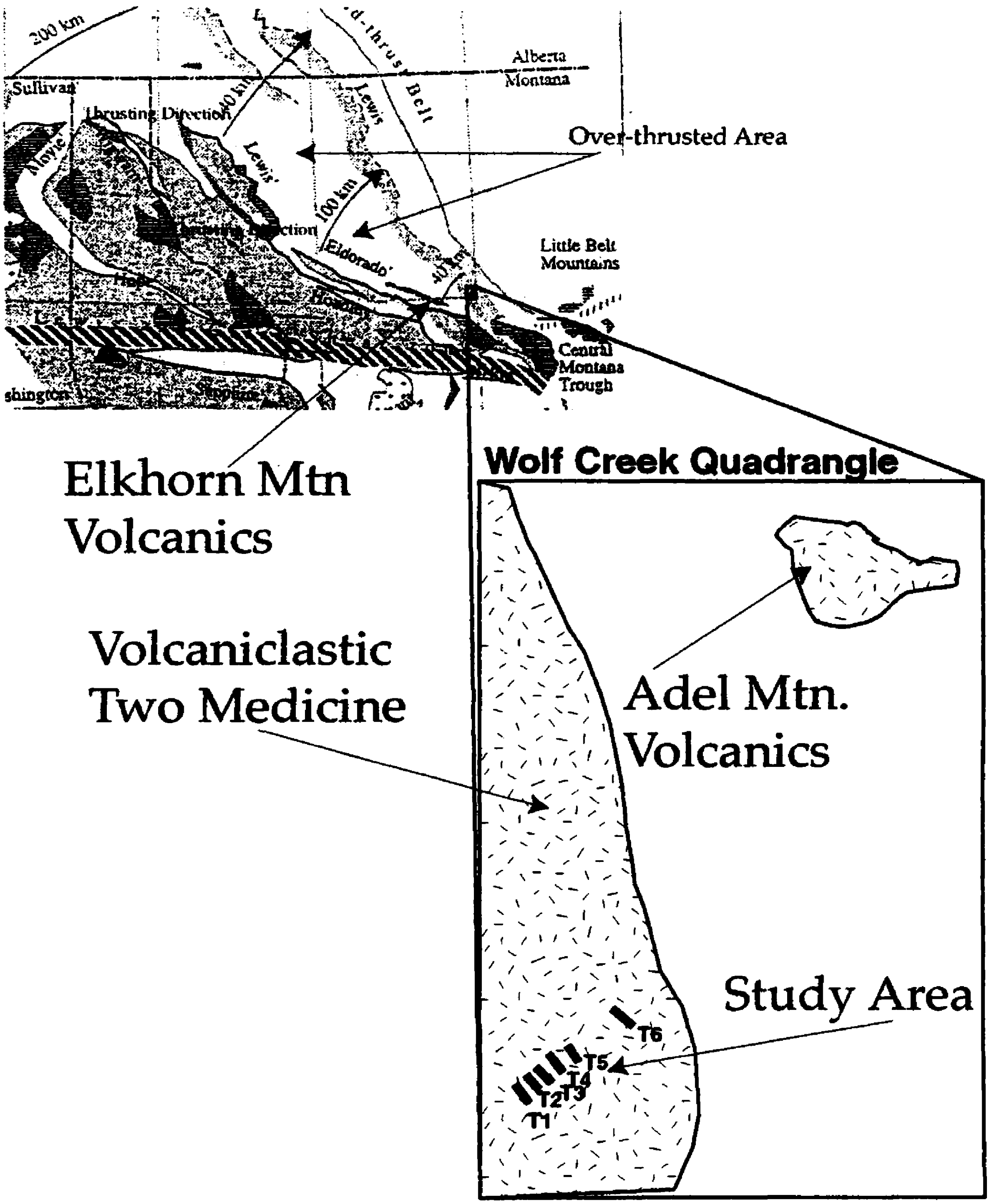

Figure 11. Location of the Volcaniclastic Two Medicine, the Wolf Creek Study Area, the Adel Mountain Volcanics and the Elkhorn Mountain Volcanics, within the Wolf Creek Quadrangle, as mapped by Schmidt (1972).The inset is shown within the palinspastic reconstruction of Price and Sears (1997).

palinspastically restored, it places the Elkhorn Volcanic source at a greater distance from the study area. In contrast, the Wolf Creek Two Medicine study area and the Adel Mountain Volcanics remain in close proximity to each other in the footwall. This, along with preliminary sandstone point-count data, supports the suggestion that both facies had the same volcanic source. Specifically, the Adel Mountain Volcanics, located 3.5 miles to the northeast of the study area, are potentially stratigraphically equivalent to the upper western facies of the Two Medicine Formation.

Conclusions

Facies analysis and thinsection petrography suggests that the southern Two Medicine consists of nearly monolithologic, volcaniclastic alluvial apron deposits. Stratal geometries suggest a rapid rate of volcanism, and abundant sedimentation, conceivably facilitated by rapid subsidence due to thrusting within the Sevier Belt. Petrology indicates an augite-rich, quartz-poor volcanic source, the nearest of which is the Adel Mountain Volcanics, previously mapped as Paleocene. However, newer dates indicate that the Adel Mountain Volcanics may have been coeval with the Two Medicine and the Elkhorn Mountain Volcanics. This allows the possibility that the Adel Mountain Volcanics and the western facies of the Two Medicine Formation were created by a single, local, volcanic source during the Late Createaceous. This supposition is supported by the palinspastic map by Price and Sears (1997) which place the Two Medicine Formation and the Adel Mountain Volcanics within the footwall of the significant Eldorado Thrust, and the Elkhorn Mountain Volcanics within the hanging wall of the thrust.

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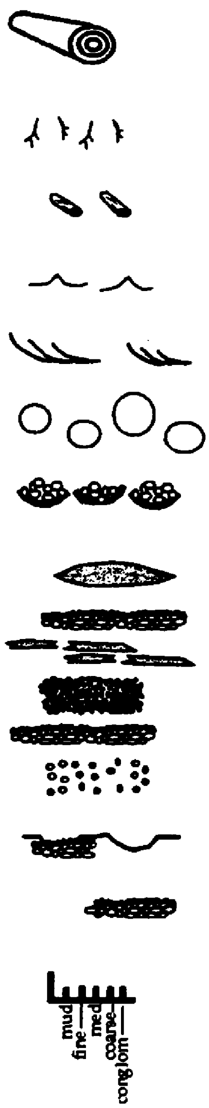
Key - Appendix A, B



tree trunk

root casts

twigs, wood fragments

ripple marks

cross bedding

large (15-30cm) clasts

small gravel channels

fine grained red mud lenses

elongate red mud clasts

coarse band

pebbly zone

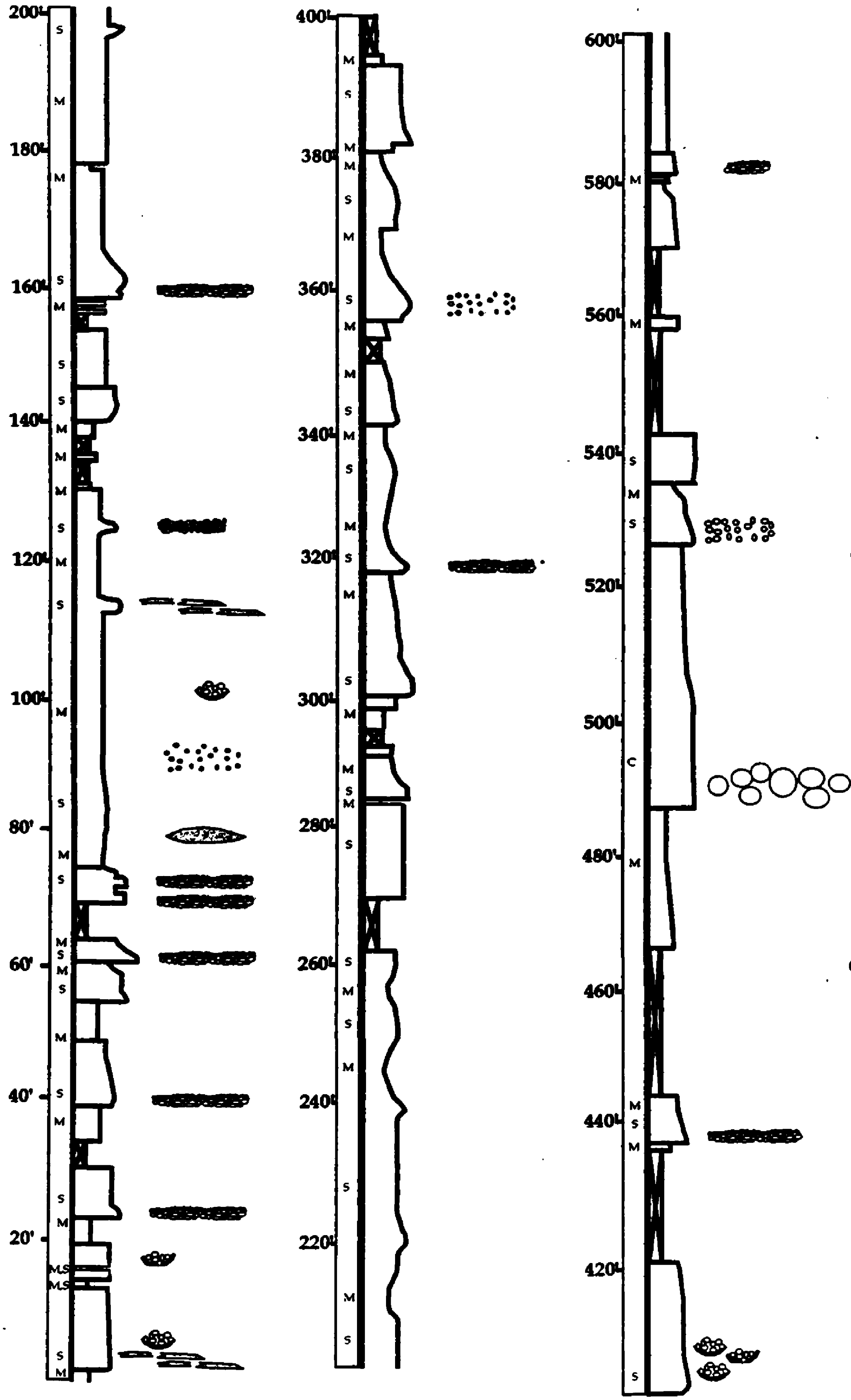
erosive contact

basal gravel

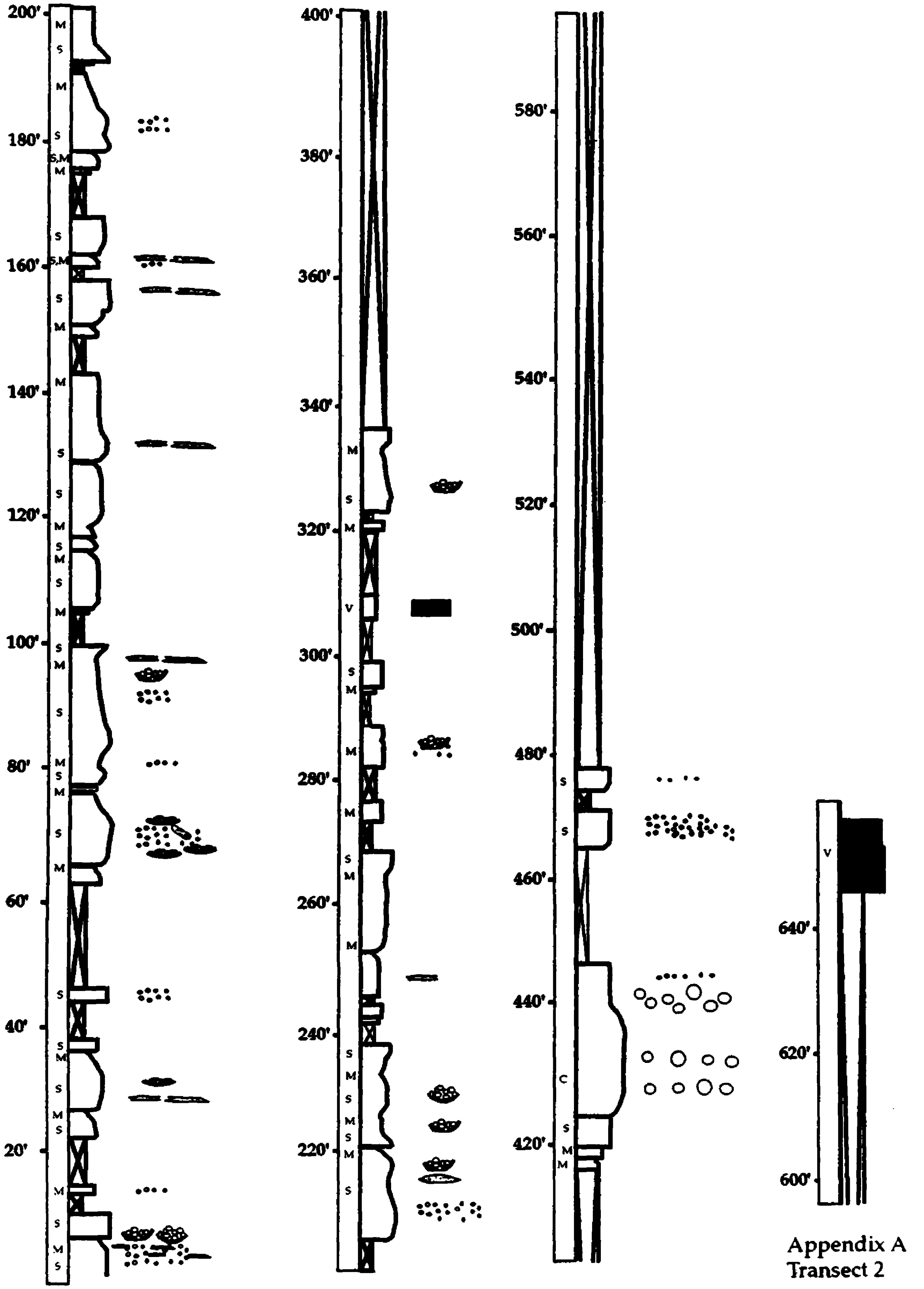
grain size scale

Key to facies

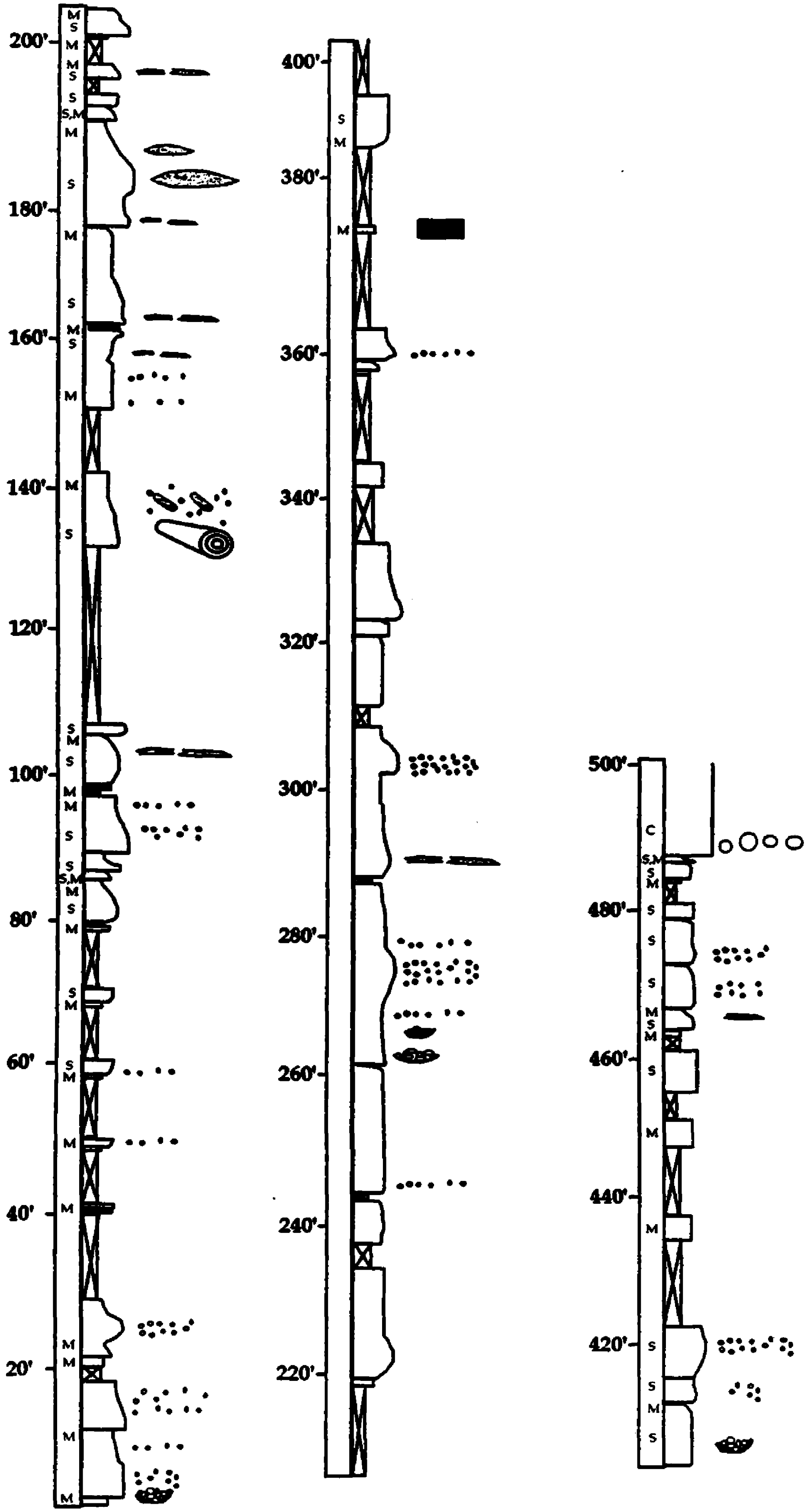
s	sandstone facies
m	mudstone facies
c	conglomerate facies
v	volcanic ash/flow facies



Appendix A
Transect 1



Appendix A
Transect 2



Appendix A
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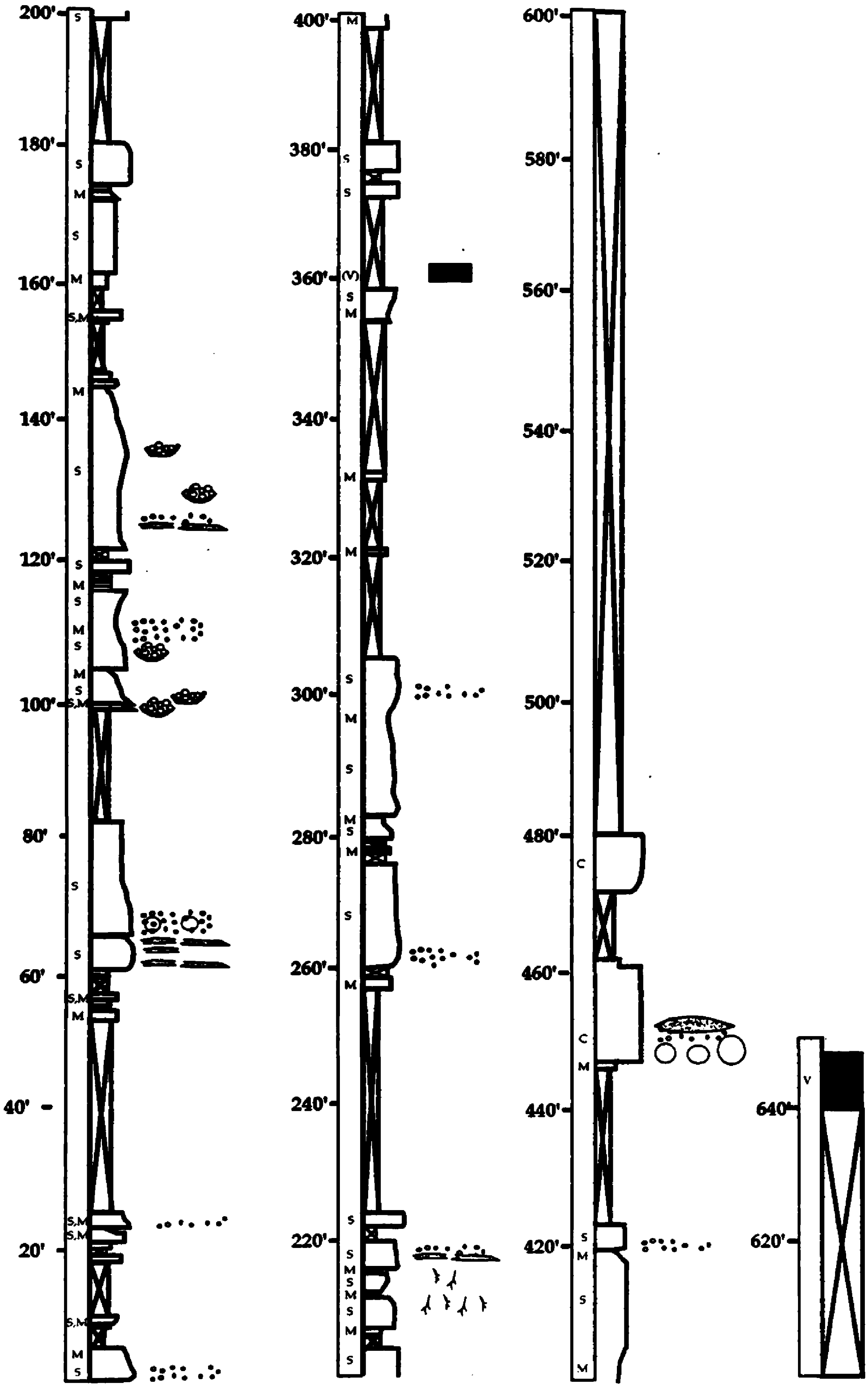

Appendix A
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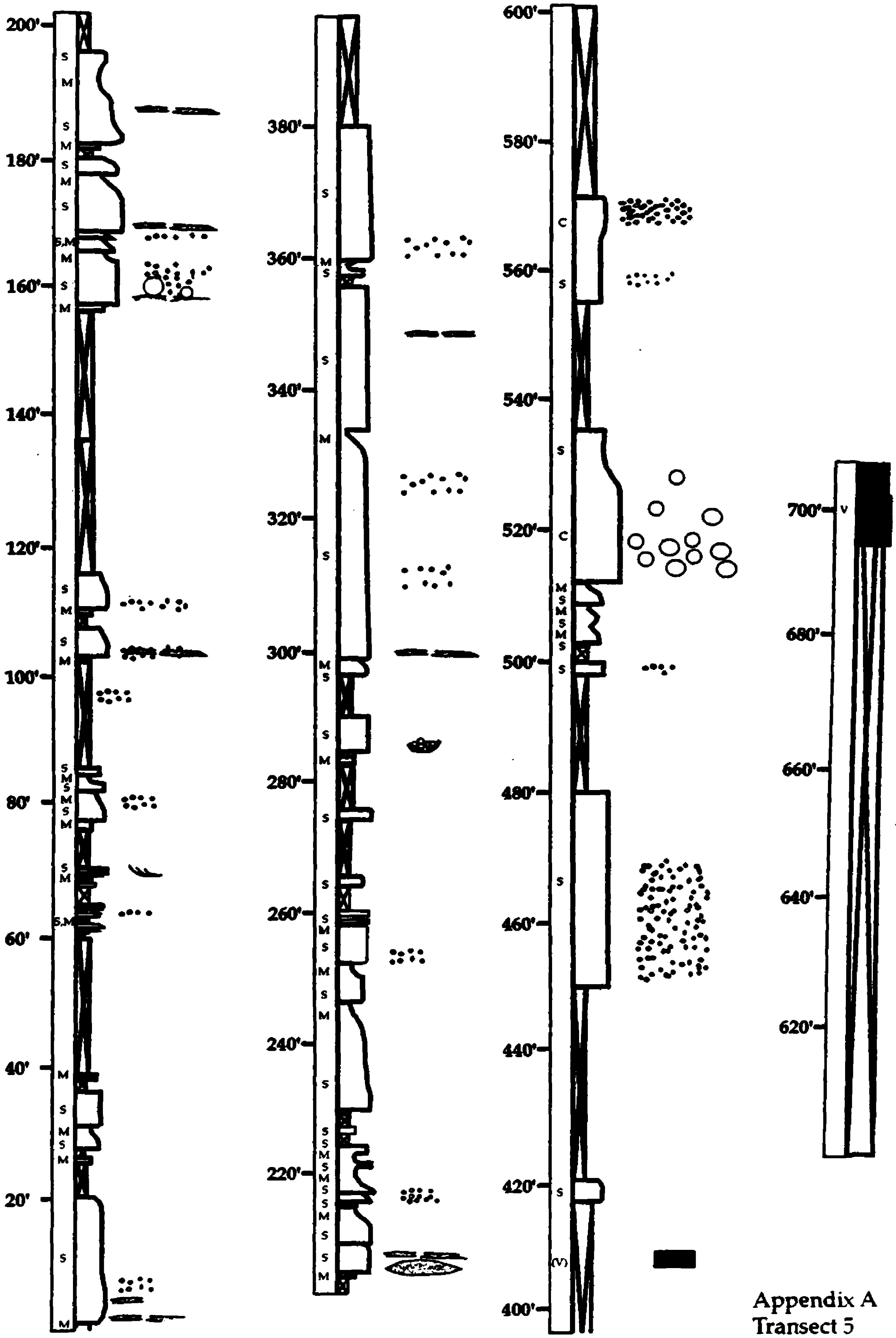

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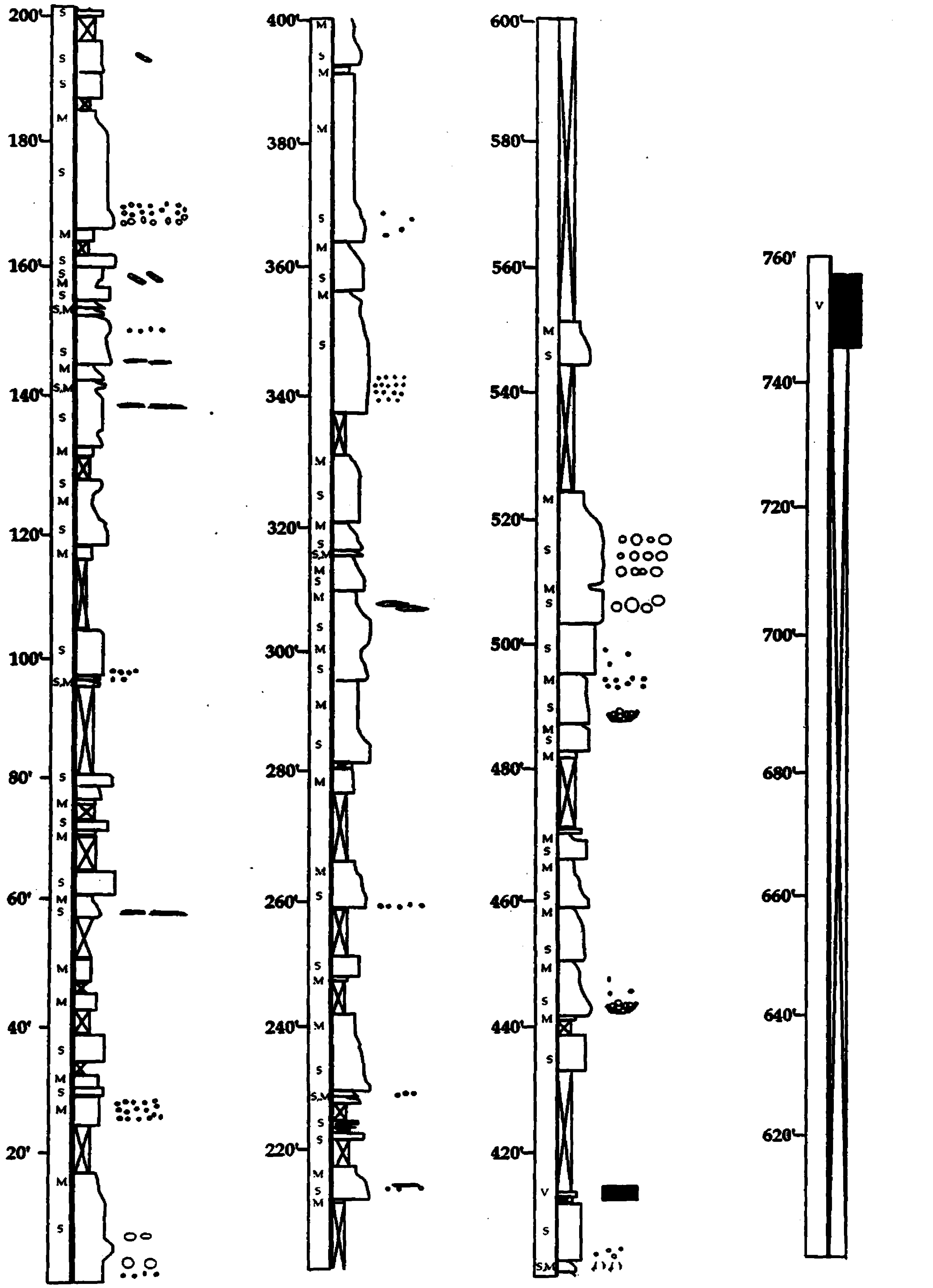

Appendix A
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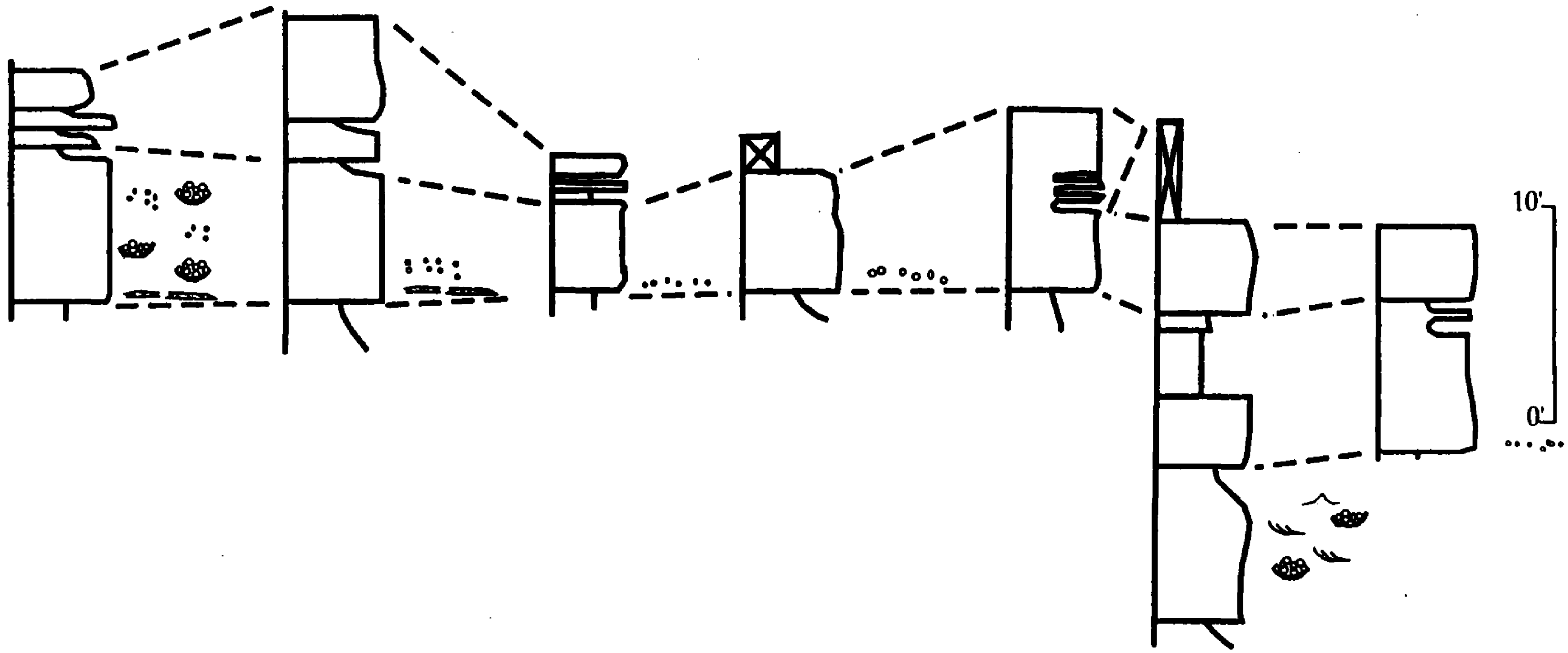
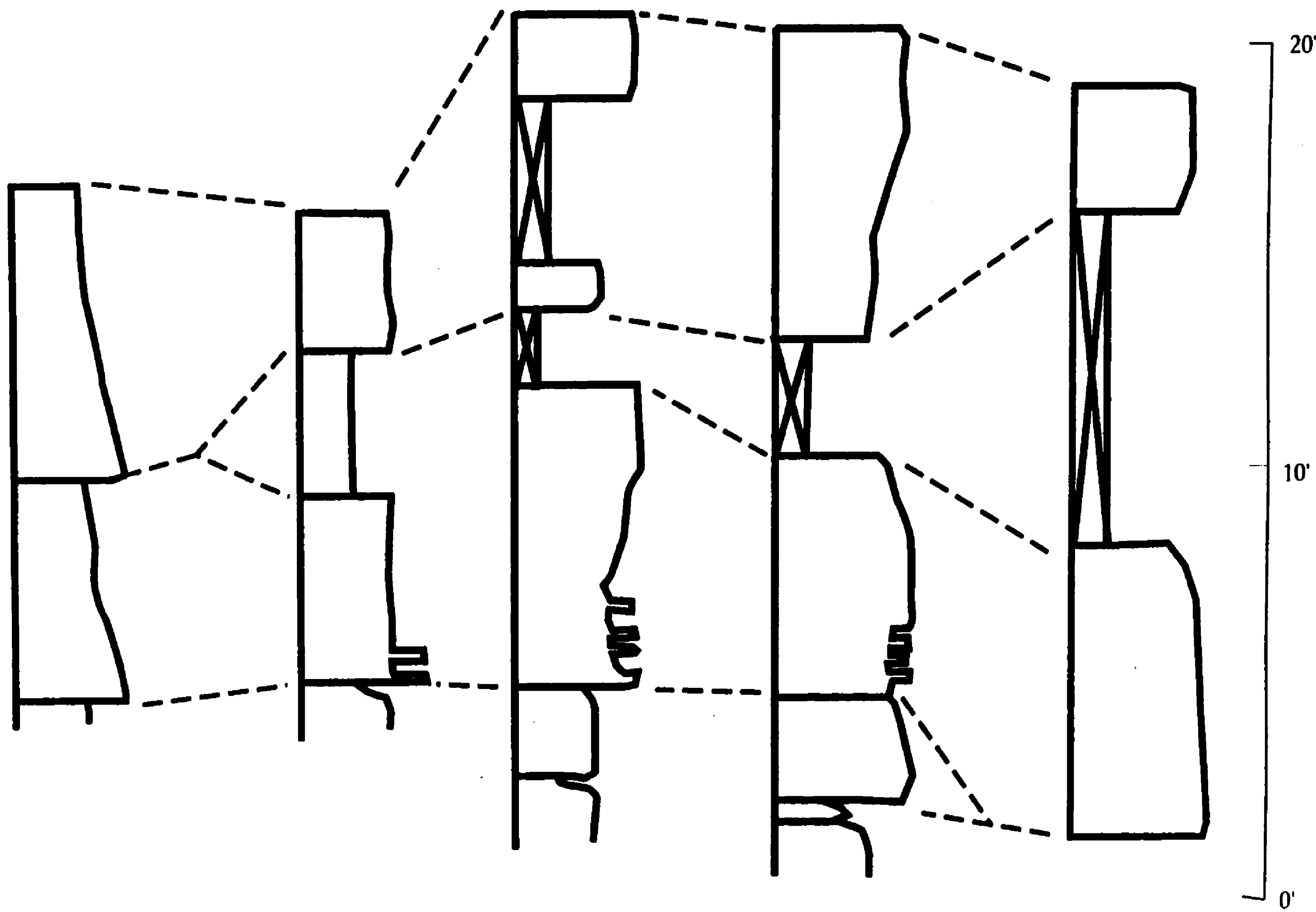


Appendix B (a) Lateral comparison of sandstone facies over apprximately 3500 ft., connecting bounding surfaces



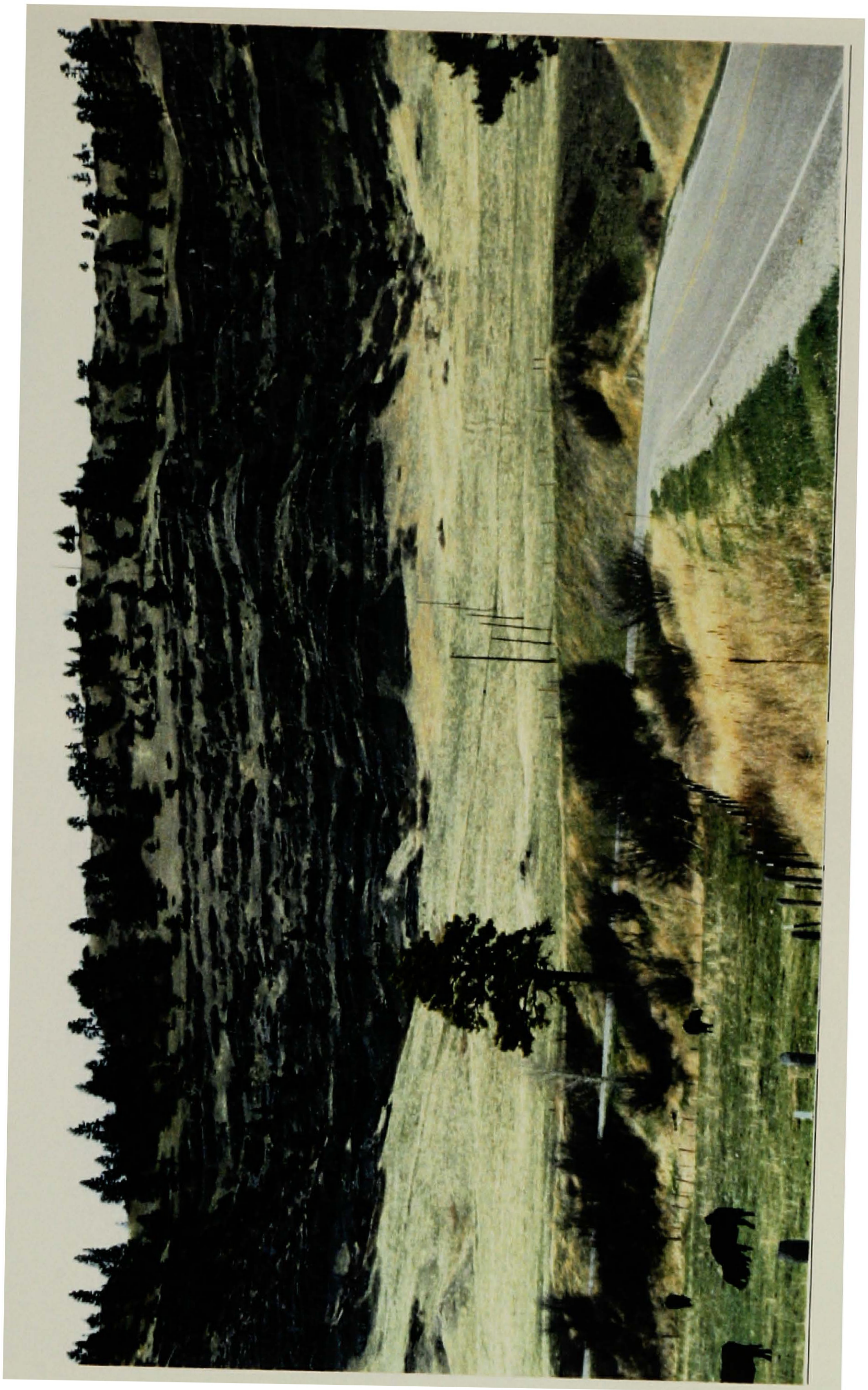
Appendix B (b) Lateral comparison of conglomerate facies over approximately 3000ft. connecting bounding surfaces

	S#	Foot	ft above ash	aug	hbl	opaque	unid L	P	Pzon	LV	LValt	VMat	CarbMat	UndMat	CarbAlt	Q m	K
T-I																	
2	8	239	-101	57	2	14	1	151	3	135	37	79		11	4		4
2	9	342	2	53	1	8		127	4	219	52	23	10				
2	12	400	60	73				86		226	44	48					
T-VI																	
6	2	97	-317	21		3		73	9	179	58	61	95				
6	4	157	-257	44		7		61	3	164	45		176				
6	6	249	-165	54		10	3	87	8	191	39	49	39	20			
6	7	263	-151	32	3	8	2	111	14	139	29	1	112	5			
6	8	277	-137	24	3	7	6	81	2	131	18	93	135				
6	11	397	-17	56	4	9	3	103	5	243	59			18			
6	13	436	22	72	2	21		125	6	216	44			13			1
6	14	471	57	71		4	4	123	3	228	22	34					1
6	15	547	133	100	1	38	2	52	2	205	19			77		1	1
T-V																	
9	2	90	-287	13	3	5	0	131	15	213	36	26	28	29	1		
9	3	134	-243	29	1	6		96	18	238	41	36	12	23			
9	4	185	-192	52	8	14		82	10	151	73	23	48	20			
9	5	225	-152	49	10	9	1	110	10	98	32	1	139	16	21	4	
9	6	259	-118	63	5	10		95	3	193	46	25	6	23	3		
9	7	272	-105	39	1	12		87	4	201	72	13	5	16	4		
9	8	357	-20	68	2	13		47	4	185	88	11	1	8	28		
9	9	407	30	64	2	8		46		190	60	31	5	6	13	1	
9	10	468	91	48		5	2	84	4	226	52	20	6	24	11	2	
9	11	488	111	120	2	72		32		125	30	31	22		16	4	
9	12	505	128	38	2	8		67	6	238	64	24		1	9	3	
10	1		Adel Sample	51		21		83		147		198					

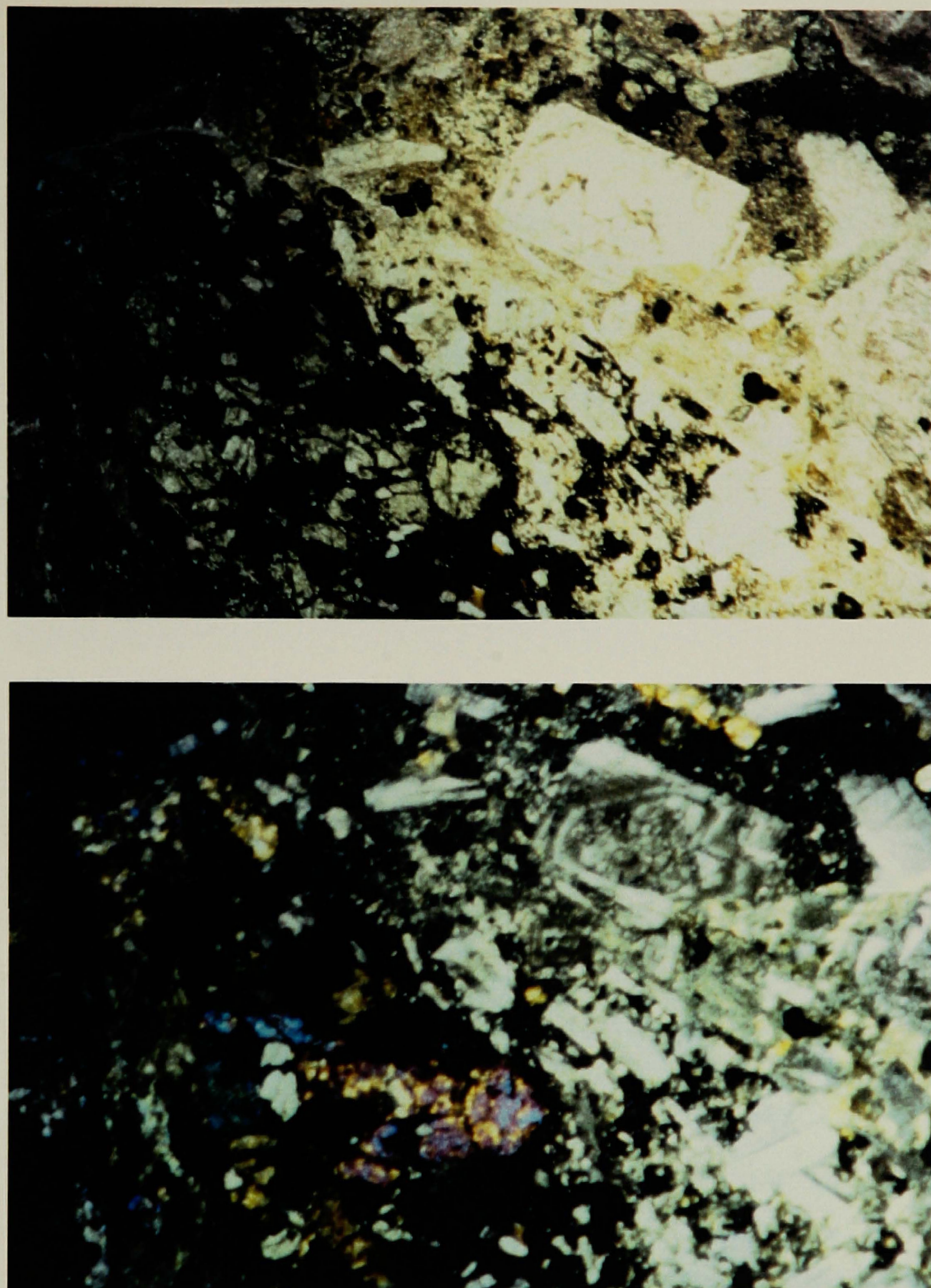
Appendix C

Point Count data

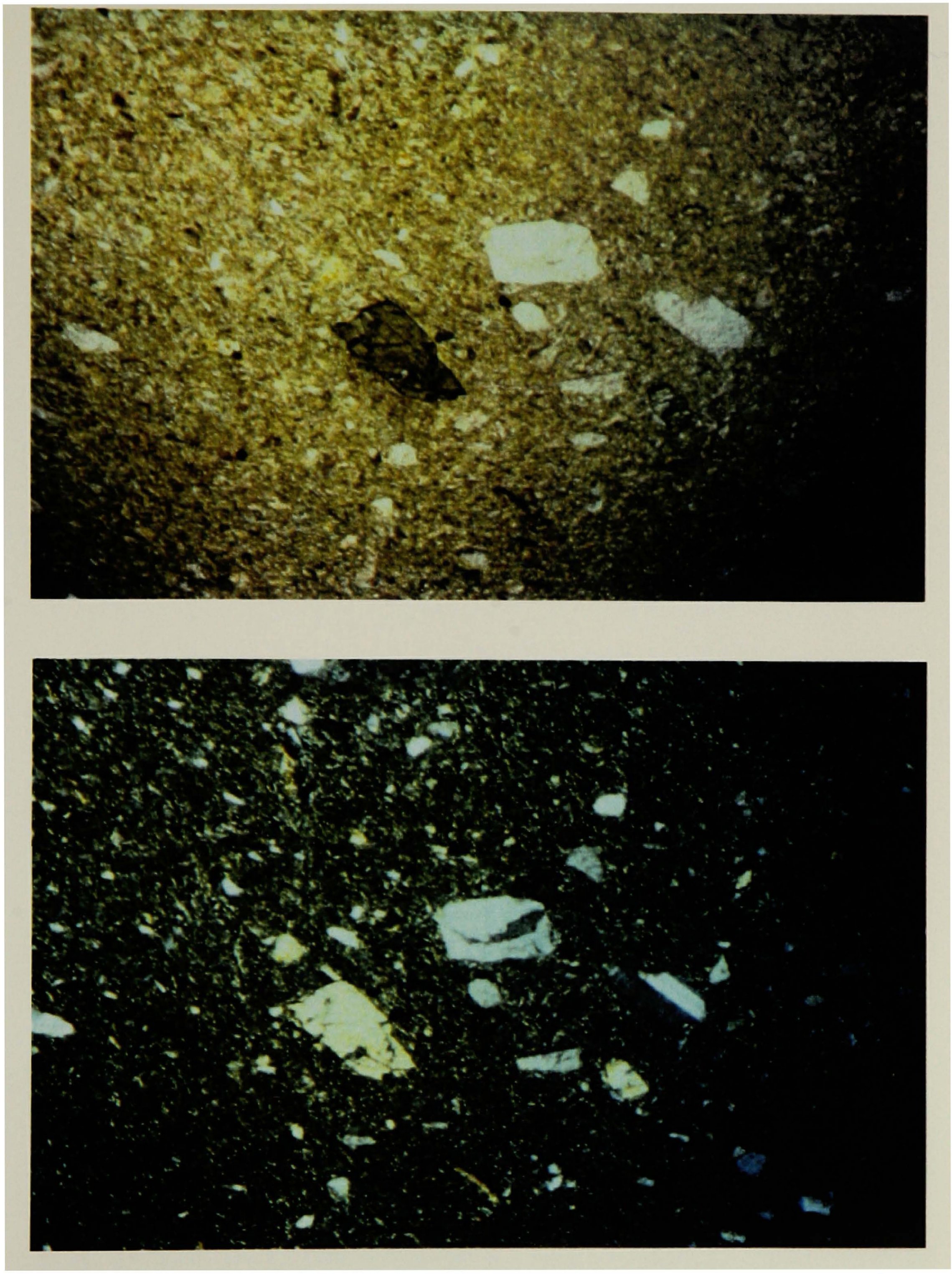
	S#	P	Lv	xb CO3	unid L	chl	heav.	Matr.	CHK
T-I									
2	8	154	172	4	15	2	59	90	510
2	9	131	271	0	8	3	54	33	511
2	12	86	270	0	0	23	73	48	514
T-VI									
6	2	82	237	0	3	1	21	156	508
6	4	64	209	0	7		44	176	510
6	6	95	230	0	13		54	108	512
6	7	125	168	0	10		35	118	469
6	8	83	149	0	13		27	228	514
6	11	108	302	0	12		60	18	517
6	13	131	260	0	21		74	13	519
6	14	126	250	0	8	1	71	34	511
6	15	54	224	0	40	2	101	77	521
T-V									
9	2	146	249	1	5		16	83	511
9	3	114	279	0	6		30	71	512
9	4	92	224	0	14	19	60	91	513
9	5	120	130	21	10		59	156	514
9	6	98	239	3	10	28	68	54	515
9	7	91	273	4	12	46	40	34	516
9	8	51	273	28	13	45	70	20	517
9	9	46	250	13	8	74	66	42	518
9	10	88	278	11	7	16	48	50	519
9	11	32	155	16	72	46	122	53	520
9	12	73	302	9	8	40	40	25	521
10	1	83	147	0	21		51	198	511



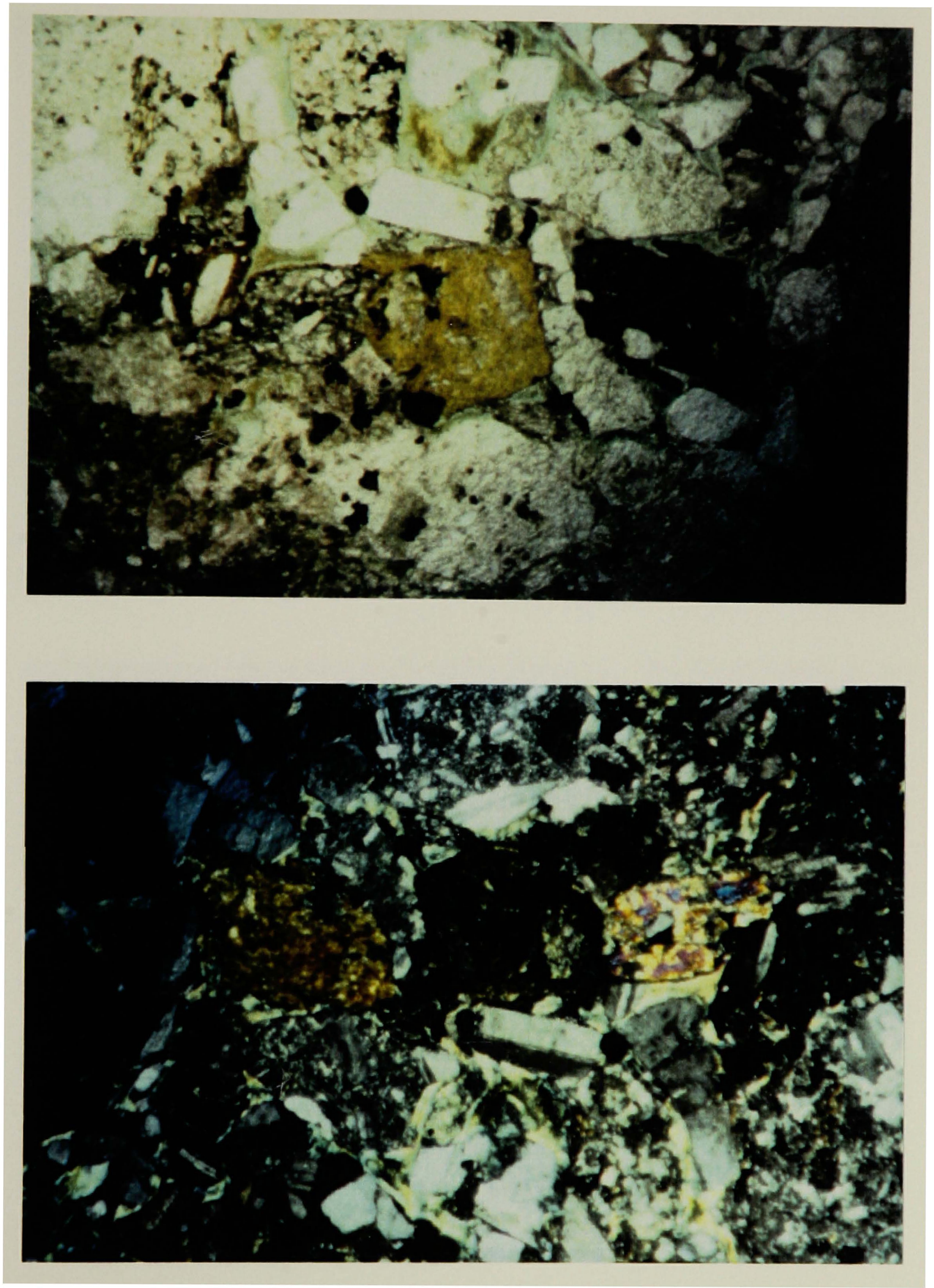
Appendix D, Photo 1; Study Area
Cliffside on the Clonninger Ranch, north of Wolf Creek Montana



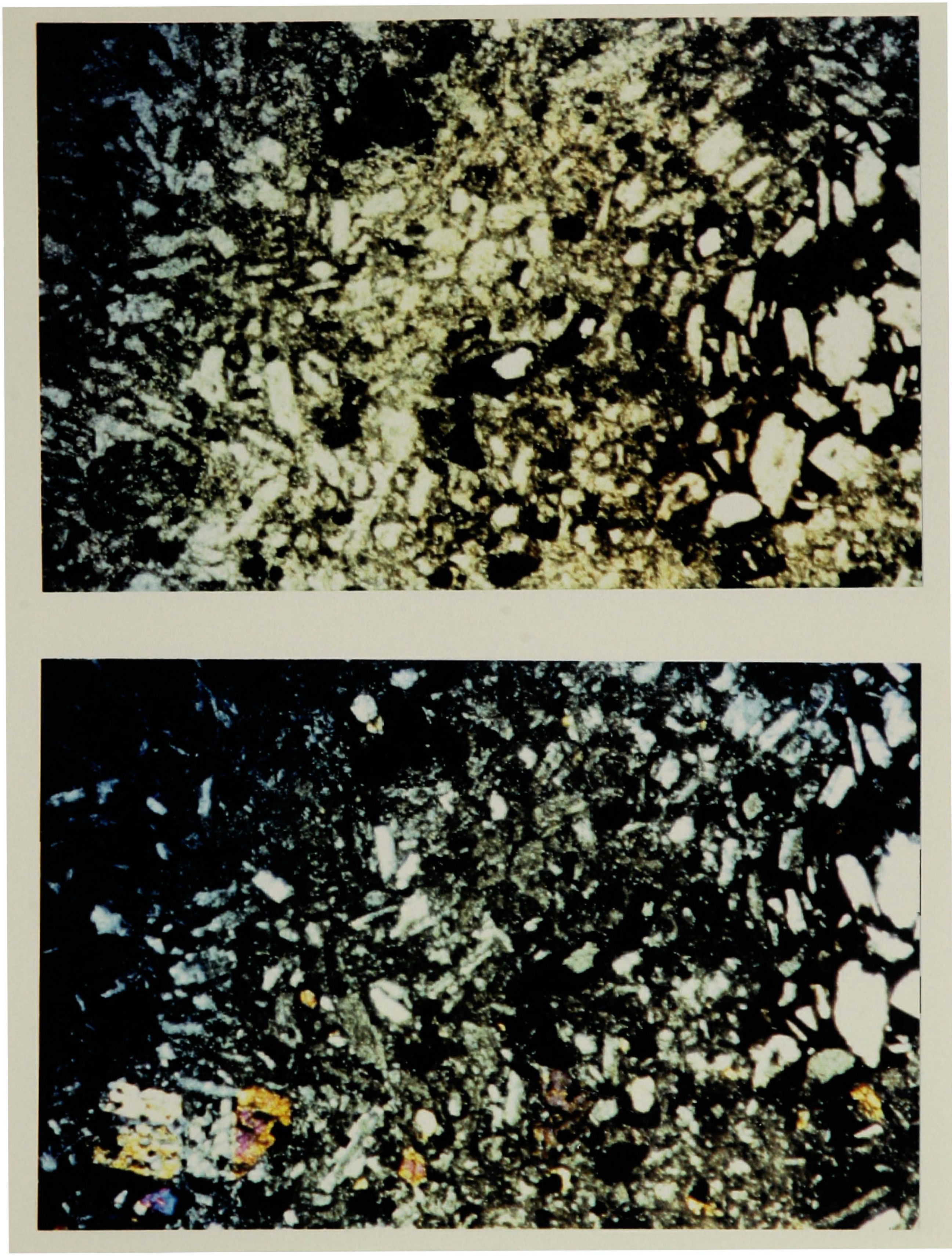
Appendix D, Photo 2; Thinsection (width 2mm); plane light (above) and crossed nichols
Coarse sandstone facies, featuring volcanic-lithic containing augite, and zoned plagioglase



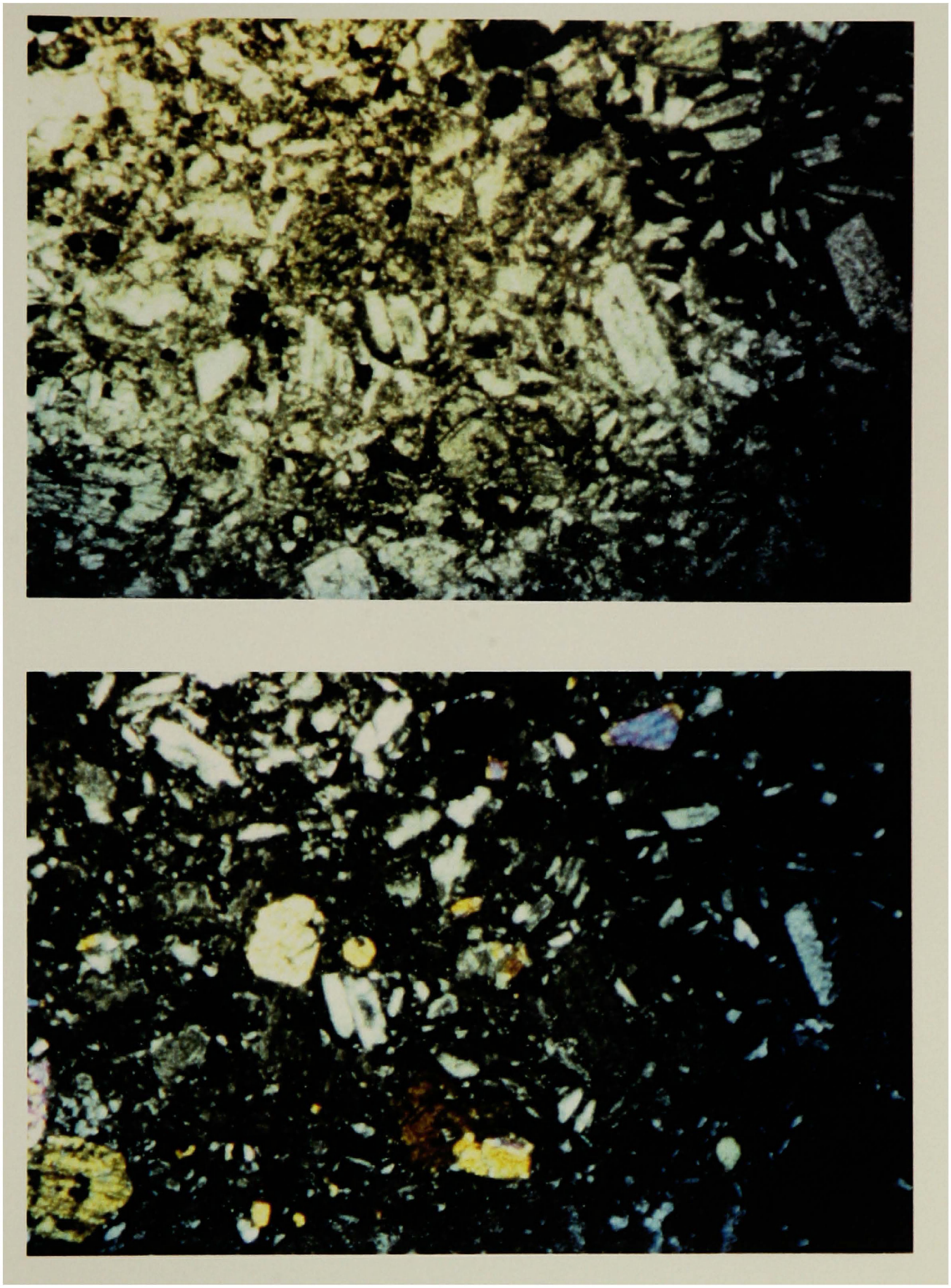
Appendix D, Photo 3; Thinsection (width 2mm); plane light (above) and crossed nichols
Sandy mudstone facies, featuring hornblende and plagioglase



Appendix D, Photo 4; Thinsection (width 2mm); plane light (above) and crossed nichols
Coarse sandstone facies, featuring hornblende (left) and augite (right)



Appendix D, Photo 5; Thinsection (width 2mm); plane light (above) and crossed nichols
Coarse sandstone facies, featuring plagioclase laths, augite (lower left) and volcanic-lithic (right)



Appendix D, Photo 6; Thinsection (width 2mm); plane light (above) and crossed nichols Adel Mountain Volcanics sample featuring plagioclase laths, augite (lower left) and volcanic-lithic (right)