2005

# Sedimentary and tectonic evolution of the Flint Creek Basin west-central Montana

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# Sedimentary and Tectonic Evolution of the Flint Creek Basin, West-Central Montana

**By**

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**B.Sc. University of Pittsburgh at Johnstown, 2000**

presented in partial fulfillment of the
requirements for the degree of
Master of Science

**The University of Montana**

**May 2005**

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5-13-05

Date

## ABSTRACT

Portner, Ryan, A., M.S., May 2005 Geology

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Chairperson: Marc Hendrix MSH

Sedimentary and volcanic rocks of the Flint Creek basin in west central Montana record the tectonic history of the region from middle Eocene time up through the late Miocene. Transtensional stress along the Lewis and Clark Lineament to the north and rapid slip with in the Anaconda metamorphic core complex to the south, were synchronous with initiation of Flint Creek basin subsidence and local volcanic outpourings during the middle to late Eocene. Existing faunal assemblages collected from Tertiary strata above basal volcanic rocks in the basin indicate a late Oligocene to late Miocene age and correlate with the Bozeman Group of southwest Montana. Paleosol characteristics, clay mineralogies and faunal assemblages of these strata suggest a subhumid to semiarid paleoclimate.

Sediments of the upper Renova Formation (Cabbage Patch beds) were deposited in alluvial, lacustrine and palustrine environments. Paleocurrent indicators and petrographic analyses of Cabbage Patch sandstones imply a northwesterly paleoflow of arkosic detritus during the late Oligocene (Arikareean North American Land Mammal Age). Exhumation of the Anaconda metamorphic core complex to the south of the Flint Creek basin would have been a primary source for the 2-mica rich feldspathic sand characteristic of Cabbage Patch sandstone facies. Volcanic detritus common to these sandstone facies was likely derived from denudation of the Elkhorn Mountain and Lowland Creek volcanic edifices, which both overlie the Boulder batholith to the southeast.

Excellent exposure of a localized 2-meter thick boulder bed with underlying smectitic clay and barite nodules represents the regionally extensive mid-Miocene unconformity (Hemingfordian North American Land Mammal Age). Massive siltstone, calcrete and gravel facies of the lower Sixmile Creek Formation (Flint Creek beds) overlies the unconformity. The Flint Creek beds were subsequently tilted and eroded some time during the middle to late Miocene when last movement on intrabasinal normal faults occurred. Sand and gravel facies typical of the upper Sixmile Creek Formation (Barnes Creek beds) were deposited in a paleovalley eroded into underlying strata. A large alluvial fan bajada complex shed detritus northward from the uplifting Flint Creek and Sapphire ranges into the axial Barnes Creek fluvial system.

## ACKNOWLEDGMENTS

Funding was provided by USGS EdMap grant #03HQA90061 and a McDonough Scholarship. This project would not have been what it is without all the people that helped me. Marc Hendrix, Jim Sears and Paul Wilson were a great committee and provided me with very helpful suggestions and comments that influenced this manuscript. Craig Christensen and Don Rasmussen established the paleontologic foundation for my research. My field assistants: Andrew Caruthers, Nate Harrison, Amy Bondurant, Damien Powledge and Christina Mosolf. The local Ranch owners: the Graybeals, Sean Wetch and the Dingwall ranch, Deb and Rusty Bruce, the nature conservancy, Ron Skinner, the Verlanics, Tom Rue, the Conn Ranch, the Throops, John Conn, Johnson Tuning Fork Ranch, Bruce Wight, the Mentzer Ranch, Cominco Mining and all the others whose land I was on with out knowing. Brian Collins and Donn Vannice for help with GIS and computer applications. Don Hyndman, Gray Thompson, Don Winston and Jim Shelden provided key insight into the geology of the region. Karen Porter, Paul Thale and Larry Smith from the Montana Bureau of Mines and Geology helped with map reviews and comments. Dan Miggins and Larry Snee from the United States Geological Survey allowed me use of their geochronology lab. Montana Board of Oil and Gas conservation granted me access to their well log reports and examination of chip samples. Luke and geoJon from Pocatello took the time to help me with zircon separation and geochemistry, hopefully that work can be built upon. I dedicate this work to my family and friends.

"Spontaneity makes Miracles, and Miracles are Magical"

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# INTRODUCTION

The Flint Creek basin (FCB) is a northeast trending Cenozoic basin that extends along the Flint Creek Valley for 24 km between Drummond and Maxville, MT (Figure 1). It is located along the northwest flank of the Flint Creek Range, bounded to north by the Garnet Range, west by the Sapphire Range and is along structural strike with the Philipsburg basin to the south. Bedrock of the FCB consists of metasedimentary strata of the Meso-Proterozoic Belt Supergroup in its western portion and Paleozoic-Mesozoic carbonate and siliciclastic strata in its eastern portion (Figure 2). The map area outlined by this study focuses on the east side of the basin where the bedrock is dominated by tightly folded Cretaceous rocks (Figures 3, Appendix A). The proximity of the FCB to the Lewis and Clark lineament (LCL), a major tectonic feature of the Northern Rockies, sets it apart from other Tertiary depocenters of southwest Montana (Figure 4).

Ongoing studies in Tertiary basins of western Montana and adjacent Idaho by Sears and Ryan, (2003); O'Neil et al., (2004); Hopkins (2004); Link et al. (2004); Hanneman (2004); Bourke, M.R., et al. (2004); Nielson and Thomas, (2004); Hodges et al. (2004); Janecke (2004) aim to clarify paleontologic, lithologic, stratigraphic and structural relationships amongst the basins (Table 1). Uncertainties still remain with the currently used coarse and fine grained lithostratigraphic subdivision (Fields, et al., 1985; Hanneman and Wideman, 1991), proposed rift shoulder model extent (Janecke, 1994) and paleoclimatic (Thompson et al., 1982) verses tectonic (Fritz and Sears, 1993) verses eustatic

(Hanneman et al., 2003) control on basin accommodation for Tertiary sediments in western Montana and adjacent Idaho. This study aims to elucidate these problems by evaluating the sedimentologic and tectonic evolution of the FCB and deciphering its association with other adjacent intermontane basins.

Paleontologic and geologic studies by Douglass (1903), Konizeski and Donohoe (1958), Gwinn (1960) and Rasmussen (1969) were among the first in the Flint Creek basin and provide the base work utilized in this study. Geologic field mapping, stratigraphic architectural studies, provenance analysis, x-ray diffraction, tephra geochronology and careful consideration of the role of the LCL are necessary for accurate assessment of the basins sedimentary and structural history. Cenozoic deposits south of the Clark Fork River and east of Flint Creek depicted in Plate 1 (Appendix B), were mapped and reexamined using previously documented biostratigraphy of D.L. Rasmussen (1969, 1973, 1974, 1977, 1989, 2003); Pierce and Rasmussen (1989, 1992); and Craig Christensen (pers. comm., 2003).

| Table 1: Previous research in other Tertiary basins of western MT | |
|---|---|
| **Basin** | **Authors of unpublished MSc and PhD work** |
| North Boulder | Lofgren (1985), |
| Beaverhead | Hoffman (1971), Petkewich (1972), Hanneman (1989) |
| Jefferson River | Kuenzi (1966), Axelrod (1984), Hanneman (1989), Ripley (1995) |
| Ruby River | Petkewich (1972), Monroe (1976), Ripley (1995) |
| Flint Creek | Rasmussen (1969) |
| Deer Lodge | Rasmussen (1977), McLeod (1987) |
| Grasshopper | Matoush (2002) |
| Smith River | Runkel (1986) |
| Muddy Creek | Dunlap (1982) |
| Divide | Rasmussen (1977), Hanneman (1989) |
| Melrose | Hanneman (1989) |
| Douglas Creek | Person (1972) |
| Missoula | Harris (1997) |
| Sage Creek | Tabrum (unpublished data) |
| Salmon | Harrison (1985) |
| Kishenehn | Constenius (1981) |

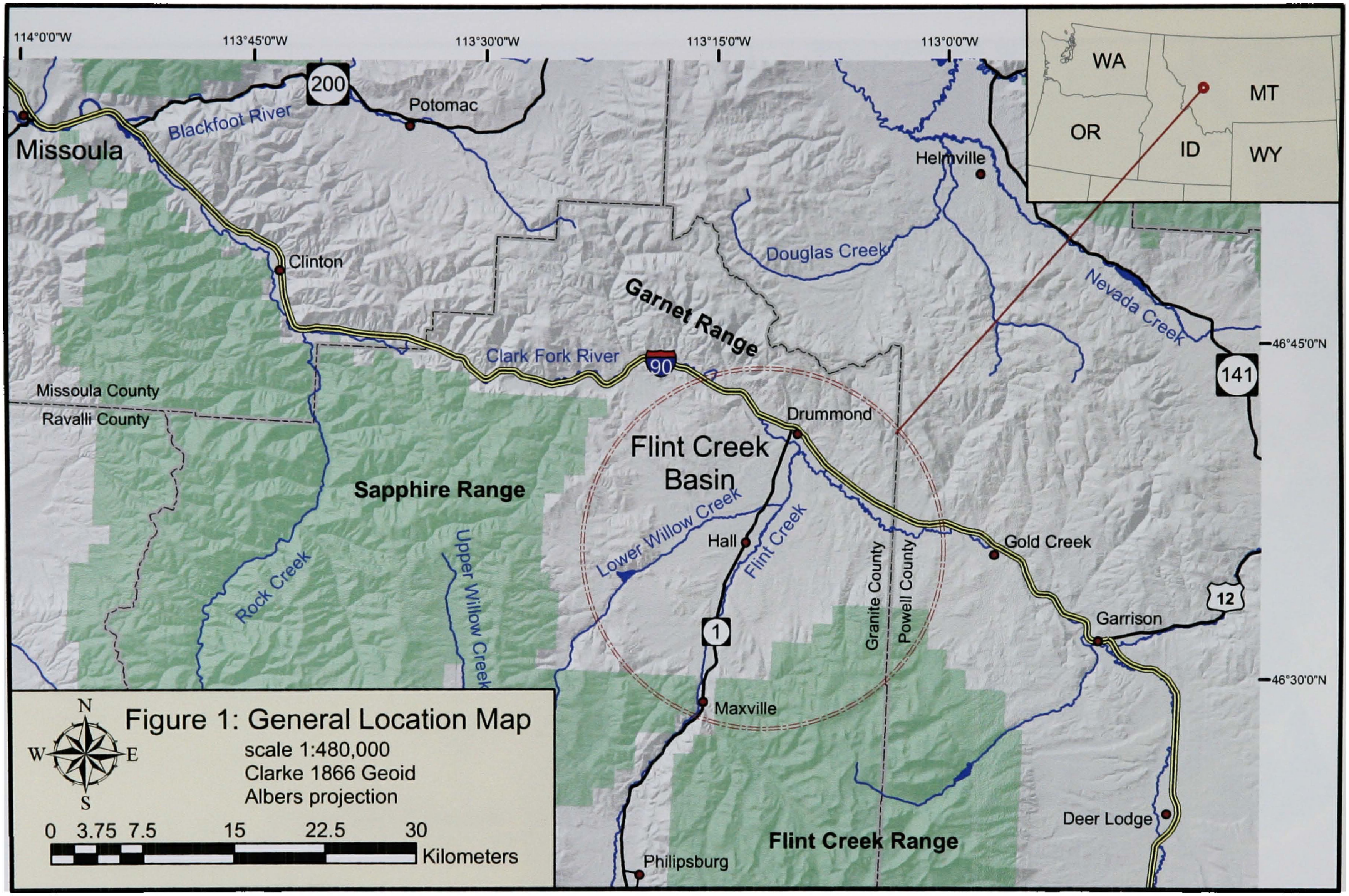



Figure 1: General Location Map

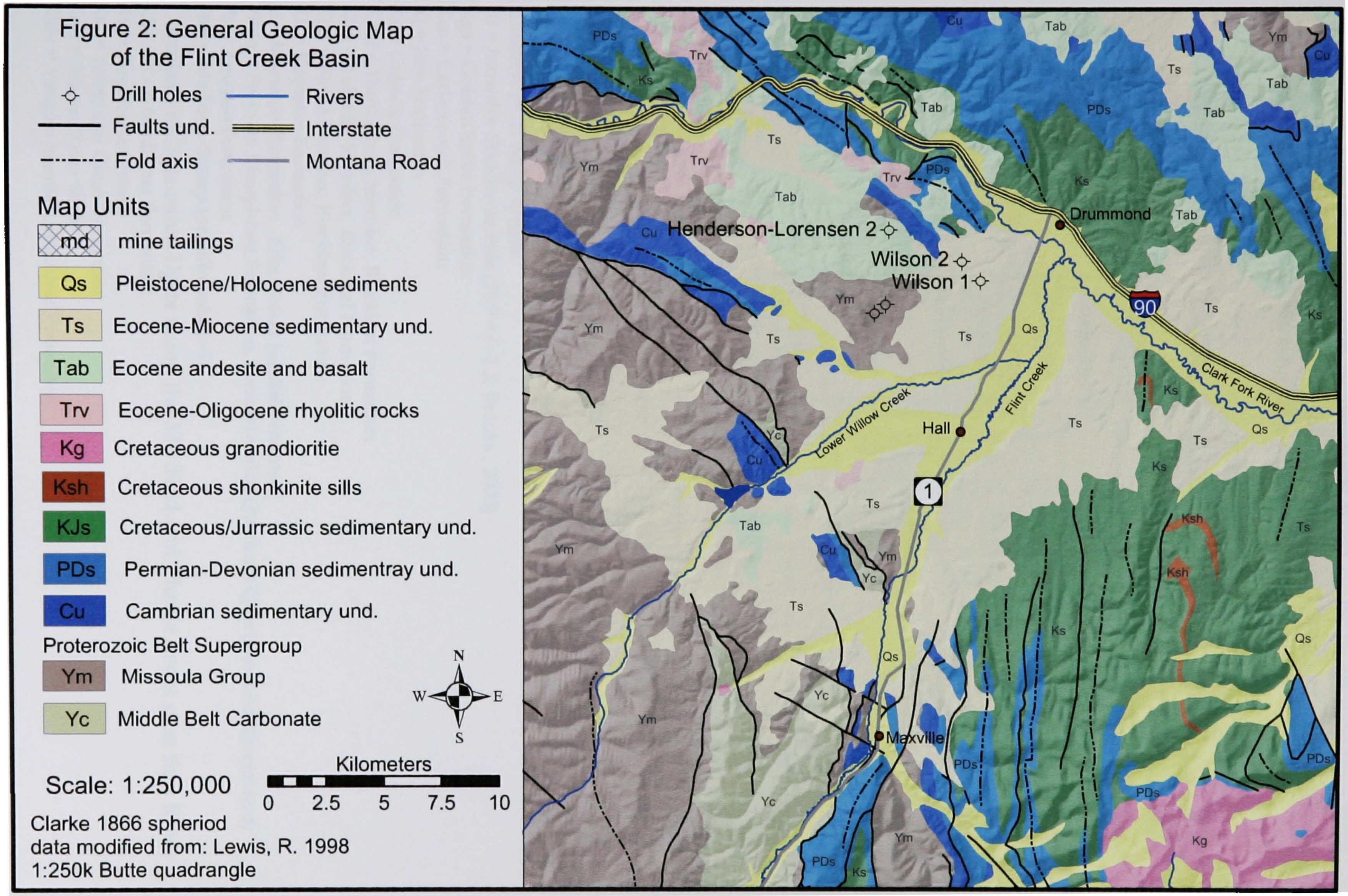
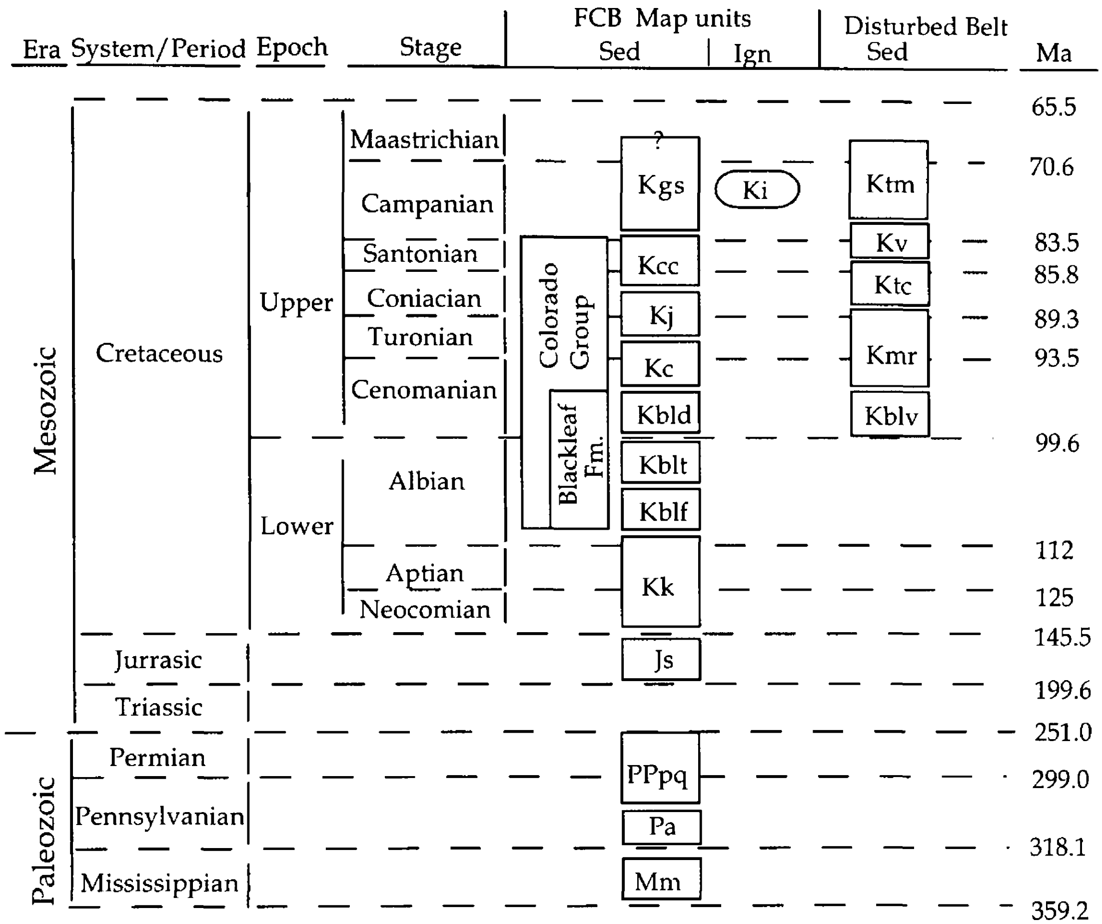


Figure 2: General Geologic Map of the Flint Creek Basin

Figure 3: Correlation chart of bedrock map units in the eastern FCB
Stages and relative ages taken from 2003 International Stratigraphic Chart
correlations taken from, O'Brien, 2003; Brooks, 2002




## Eastern FCB Map Units:

Ki = Intrusive Shonkinite Sills (75.9 +/- 1.2; Brooks , 2002)
Kgs = Golden Spike Formation
Kcc = Carten creek Formation
Kj = Jens Formation
Kc = Coberly Formation
Kbld = Dunkleberg Member, Blackleaf Formation
Kblt = Taft Hill Member, Blackleaf Formation
Kblf = Flood Member, Blackleaf Formation
Kk = Kootenai Formation
Js = Morrison Formation , Ellis Group (undifferentiated)
PPpq = Permian Phosphoria Formation, Pennsylvanian Quadrant Quartzite (undifferentiated)
Pa = Amsden Formation
Mm = Madison Group (undifferentiated)

## Correlative Cretaceous Units along the MT Fold and Thrust Front near Sun River

Ktm = Two Medicene Formation
Kv = Virgelle Sandstone
Ktc = Telegraph Creek Formation
Kmr = Marias River Shale
Kblv = Vaughn member, Blackleaf Formation

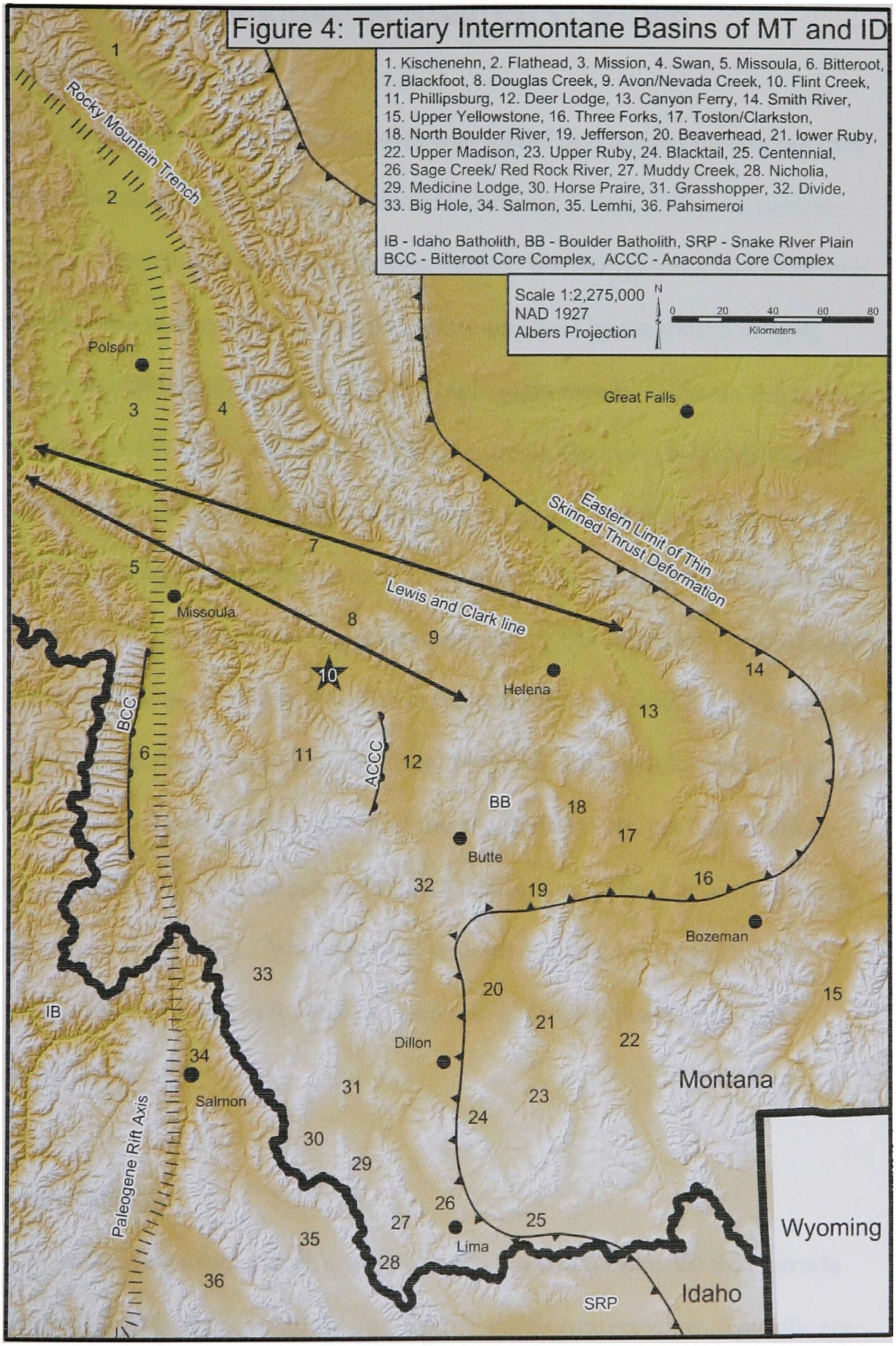


Figure 4: Tertiary Intermontane Basins of MT and ID
1. Kischenehn, 2. Flathead, 3. Mission, 4. Swan, 5. Missoula, 6. Bitteroot, 7. Blackfoot, 8. Douglas Creek, 9. Avon/Nevada Creek, 10. Flint Creek, 11. Phillipsburg, 12. Deer Lodge, 13. Canyon Ferry, 14. Smith River, 15. Upper Yellowstone, 16. Three Forks, 17. Toston/Clarkston, 18. North Boulder River, 19. Jefferson, 20. Beaverhead, 21. lower Ruby, 22. Upper Madison, 23. Upper Ruby, 24. Blacktail, 25. Centennial, 26. Sage Creek/ Red Rock River, 27. Muddy Creek, 28. Nicholia, 29. Medicine Lodge, 30. Horse Praire, 31. Grasshopper, 32. Divide, 33. Big Hole, 34. Salmon, 35. Lemhi, 36. Pahsimeroi
IB - Idaho Batholith, BB - Boulder Batholith, SRP - Snake River Plain
BCC - Bitteroot Core Complex, ACCC - Anaconda Core Complex
Scale 1:2,275,000
NAD 1927
Albers Projection
N
0 20 40 60 80
Kilometers
Rocky Mountain Trench
Eastern Limit of Thin Skinned Thrust Deformation
Lewis and Clark line
Paleogene Rift Axis
Polson
Great Falls
Missoula
Helena
Butte
Bozeman
Dillon
Salmon
Lima
BCC
ACCC
BB
IB
SRP
Montana
Wyoming
Idaho

## REGIONAL TECTONIC BACKGROUND

### *Laramide Orogeny*

Bedrock of the Flint Creek basin was folded and faulted during the Late Cretaceous and early Paleocene Laramide Orogeny (Sears, 2001). An eastern transport direction of low angle thrusts, namely the Georgetown and Princeton thrusts of the western Flint Creek Range are opposed by westward verging overturned folds and eastward dipping high angle reverse faults on the east side of the Range (Gwinn, 1960; McGill, 1965; Figure 5). Gwinn (1961) and McGill (1965) interpreted this conflicting structural transport direction in the northern Flint Creek range as a consequence of intrusion of the Boulder batholith to the east. An extreme example of this is documented by the westward-verging nearly recumbent isoclinal Coberly syncline in the middle of the field area (Plate 1). A similar occurrence of opposing structural vergence has been documented in Cretaceous rocks along the foothills of the Montana overthrust belt near Sun River Montana and is interpreted to be a continuation of the Canadian triangle zone (Sears et al., 2002). Compressional structures of the northern FCB are younger than a swarm of folded and faulted 76 Ma sills (Sears et al., 2000; Brooks, 2002).

### *Igneous Geology*

In the map area, a thick sequence of 76 Ma shonkinite sills that intrude Cretaceous strata are concordant and have hornfels contact zones. The sills are

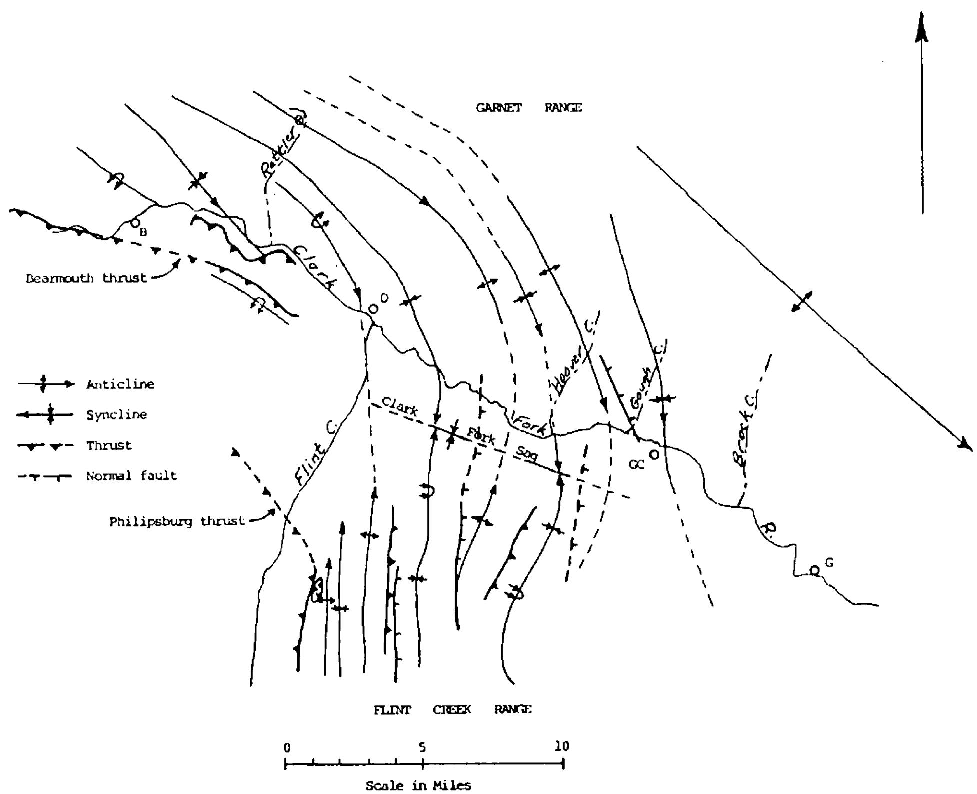



**Figure 5:** Structure map of North East FCB. (taken from Gwinn, 1965)
B= Bearmouth, D=Drummond, GC=Gold Creek, G=Garrison.

interpreted by Kunz (2003) to be an extension of the central Montana alkalic province and are inferred to be chemically similar to the alkaline-mafic Kokuruda complex on the northern flank of the Boulder batholith.

The Late Cretaceous Boulder batholith is a large, felsic batholithic assemblage located approximately 50 miles southeast of the FCB (Figure 6). It crystallized between 78-69 Ma and predominantly consists of biotite- and hornblende- bearing quartz monzonite (Johannesmyer, 1999). Any muscovite present is minimal and probably not primary (D. Hyndman, pers. comm., 2004). A large portion of the northwest and northeast extent of the batholith is covered by the 80-77my Elkhorn Mountain volcanics (Johannesmyer, 1999). Mylonitized granite that may be associated with either the Boulder batholith or the nearby Flint Creek Range plutons was penetrated at the bottom of the Amoco Jacobsen well in the Deer Lodge basin at a depth of 11,500 feet and was first inferred by D.Hyndman to have been created by processes similar to that formed by the Bitterroot core complex (McLeod, 1985).

Several comagmatic granodiorite plutons in the Flint Creek Range intruded to an epizonal level between ~74 and ~60 Ma (Allen, 1962; Hyndman et al., 1982; Marvin et al., 1989; Figure 6). Most K-Feldspar has grid-twinning and accessory minerals in the plutons are dominated by biotite and hornblende. A notable exception is the muscovite-bearing 2-mica granodiorite of the youngest Mount Powell batholith (Allen, 1962). Due to the presence of numerous roof pendants Allen (1962) inferred that the upper reaches of the 132 square km

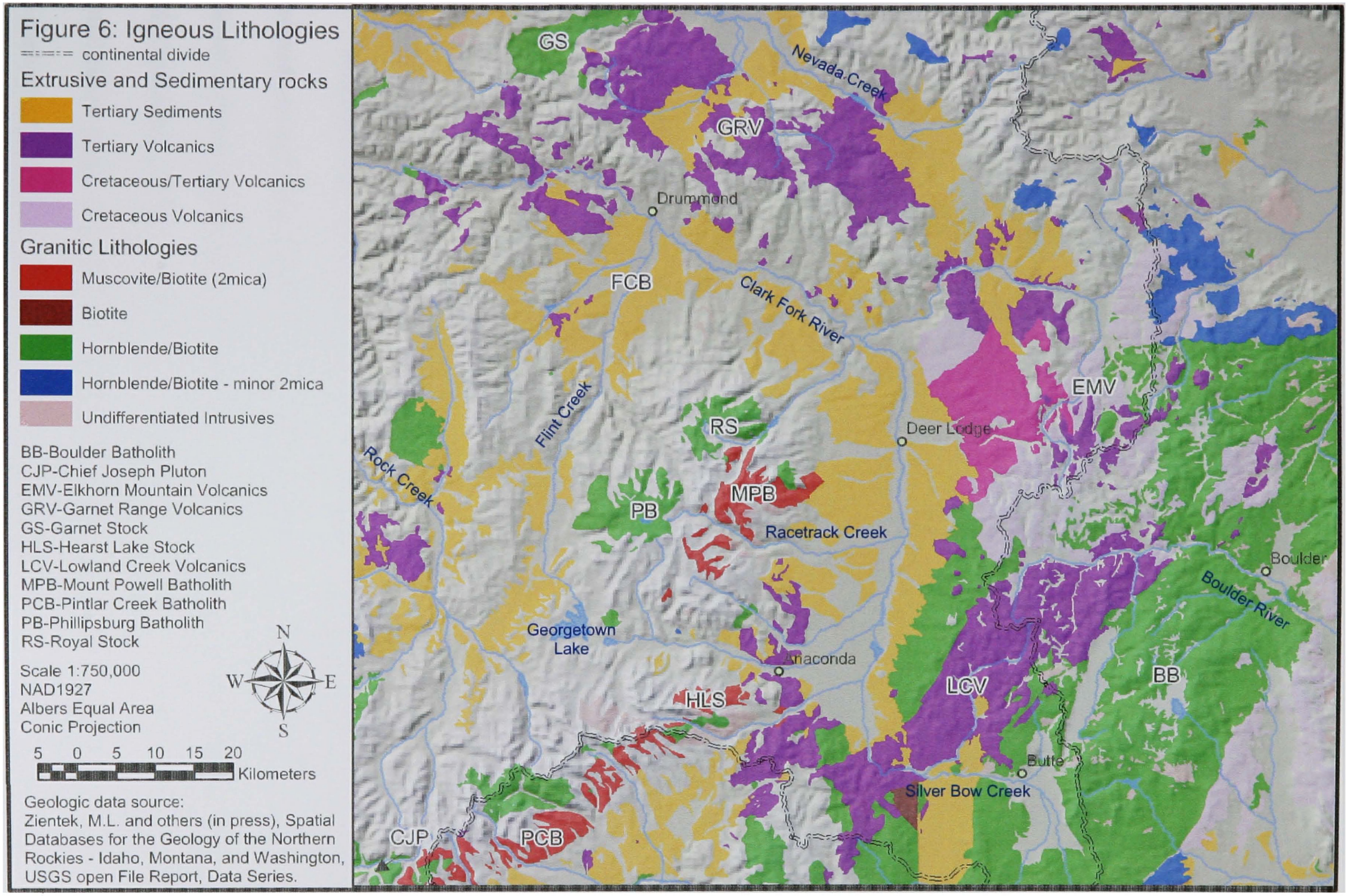


Figure 6: Igneous Lithologies

Mount Powell batholith must be exposed. The Flint Creek plutons crystallized during the late Paleocene before the early- to middle- Eocene Lowland Creek volcanics were extruded onto the southeast flank of the Flint Creek Range.

The Lowland Creek volcanics attain a thickness of 1900m and are composed of quartz latitic lavas, welded tuffs and synsedimentary pyroclastic breccias on the west and east sides of the Boulder batholith. Smedes (1962) recognized six volcano-tectonic phases that are separated by unconformities and faulting episodes. These rocks were extruded between 50-48 Ma during the same time as volcanic rocks of the 49-44 Ma Garnet Range volcanic sequence in the western FCB (Smedes, 1965; Carter, 1982). Coarse conglomeratic material of the Anaconda beds are stratified with the Lowland Creek volcanics and are overlain by Oligocene-Miocene aged deposits in the northern flank of the Flint Creek Range (O'Neil et al., 2004). The Anaconda beds are usually composed of red clay and dominated by quartzite gravel (Kalakay, 2003; O'Neil pers. comm., 2004).

### *Foreland Extensional Collapse*

Foreland fold and thrust belt collapse of the northern Cordillera is marked by relaxation and denudation of compressional structures during a phase of regional Tertiary extension (Constenius, 1982; O'Neill and Pavlis, 1988; Janecke, 1994; Constenius, 1996; Sears, 2001). Both high angle normal and low angle listric normal faults formed during several episodes of extension in western Montana and east central Idaho, beginning no earlier than 53-48 Ma and continuing to the present day (Pardee, 1950; Janecke, 1995; Fritz and Sears, 1993; Ruppel, 1993; Sears et al., 1995; Thomas et al., 1995; Hurlow, 1995a, b; Sears and Fritz, 1998; Vandenburg et al. 1998; Foster et al. 2001). Gravitational collapse of an over-thickened orogenic wedge was accompanied by the development of a linear rift zone during Eocene time (Janecke, 1994). This rift zone was oriented along the axis of the Cordillera west of the FCB (Figure 4). Paleovalleys associated with the rift zone and others in southwest Montana were reorganized during Neogene time (16-6ma) by a period of renewed uplift and faulting (Fritz and Sears, 1993; Sears and Ryan, 2003).

Paleogene extension in the northwest Cordillera was accommodated by rapid uplift and exhumation of regional metamorphic core complexes and associated detachment faults (Constenius, 1996; Figure 7). Mylonite along the eastern edge of the Flint Creek Range is associated with the Mount Powell batholith and has been interpreted by O'Neil, et al. (2002) to be part of the regionally extensive Anaconda metamorphic core complex (ACC). Winegar (1968) also documented mylonite along the eastern edge of the Lost Creek stock south of the Mount Powell batholith. Sheared granodiorite of the mylonitized Hearst Lake stock in the Anaconda Range yielded 53 Ma U-Pb zircon dates and represents the oldest age of the core complex (Kalakay 2003). Syntectonic muscovite fish with 47 ma $^{40}Ar/^{39}Ar$ dates in footwall rocks and syntectonic upperplate detritus of the Anaconda beds were deposited during the youngest age of the ACC (O'Neil, et al. 2004). The stretching lineations of 106° in the

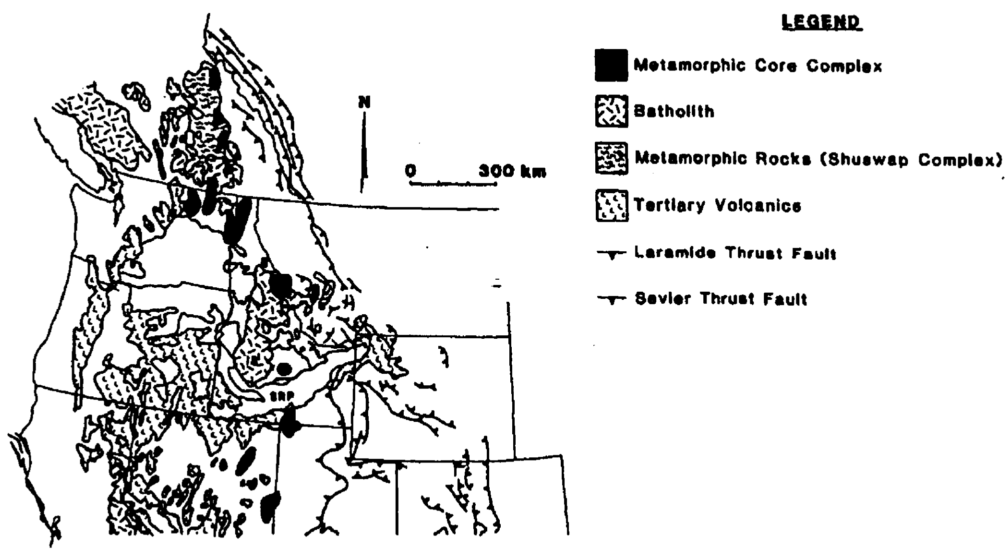



**Figure 7:** Regional Distribution of Cordilleran Metamorphic Core Complexes. SRP=Snake River Plain, IB=Idaho Batholith, taken from O'Neil and Pavlis, 1988)

Hearst Lake stock and 114° in the Mount Powell batholith are very close to the Bitterroot, Boehls Butte and Priest River core complexes (O'Neil, 2002, Kalakay, 2003, Sha, 2003, Lonn et al., 2003, Foster, 2003). Foster (2003) suggested that extension within these core complexes is linked to dextral transtension across the LCL. The enigmatic northern extent of the ACC has been proposed to die out into the Lewis and Clark line in the vicinity of the FCB (O'Neil, 2004).

*Lewis and Clark Shear Zone*

Structural trends across the Clark Fork River Valley in the FCB change from N-S south of the river to NW-SE north of the river and have been interpreted to be a consequence of left-lateral motion along the Lewis and Clark line during Late Cretaceous compressional deformation (Figure 5; Gwinn, 1960, Lorenz, 1983; Reid, 1984; Baken, 1984, Hyndman et al., 1988; Lonn and McFaddan, 1999; Sears and Clements, 2000; Geraghty and Portner 2003). The lineament accommodated rotational stress about a pole centered at Helena, MT with thrust displacements increasing to the north (Sears, 2001). Geraghty and Portner (2003) and Sears and Hendrix (2004) suggested that the lineament is a transpressional flower structure with the deeper levels exposed to the west near Saint Regis, MT and higher levels exposed to the east near the FCB. A structural depression marked by opposing plunges (Clark Fork Sag of Gwinn 1960) is associated with the change in regional strike and was interpreted by Weidman (1965) to be kinematically linked to the lineament (Figure 5).

Several workers have suggested that right lateral motion along the Lewis and Clark line accompanied extension during Tertiary time (Harrison et al., 1974; Reynolds and Kleinkopf, 1977; Wallace et al., 1990; White, 1993; Yin et al., 1993; Doughty, 2002). Doughty and Sheriff (1992), Doughty (2002) and Foster (2003) showed evidence to suggest that the Lewis and Clark shear zone was a dextral transtensional system that accompanied Eocene crustal extension. Transition from Cretaceous transpressional to Tertiary transtensional stress along the Lewis and Clark line occurred during Eocene time between 59 and 53 Ma (Sears, 2001; Foster, 2003). This marks the initiation of uplift and exhumation of regional metamorphic core complexes, voluminous volcanism, and delineation of Tertiary depocenters including the FCB (Chadwick, 1985; Fields, et al., 1985; Fritz and Harrison, 1985; O'Neill and Pavliss, 1988; Foster and Fanning, 1997; Doughty and Price, 2000; Doughty, 2002; Vanderhaeghe et al., 2003; O'Neill, et al., 2004).

# METHODS

## *Geologic Mapping and Spatial Database*

Previous mapping in and adjacent to the Flint Creek basin by J.C. Maxwell 1965; K.K. Smallwood 1956; V.E. Gwinn 1961; D.L. Rasmussen 1969; B.A. Carter 1982; R. Lewis 1998; Lonn et al. 2003 was used as the base work for the study's final map interpretation and compilation (Figure 8). Geologic features of the study area were mapped at 1:24,000 using the Drummond 1:24k, Limestone Ridge 1:24k, Dunkelberg Creek 1:24k and the Hall 1:24k USGS quadrangles as base topographic maps. The geologic map by Lewis et al. (1998) was used as a base layer with aerial photos and a 30 meter digital elevation model (DEM) resampled to 10 meter resolution. A brunton azimuth compass, a barometer and a GARMIN Etrex vista GPS were used for station location and mapping contacts. Three balanced structural cross-sections were constructed to true scale and give a sense of bedrock structure across the width of the map (Plate 2).

Upon completion of field mapping after the summer of 2003 field work, geologic contacts and other features were digitized manually. Original field maps were transposed onto corresponding 1:24k scale digital quadrangle maps using ArcGis v.8.3 software. Contact accuracy was enhanced with ~6 meter accurate GPS point data (point features) collected in the field (Appendix C). Contacts (line features) and map units (polygon features) were assigned specific attributes regarding formation name and contact type (inferred contact, fault

Figure 8

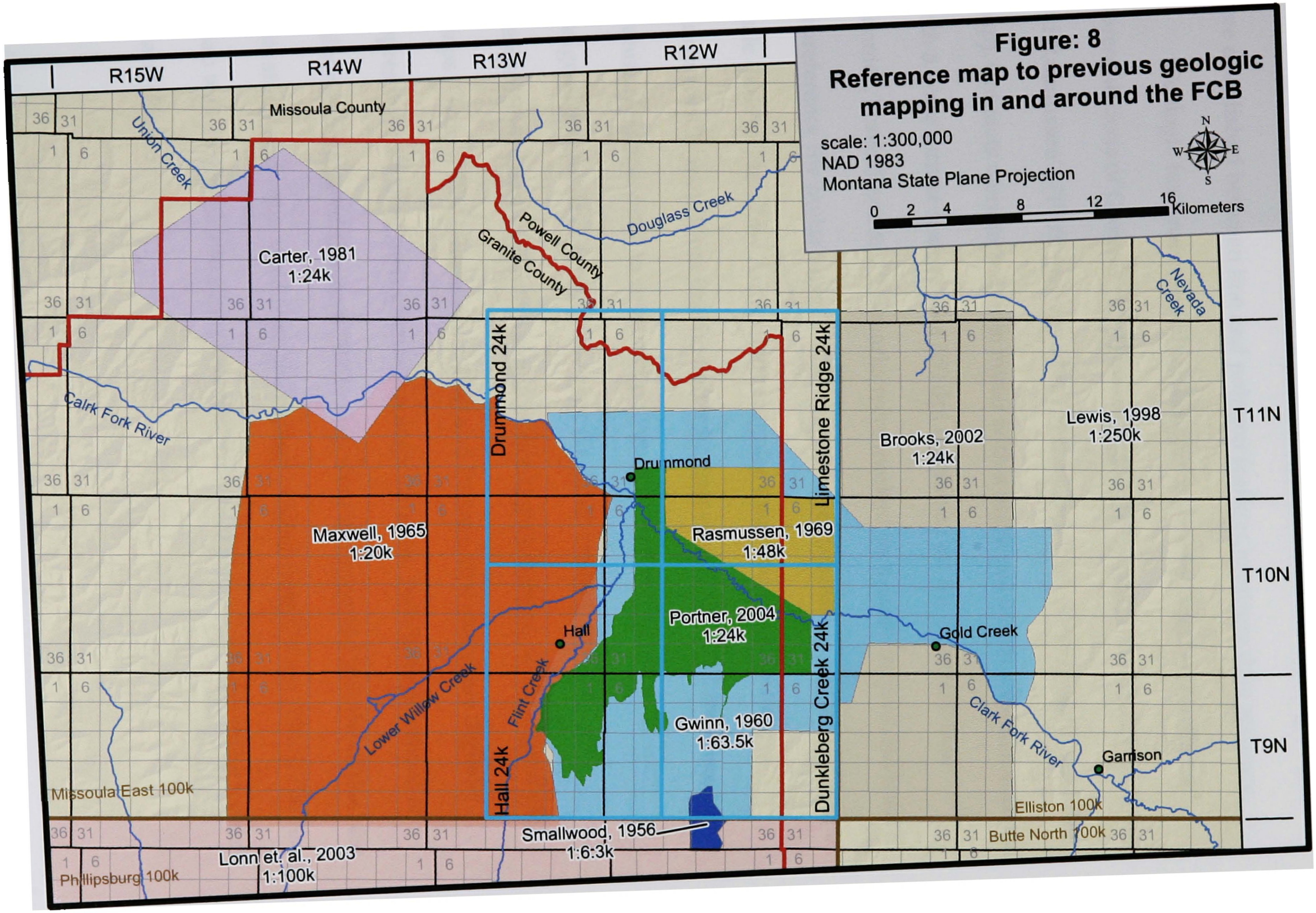



**Figure: 8**
**Reference map to previous geologic mapping in and around the FCB**

etc.). Data was implemented into a personal geodatabase and topologic rules were established between line and polygon features to ensure data accuracy.

Geologic features mapped by this study were combined with digital representations of Gwinn's (1961) bedrock geology south of the Clark Fork River and Rasmussen's (1969) geology north of the Clark Fork River (Plate 1: see inset map). Contacts were traced onto mylar with a black pen which was then scanned with a large format scanner to a 350 dpi resolution tiff file (courtesy Don Vannice, Forest Service). Tic marks were marked on section corners and used to georeference the mylar images. The images were classified to a black and white scale (bi-level) to allow ArcScan to recognize them and subsequently automatically trace them (method after Portner et al., 2003). The resulting line feature class was used to construct polygons in ArcCatalog and both were assigned attributes regarding line type (i.e. fault, contact) and map unit designation. Combined into a single personal geodatabase, all three geologic maps (Gwinn, 1961, Rasmussen, 1969 and Portner, this study) are digitally represented by their own unique topologic datasets. New interpretations of minor structures on Gwinn's (1961) map were incorporated into the dataset for this study and subtracted from the dataset created from Gwinn (1960). The final map was projected into stateplane coordinates and overlaid with topographic maps (Plate 1).

*Measured Stratigraphic Sections*

Stratigraphic sections were measured with a 1.8 meter jacob staff, brunton compass, rock hammer and pick. Color was estimated, HCl acid was used to determine $CaCO_3$ content and grain size was deduced with a 10x hand lens and grain scale card. All measured sections were exposed in small ephemeral gulches, though one artificial exposure was used along Douglas Creek (Appendix D). Sections were drafted up and traced in Adobe Illustrator v.10 software (Plate 3). Detailed section descriptions and previous paleontologic work (Rasmussen, 1977; Craig Christensen, pers. comm.) aided in the mapping of geologic units.

*X-Ray Diffraction*

Representative samples of fine- grained lithologies were collected from fresh surfaces after overlying slope material was cleared away and weathered surfaces removed. Clay samples were dried at room temperature before treatment. All samples were crushed in a glazed porcelain mortar to a fine powder and prepared in a backloader for randomly oriented whole rock mineralogy. The crushed claystone and mudstone samples were disaggregated with an ultrasonic probe after treatment with sodiummetahexaphosphate to deflocculate the clay. The $<2\mu$ size fraction was separated out after centrifugation at 1000rpm's for 2 minutes. The $<2\mu$ samples were saturated with strontium (Sr) order to eliminate variations in glycol thickness due to treatment by sodiummetahexaphosphate and washed to remove any excess electrolyte.

Clay samples were oriented to the A/B plane using the filter-membrane peel technique (Moore and Reynolds, 1997). Samples were then placed in an ethylene glycol chamber for 24 hours. A CuK$\alpha$ Norelco automated/digital X-ray diffraction unit was used to analyze the samples and diffraction patterns were plotted using MacDiff software. X-ray diffraction patterns were modeled for clay compositions with Newmod software.

### *Petrography*

Cemented sandstone samples were cut to standard 2x1 inch billets and sent to the University of Oregon for preparation. Mounted thin sections were analyzed with a binocular microscope and point counted using an automated tabulator. Five hundred grains, not including cement, were counted on each slide using a constant step interval. The traditional method of counting lithic grains was used in most samples, rather than the Gazzi-Dickinson method of counting individual minerals within lithic grains. Due to grain size distribution of sample 27.1, a very coarse sandstone, the Gazzi-Dickinson method was used (after Ingersoll et al., 1984). This method produces an increase in feldspar and quartz relative to lithic counts.

Clast counts of gravel bearing stratigraphic units were performed in the field using a measuring tape to delineate a square meter. Fifty or more random >3mm sized clasts from each locality were counted from a square meter grid.

### *Paleocurrent Indicator Analysis*

Inferred orientations of trough and planar foresets in cross bedded sandstone were measured in the field along the entire outcrop exposure. Cross bed orientations were restored when bedding dip exceeded 10 degrees for trough cross beds and 30 degrees for planar cross bedded sands (procedure from Miall, 2000, chapter 5.6.3). Clast imbrication orientations in conglomerates and gravel beds were measured in the field using the long axis of clasts. Multiple clasts were measured at all stratigraphic levels and across the breadth of the outcrop. Final restored lineations of clasts imbrication and cross bed orientations were plotted on rose diagrams using rockworks v.10 software. Localities containing less than 10 measurements were not plotted onto rose diagrams but were averaged and plotted as unidirectional arrows on the final map (Plate 1).

### *Geochronology*

Basal portions of three volcanic ash beds were sampled and prepared by the author for $^{40}Ar/^{39}Ar$ analysis at the USGS geochronology laboratory in Denver, CO (Dan P. Miggins pers. comm., 2004) Samples were crushed and milled with a mortar and pestle for approximately 5 minutes into a fine powder.

Samples were then washed with cold water and very fine silt was poured off until the water was clear. The remaining coarsest fraction was digested in a %15 solution of hydrofluoric acid (diluted with deionized water) and placed in an ultrasonic bath for 5 to 10 minutes. This procedure disaggregated and dissolved fine glass and glass that was adhered to feldspar and quartz grains. Acid was poured off and the samples were washed with cold tap water 15-20 times. Large magnetic grains were isolated from dried samples using a Franz L-1 magnetic separator by passing the sample through a paper funnel over the outside of the Franz. Fine samples were then passed through the Franz using 1.75 amps (full power) with the arm at 7 degrees. This was done at lower arm angles (4-7 degrees) until the majority of volcanic glass was separated out. The resulting mineral separates were predominantly feldspar, quartz and zircon. This fraction was passed through a LST (Lithium Heteropolytungstate) heavy liquid with a density of 2.58 $g/ml^3$. The final separate of 99.9% sanidine was soaked in acetone for 10 minutes, soaked in ethyl alcohol for 10 minutes, washed with deionized water, and dried.

Muscovite and K-feldspar from a semi-consolidated two-mica sandstone sample (II95.1) was separated out using a variation on the method described above. The sand was sieved with nested 28 and 80 mesh screens and the >180μ to <644μ size fraction was retained. After hand magnetics were separated out using the paper funnel method describe above, a majority of hornblende and biotite was separated out using the Franz set at 0.5amps with the arm at 15 degrees. The nonmagnetic separate was run through the Franz again with the instrument set at 1.5 amps. This procedure isolated feldspar and quartz from muscovite. The final muscovite separate was cleaned in an ultrasonic bath for 15 minutes, sieved through a 44 mesh, and the >360μ to <644μ fraction was franzed at 0.7 amps before being hand-picked under a binocular microscope. The feldspar and quartz separate was passed through a 2.58g/cm$^3$ LST heavy liquid that floated the K-feldspar. The K-feldspar separate was franzed at 9 amps and 5 degrees, then franzed at 1.5 amps and 4 degrees, and sieved though a 60 mesh screen. The resulting >250μ to <644μ K-feldspar fraction was hand-picked. The final muscovite and k-feldspar separate was washed in an ultrasonic bath for 10 minutes, washed 15 times with cold tap water, soaked in acetone for 10 minutes, soaked in ethyl alcohol for 10 minutes and washed with deionized water.

All final mineral separates will be radiated at the USGS geochronology laboratory in Lakewood, Colorado following completion of this manuscript. The samples will then be analyzed with a mass spectrometer for $^{40}Ar/^{39}Ar$ gas and final age determinations will be inferred (Dan Miggins pers. comm., 2005).

# STRATIGRAPHY

## *Regional Background*

Intermontane Tertiary deposits of western Montana were first studied for their rich vertebrate fossil collection (Hayden 1869, 1872, 1873; Douglass, 1899, 1901, 1903; Mertie et al., 1951; Donohoe, 1956; McDonald, 1956; Freeman et al., 1958; Konizeski, 1958). Weed and Iddings (1894) and Peale (1896) first designated Tertiary deposits in the Three Forks area as the "Bozeman lake beds". Robinson (1963) defined the Bozeman Group as "...the Tertiary fluvial, eolian and lacustrine rocks which accumulated in the basins of western Montana after the Laramide orogeny...". Further subdivision of the Bozeman Group by Kuenzi and Fields (1971) was based upon a litho- and bio- stratigraphic framework. This stratigraphic subdivision included a generally finer- grained unit with minor conglomerate, the Eocene to early Miocene Renova Formation, unconformably overlain by a generally coarse grained unit, the middle- to late- Miocene Sixmile Creek Formation. Their contact is locally angular and has been associated with a depositional hiatus during Hemingfordian time (NALMA - North American Land Mammal Age; Robinson, 1960; Dorr and Wheeler, 1964; Rasmussen, 1973; Axelrod, 1984; Lofgren, 1985; Runkel, 1986). This mid-Miocene (~17-16 Ma) unconformity is regionally extensive throughout the intermontane basins of western Montana and southeast Idaho (Fields et al., 1985).

Hanneman and Wideman (1991) abandoned the established lithostratigraphy mentioned above and proposed five unconformity bounded

**Figure 9: Cenozoic Correlation chart of map units in the eastern FCB**

North American Land Mammal ages (NALMA) and Ma taken from www.stratigraphy.org/ geowhen/timeline. html; ISC 2004

ad = anthropogenically deposits,
Qal = Alluvium of modern streams
Qls = Landslide deposit
Qc = Colluvium
Qaf = Alluvial fan deposit
Qghc = Gravel of Hoover Creek
Qlo = Loess and matrix supported angular garvel
QTgr = Gravel deposit, undivided, includes Sixmile ceek Formation
QTgrm = Gravel and mud deposit, undivided, includes Sixmile creek Formation
Tscgs = Gravel and sand deposit of Sixmile Creek Formation
Tscb = Barnes Creek beds, informal, of Sixmile Creek Formation
Tscf = Flint Creek beds, informal, of Sixmile Creek Formation
Tscfg = Flint Creek beds basal gravel bed, informal, of Sixmile Creek Formation
Trcp = Cabbage Patch beds, informal, of Renova Formation
Trt = Rhyolitic tuff, ash flow, welded
Tv = Volcanic rocks, undivided
Tml = Eocene laterite developed on K/T boundary

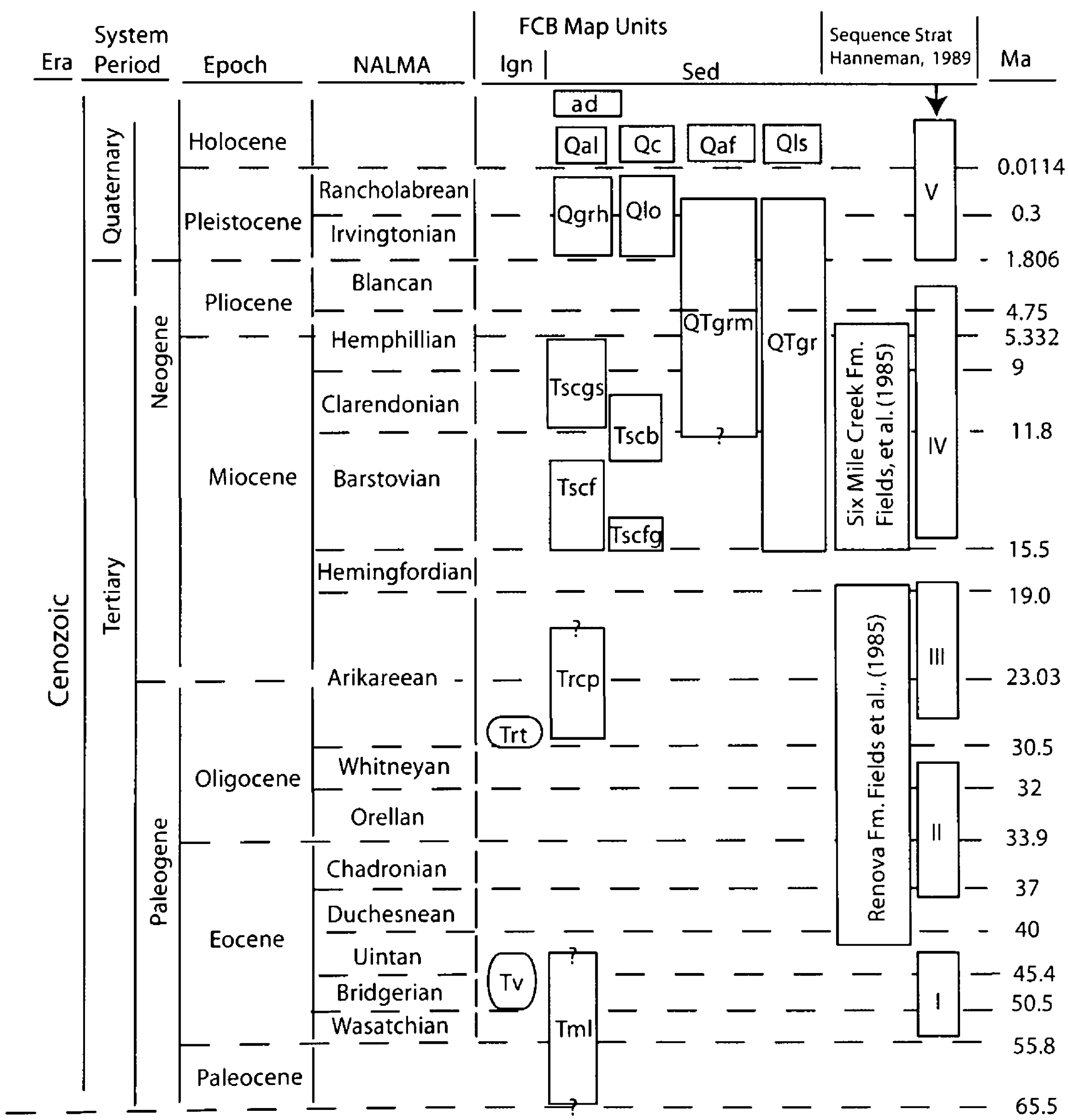


**Figure 10:** Columnar Jointing in Eocene basalt of western FCB .
(Unit Tv on plate 1; lat = 46.549433, long = -113.284733)

**Figure 11:** Basal Diamict bed with vivid ochre red clay matrix
(Unit Tml on plate 1; lat = 46.580133, long = -113.0469)

17,375 foot exploratory borehole (Henderson-Lorensen #2) drilled in the northwestern portion of the basin (Figure 2; Appendix E).

A stratigraphic equivalent of the syntectonic Anaconda beds (see pg. 10-11) in the western FCB may have been encountered in borehole Wilson #2 at 780 feet where "unconsolidated quartzite gravels, sand and bright brick red clay" was penetrated (Figure 2; Appendix E). In the eastern FCB a thin ocher red clay rich horizon locally occurs along the K/T boundary and is exposed in one locality along Dunkleberg Creek (Tml – Figure 9). There, it contains large boulder clasts in a red clay rich matrix support (Figure 11). Gwinn (1960) suggested that the reddish maroon pebbly clay along Dunkleberg Creek might be stratigraphically equivalent to red conglomerates (anaconda beds) in the SW and SE Flint Creek Range. The very poor exposure of the basal FCB red clay horizon makes a stratigraphic correlation with the Anaconda beds difficult to determine.

Sequence #2:

Late Eocene to early Oligocene (Chadronian NALMA) vertebrate, invertebrate and plant fossils were collected from lower Renova Formation strata in the Douglas Creek basin 10 miles north of the FCB (Konizeski, 1965; Person, 1972). This fauna and flora correlates with unnamed fissile shales and a low grade coal bed exposed in the western FCB (Rasmussen, 1977, 1989). Bentonitic shales exposed in the western FCB and penetrated in boreholes Wilson #1 and

Wilson #2 may be correlative to the lower Renova Formation, but correlative strata were not observed in the eastern FCB (Figure 9).

Sequence #3:

A 29.5 Ma (zircon fission track age) rhyolitic ash-flow tuff exposed at the mouth of Coberly Gulch can be used as a stratigraphic marker bed for the FCB (Figure 12a; Gwinn 1960; Rasmussen 1969; Rasmussen 1977). It contains phenocrysts of euhedral smoky quartz and sanidine. Konizeski and Donohoe (1958) identified Arikareean vertebrate fossils in bedded tuffaceous sediments above the ash flow-tuff in the northern Flint Creek basin and named those units the Cabbage Patch beds after a local tavern (Trcp - Figure 9; Figure 12b). These units are correlative to the middle Oligocene- to early Miocene- upper Renova Formation of southwest Montana (Rasmussen, 1989).

Composite stratigraphic sections measured by Rasmussen (1977) depict a >700 meter thickness for the Cabbage Patch beds. Rasmussen (1977) defined a biostratigraphic subdivision for the Cabbage Patch beds into an upper, middle and lower unit (Appendix F). Magnetostratigraphic sections of the Cabbage Patch beds using the basal ash-flow tuff as a datum, permits biostratigraphic correlation with sediments in Oregon, Nebraska and South Dakota and constrains their age to be between 29.5 and ~23 mya (Figure 13; Rasmussen and Prothero, 2003). The upper age limit of the Cabbage Patch beds is not well

**Figure 12:** (above) Exposure of Cabbage Patch beds basal ash flow tuff at mouth of Coberly Gulch (left of photo; lat = 46.617133, long = -113.102217) (below) Typical fine grained bedded tuffaceous rocks of the Cabbage Patch beds. Dingwall fault on right side of photo (lat = 46.615017, long = -113.1225)

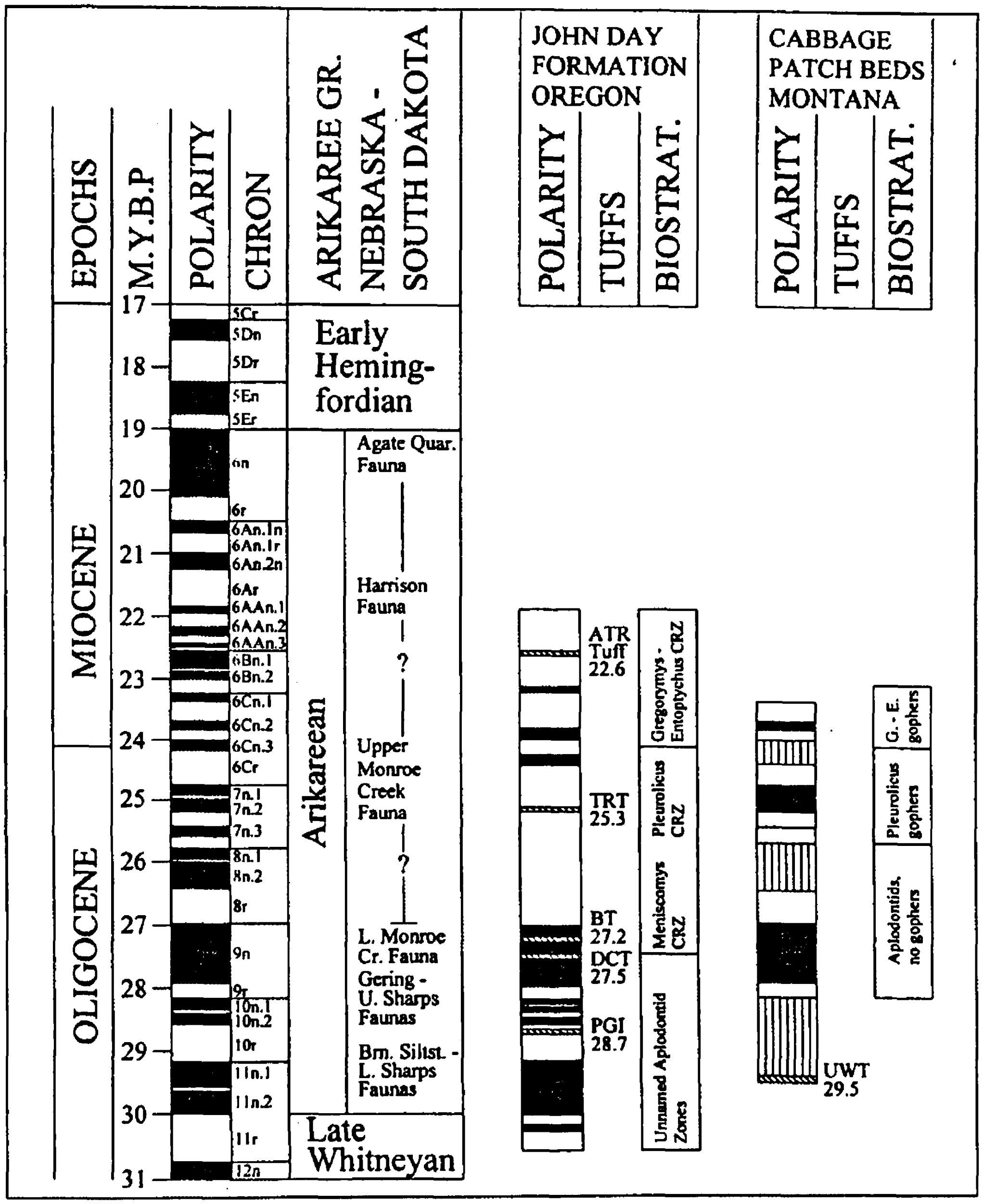


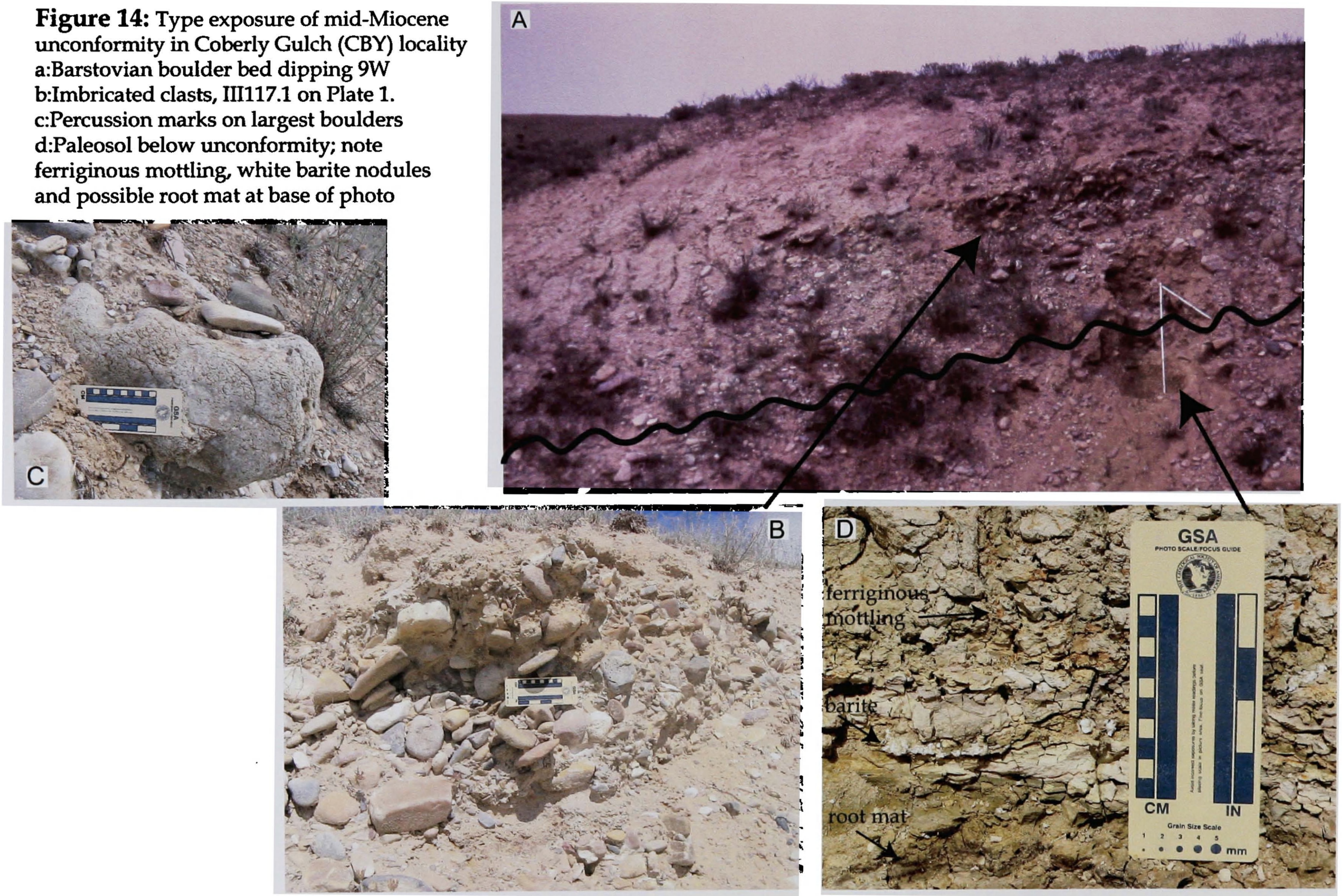

**Figure 13:** Biostratigraphic and magnetostratigraphic correlation of Cabbage Patch beds (taken from Rasmussen, 2003).

defined, but the absence of Hemingfordian vertebrate fossils suggests that the unit is solely Arikareean in age (Figure 9; Rasmussen and Prothero 2003).

Mid-Miocene Unconformity:

Rasmussen (1973) biostratigraphically identified the "mid-Miocene" unconformity in the FCB and observed an angular relationship across it, but failed to observe a good exposure of it. The basal erosion surface of a well-exposed 2-meter thick boulder bed west of Coberly Gulch separates Arikareean aged strata from Barstovian aged strata (Tscfg – Figure 9; Figure 14). This relationship delineates the presence of a major unconformity that was developed during Hemingfordian time (Craig Christensen, pers. comm., 2004). The basal erosion surface of the boulder bed correlates with the regionally extensive "mid-Miocene" unconformity (Portner et al. 2004). This observation conflicts with the placement of the "mid-Miocene" unconformity on Gwinn's (1961) geologic map. The boulder bed is a locally occurring facies that can be traced for approximately 2 miles along a ~4370ft bench. It has been observed on the north side of Clark Fork River and may or may not be present in other adjacent basins (Rasmussen, pers. comm., 2005). It is overlain by massive siltstone lithologically similar to facies seen in the underlying Cabbage Patch beds, making it a relatively resistant unit that is easy to recognize in the field.

**Figure 14:** Type exposure of mid-Miocene unconformity in Coberly Gulch (CBY) locality
a:Barstovian boulder bed dipping 9W
b:Imbricated clasts, III117.1 on Plate 1.
c:Percussion marks on largest boulders
d:Paleosol below unconformity; note ferriginous mottling, white barite nodules and possible root mat at base of photo



Sequence #4a:

Douglass (1903) collected Barstovian vertebrate fossils from tuffaceous siltstones south of the homestead of New-Chicago and named those units the Flint Creek beds (Tscf – Figure 9; Figure 15). These beds can be correlated with the lower Sixmile Creek Formation. Vertebrate fossils collected from the Flint Creek beds indicate an early Barstovian age, between 14.8 and 16 mya (Figure 16; Appendix G). In many places the Flint Creek beds are lithologically indistinguishable from the underlying Cabbage Patch beds (Rasmussen 1969). The base of the unit is typically covered.

Sequence #4b:

Overlying the Flint Creek beds are poorly consolidated interbedded sand, gravel and reddish orange mudstone facies of the Barnes Creek beds (Tscb - Figure 9) named by Gwinn (1960) for exposures east of the town of Hall at the mouth of Barnes Creek (Figure 17). The basal erosion surface of the Barnes Creek beds was recognized as an angular unconformity by Gwinn (1960) and Rasmussen (1969) and is well exposed west of Coberly Gulch. Vertebrate fossil collections from the unit suggest a late Barstovian age (Appendix H; Craig Christensen pers. comm., 2004). Konizeski (1958) and Rasmussen (1969) identified Clarendonian fossils from the "Bert" Creek beds (north of the Clark Fork River) that are later referred to as the Barnes Creek beds in Fields et al. (1985). The Bert and Barnes Creek beds are lithogically the same, can be

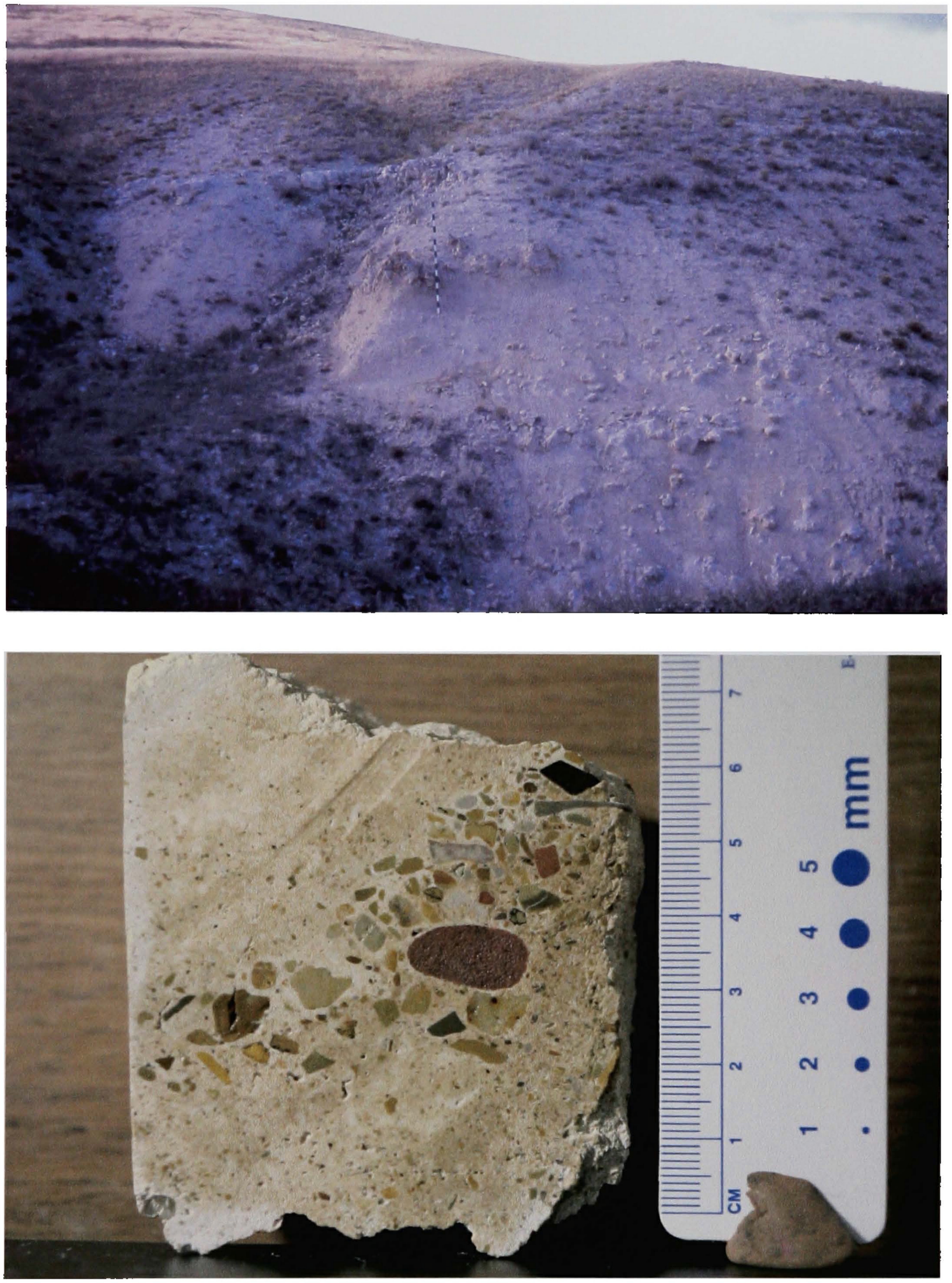



**Figure 15:** (top) Flint Creek beds in Coberly Gulch. Note pervasive carbonate nodules that coalsce into tabular beds. Beds dip 9 degrees west. (lat = 46.594333, long = -113.1149). (bottom) Polished slab of carbonate nodule.

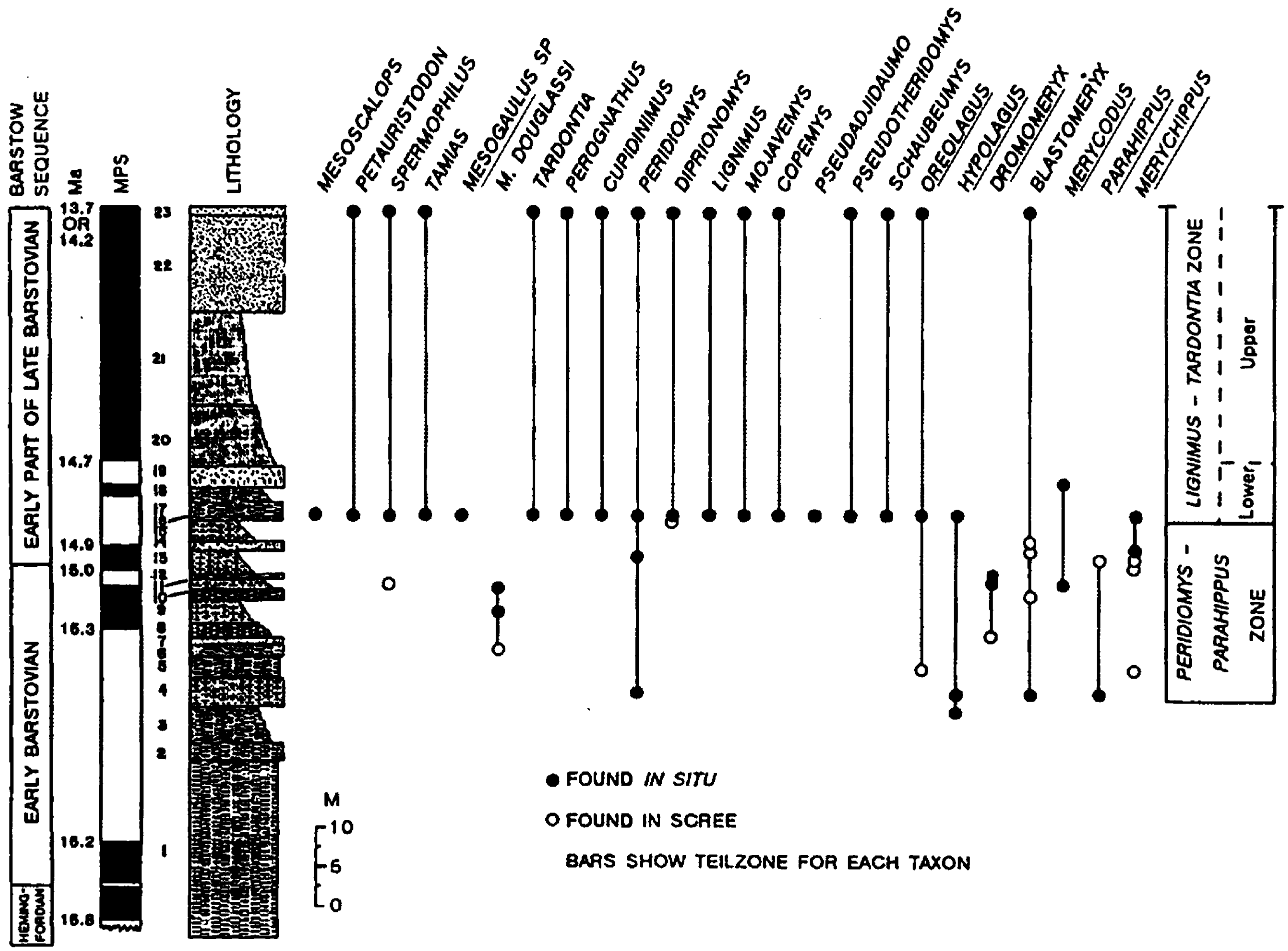
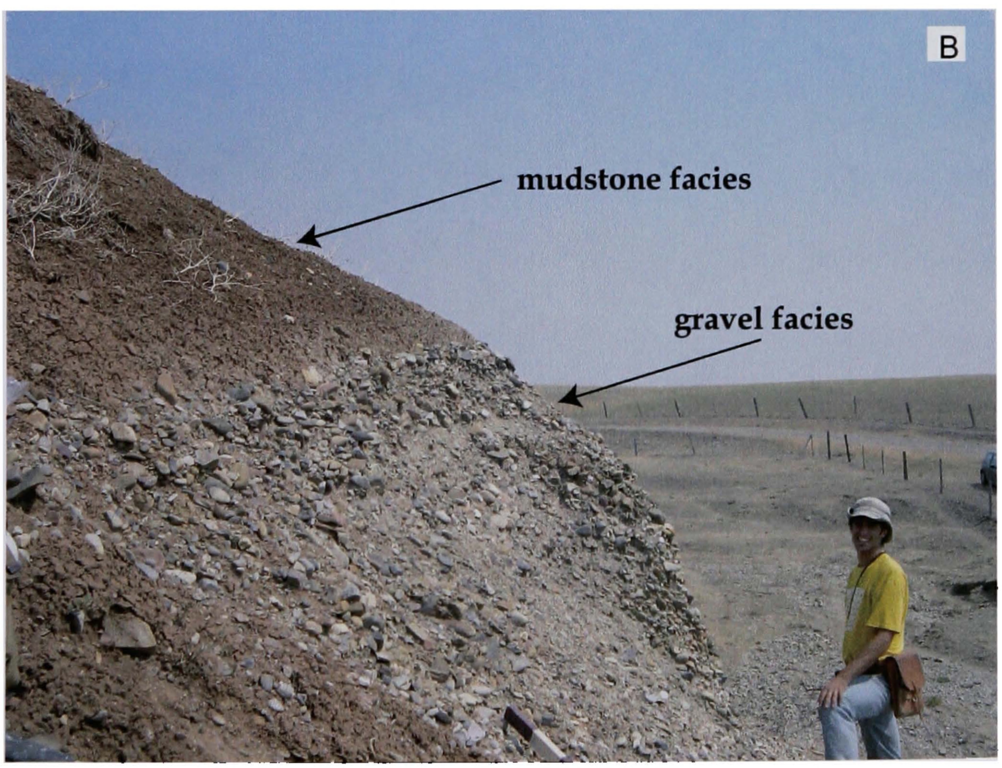



**Figure 16:** Biostratigraphy and magnetostratigraphy of Hepburns Mesa Formation in Upper Yellowstone basin (# 15 in figure 4). Vertebrates found in the FCB from the Barstovian Flint Creek beds underlined. (modified from Burbank and Barnosky, 1990)


**Figure 17:** Barnes Creek beds - gravel and sand facies (A above; lat = 46.5918, long = -113.121367) in Coberly Gulch. Red mudstone facies overlying gravel faceis (B below; lat = 46.58378, long = -113.14663) in Barnes Creek .



correlated with the mid- to upper- Miocene Sixmile Creek Formation, and are likely stratigraphic equivalents (Fields et al. 1985 and Rasmussen, pers. comm., 2004).

The Barnes Creek beds are stratigraphically equivalent to boulder-sized conglomerates and interbedded sands (Tscgs on Plate 1) exposed southeast of the town of Hall along Douglas creek. High terrace gravels exposed north of Barnes Creek are likely later stage deposits of the Barnes Creek beds (Rasmussen 1969). Fields et al. (1985) correlated these gravels with the Deer Lodge beds which yielded Hemphillian vertebrate fossils. This correlation suggests that the unnamed high terrace gravels of the FCB may be upper Miocene in age.

Sequence #5:

Stratigraphically above the Sixmile Creek Formation are unconsolidated deposits of reworked Bozeman Group strata, loess, and angular gravel that have a basal erosion surface (Qlo – Figure 9; Figure 18). This unit forms a pediment surface that has since been dissected during Holocene time. Late Pleistocene vertebrate fossils were identified from this unit in a small draw north of the mouth of Barnes Creek (Rasmussen, 1974). Stratigraphic equivalents to the pediment cap deposits were identified west of the homestead of Jens in a gravel bench exposed 30 feet above the modern day Clark Fork River flood plain (Rasmussen, 1969). Rasmussen (1969) named these gravels the Hoover Creek

**Figure 18:** Quaternary diamict overlying siltstone of the Flint Creek beds (lat = 46.58292, long = -113.10608) .

gravels (Qgrh - Figure 9) and suggested that they were deposited by a proto Clark Fork River.

### *Measured Sections*

Stratigraphic sections were measured in five separate localities and represent the major Tertiary units that are well exposed in the eastern FCB (see Plate 1 for location; Appendix D). The Dingwall ranch (DNGWL1-2) and Dunkleberg Creek (DNKB1-8) localities contain strata from the Cabbage Patch beds (Plate 3). The Douglas Creek (DGC1-4) and Barnes Creek (BNC1-2) localities contain strata from the Flint Creek and Barnes Creek beds (Plate 3). A well-exposed 75 meter long nearly continuous section of Cabbage Patch, Flint Creek and Barnes Creek strata was measured in a western draw of Coberly Gulch (CBY1-2) and is used as a reference stratigraphic section for the "mid-Miocene" unconformity (Plate 3).

Assuming no major structural disruption, the base of CBY2 can be projected along strike to a point stratigraphically above the top of DNGWL1. Rasmussen (1977) previously measured strata in DNGWL1-2 and identified a *Pleurolicus* gopher (family *Geomyidae*). *Pleurolicus* is an Arikareean index fossil and constrains the stratigraphic position of DNGWL1-2 to the middle Cabbage Patch beds (Figure 13). This biostratigraphic correlation can be extrapolated to the CBY2 section placing it in the middle- to upper- Cabbage Patch beds. An Arikareean *Mylagaulus (sp.)* vertebrate fossil found in DNKB7 permits the assignment of DNKB sections to the Cabbage Patch beds. Stratigraphic correlations suggest that DNKB 1, 2, 4, 6 are in lower- to middle- Cabbage Patch beds and DNKB5, 7, 8 are in middle- to upper- Cabbage Patch strata.

BNC sections consist of westerly dipping (7-16 degrees) strata that correlate with Barstovian fossil localities identified by Douglass (1903) and Pierce and Rasmussen (1989). A gravel unit measured in BNC2 is lithologically similar to the Barnes Creek beds, but grades up into siltstone facies typical of the Flint Creek beds. Displacement of this distinctive gravel bed was used to calculate 60 meters of throw in a down to the east high angle normal fault (Figure 19). General correlation of BNC strata with DGC strata is dependent upon a Barstovian *Artiodactyla* (fm.) identified in DGC2. Upper Sixmile Creek Formation gravel beds (Tscgs) in the DGC sections show a clear angular unconformity with underlying Flint Creek strata (Figure 20). These gravels can be correlated with similar facies overlying the Flint Creek and Barnes Creek beds in the BNC area (QTgrm on Plate 1).

### *Tephra Correlation*

Volcanic air fall ash beds were sampled from three different localities of Cabbage Patch strata in the Coberly Gulch and Dunkleberg Creek drainage areas. A two-meter thick very fine-grained air fall ash bed that has been reworked is well exposed in the base of CBY2 (Figure 21). This ash bed can be used as a stratigraphic marker bed for the FCB. It probably correlates with a two-meter thick air fall ash bed in DNKB8 and a fine-grained ash bed in DNKB7 (Figure 21). Here it is named the "Flint Creek air fall ash". An age date from this ash bed (work in progress) will provide constraints on the upper age limit of the Cabbage Patch beds and compliment the existing magnetostratigraphic correlation. Furthermore, it will provide key chronologic information that will assist in correlation with currently identified regional tuff marker beds in other basins of southwest Montana (Hanneman and Wideman, 2004).

**Figure 19:** East dipping normal fault in upper Flint Creek beds of the BNC2 measured section. Beds dip 9-15 degrees west. Jacob staff is 1.8 meters.

**Figure 20:** Massive siltstone of the Flint Creek beds dipping 24 degrees west in DGC measured sections. Overlain by boulder sized gravel of QTgrm map unit (Plate 1).

**Figure 21:** Tephra beds of the FCB
a: CBY1 rippled airfall ash (~1.7m thick)
b: well preserved ripples of CBY1 ash
c: DNKB8 tephra. Well preserved soft sediment deformation features.



## SEDIMENTOLOGY

### *Facies Descriptions*

Tertiary and Quaternary rocks of the FCB share similar characteristics and prove difficult to recognize and map in the field. Measurement of detailed stratigraphic sections has provided the basis for recognition of several facies used to identify individual map units. The facies described below have been observed in the map area and can be assigned to the major units (Table 2).

**Table2: Facies Distribution of Cenozoic map units**

Note: other gravel units (ie. QTgr) contain proportions of Tscgs and QTgrm

| | Sb | Sl | Gf | Gm | Fb | Fm | Cc | Cm |
|---|---|---|---|---|---|---|---|---|
| Qal | | 12% | 50% | | | 38% | | |
| Qlo | | 12% | | 50% | | 38% | | |
| QTgrm | | | | 100% | | 12% | | |
| Tscgs | | | 88% | | | | | |
| Tscb | 25% | | 50% | | | 25% | | |
| Tscf | | 6% | | | 12% | 50% | 32% | |
| Tscfg | 12% | | 88% | | | | | |
| Trcp (u) | 12% | | | 6% | 58% | 12% | | 12% |
| Trcp (l) | 50% | | | | 25% | 25% | | |
| Tml | | | | 12% | | 88% | | |

**Gf - Gravel, framework supported**

Clasts are pebble to boulder sized (max diameter - 60 to 70cm) and commonly imbricated (Figure 14b). Clasts are dominantly well-rounded to sub angular, spherical clasts and moderately- to well- sorted. Matrix is composed of angular very coarse sand. Facies distinguished by a loose to tight framework support and interbedded sandy lenses.

**Gm - Gravel, matrix supported**

Clasts are granule to boulder sized (max diameter – 50cm), poorly sorted and nonstratified. Clast shape is rounded to very angular with low sphericity. Matrix typically is composed of brown sandy mud. Facies distinguished by an open framework (Figure 22)

**Sb - Sandstone, bedded**

Very fine- to very coarse-, subround- to very angular-, poor- to moderately-sorted sand. Trough and planar cross beds are common (Figure 23). Bedforms are more easily discerned in cemented outcrops that tend to form competent exposures. Beds are generally massive to thick and commonly wedge to ribbon shaped.

**Sl - Sandstone, lenticular**

Very fine- to very coarse-, very angular, very poorly- sorted sand that lacks cement. Bedforms are rare but include planar cross-stratification. Bedding is typically lenticular and laterally discontinuous. Facies distinguished by abundance of granule- to pebble- sized angular chips of locally derived bedrock (Figure 24).

**Fb – Fine grained bedded sediments**

Facies dominated by thin- to medium- bedded tuffaceous mudstone, siltstone and claystone with minor fissile shale. Root traces, ferruginous mottling, granular texture and rare slickensides typify pedogenically modified beds. Colors dominantly include shades of brown, green, tan, pink, gray and dark

**Figure 22:** Gm facies - Matrix supported angular boulders. Exposure of west dipping Flint Creek beds 750 ft east of the Dunkleberg Fault.

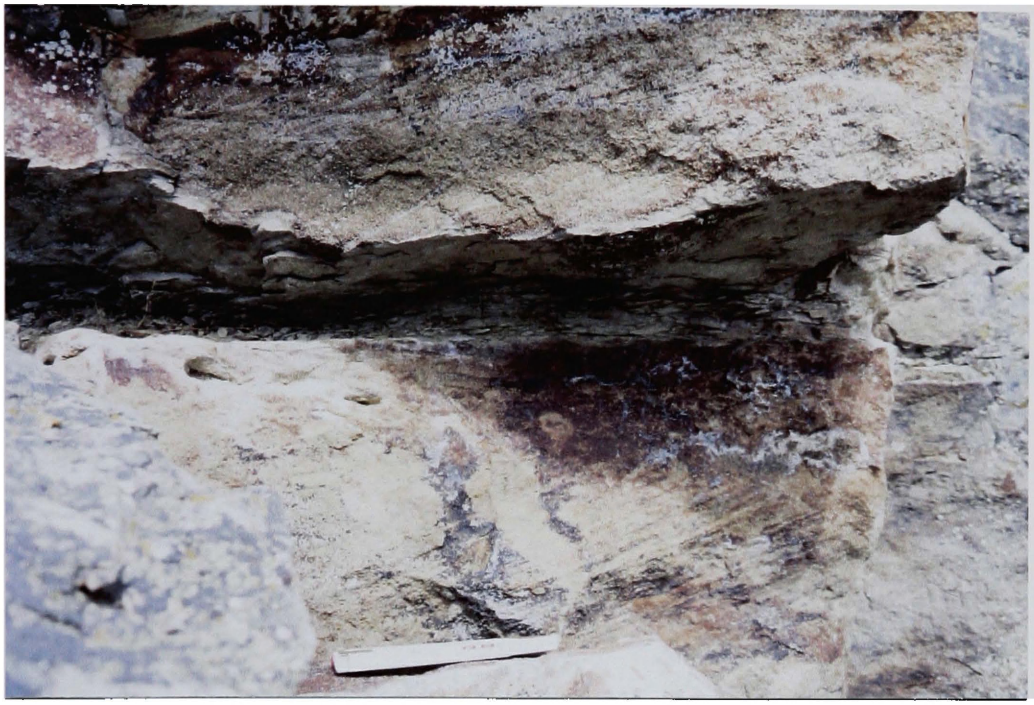


**Figure 23:** Sb facies - bedded sandstone. Basal Cabbage Patch sandstone from Dunkleberg Creek locality.

**Figure 24:** Sl facies - lenticular pebbley sandstone. BNC section of Flint creek beds

maroon on fresh surfaces. Unweathered volcanic glass and reworked air fall ash (tephra) beds are a distinguishing component of this facies (Figure 12b).

**Fm - Fine grained massive sediments**

Facies is dominated by massive siltstone and mudstone. Devitrified volcanic glass is commonly a major component. Pedogenic modification is locally well expressed in clay rich units with mottling, caliche, root traces and a complex network of cracking and veining. Siltstone color is typically light tan (buff), and mudstone colors range from dark brown to brick red. Facies distinguished by total lack of bedding (Figure 20).

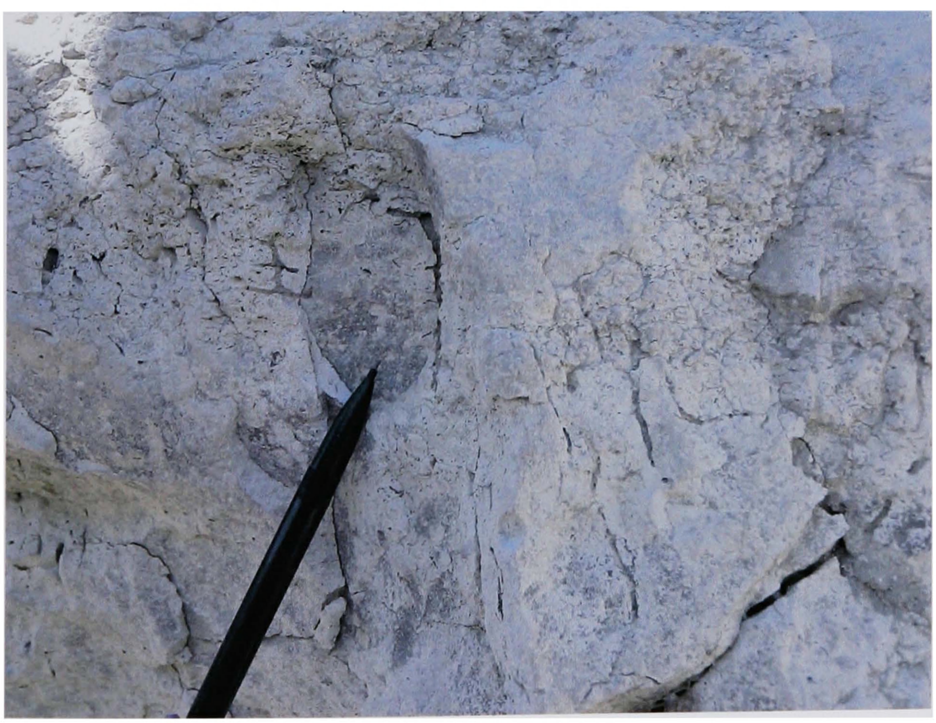
**Cc - Carbonate calcrete**

Calcrete is here defined as a terrestrial accumulation of $CaCO_3$ that occurs in nodular and highly indurated, massively- bedded forms (after Wright and Tucker, 1991; Figure 15a). The facies locally contains granule to pebble sized detritus that show displacive growth by calcite cement (Figure 15b). This facies generally lacks invertebrate fossils, contains burrows and commonly preserves vertebrate fossils.

**Cm - Carbonate marlstone**

Fossiliferous carbonate units are well bedded and typically are clay- rich (micritic). Invertebrate fossils include gastropods, pelecypods, ostracods, diatoms, fresh water sponges and algae (Figure 25a). Facies is commonly very

**Figure 25:** (above) Cm facies - fossiliferous marlstone, includes gastropods, pelecypod and ostracods. Sample from Dunkleberg Creek locality. (below) Marlstone bed (upper part of unit 2 of DNGWL1b) that exhibits vertically elongate downward branching root tubules.



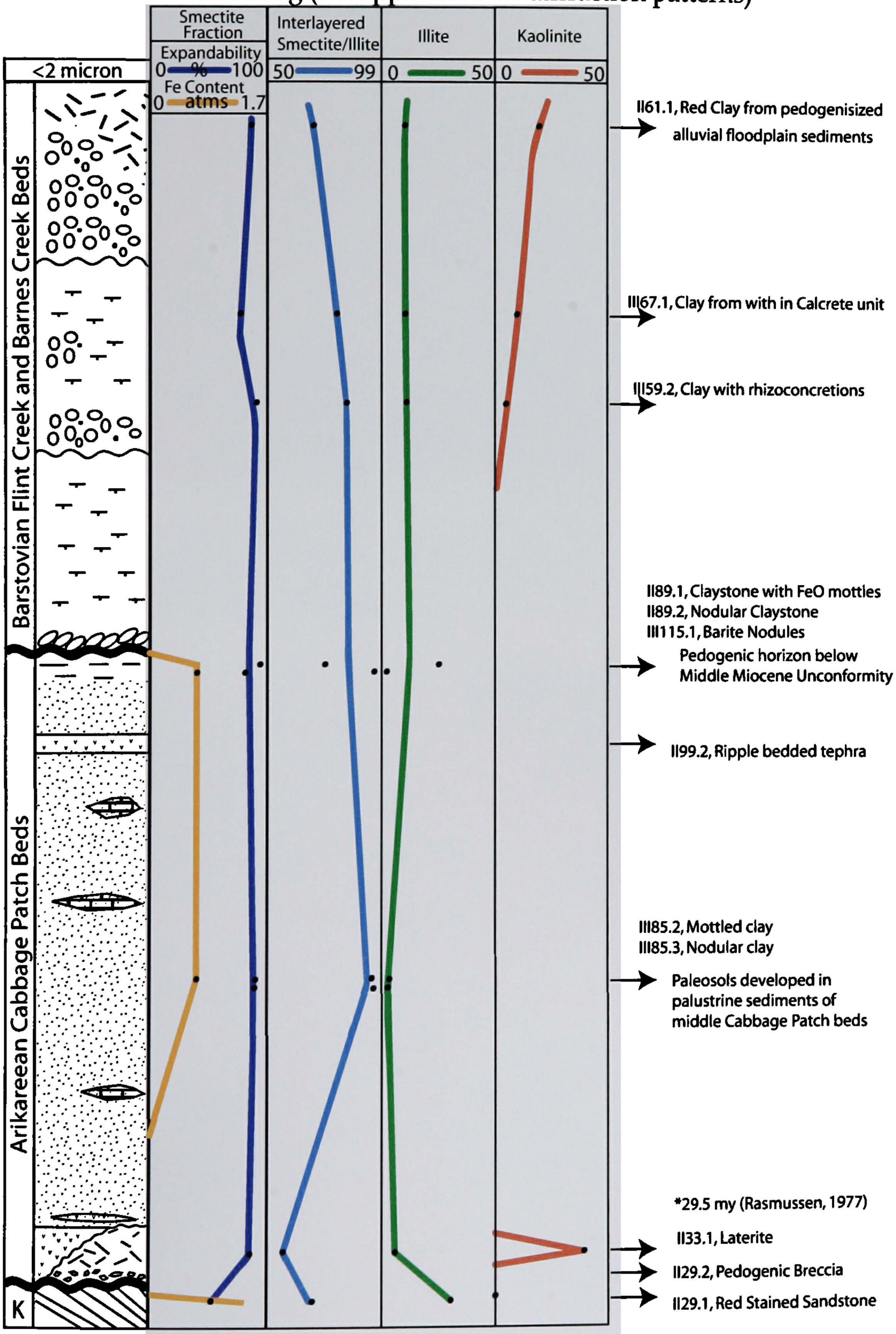
thinly to medium bedded. Units locally display evidence of pedogenesis and exhibit rhizotubules, complex cracking, and abundant mottling (Figure 25b). Facies distinguished by carbonate content, internal bedding and invertebrate fossils.

### *Paleosols and Clay Mineralogy*

Clay samples were taken in measured sections of the Bozeman Group along key bounding unconformities and within pedogenically altered strata. Diffraction patterns of oriented <2 micron grain size samples were modeled with the NEWMOD program to estimate relative percentages of clay minerals (Reynolds and Hower, 1970; Appendix I). Figure 26 shows the relative distribution of clay types, expandability of interlayered swelling clay and iron (Fe) content of smectite. Interlayered smectite/illite clay is the dominant clay in all samples.

A high proportion of halloysite (Kaolinite group mineral; 7.2 angstrom-d spacing) occurs in basal red **Gm** and **Fm** facies (Tml on Plate1, Figure 11; Figure 26). Cretaceous bedrock immediately underlying the horizon exhibits reddening that decreases downward from the K-T boundary. Along the contact, a claystone breccia with radiating calcite cement and abundant hematite forms a competent unit only 10 cm thick (Figure 27). The claystone is lithologically similar to

**Figure 26:** Clay mineralogy normalized and interprted from NEWMOD modeling (see appendix I for diffraction patterns)



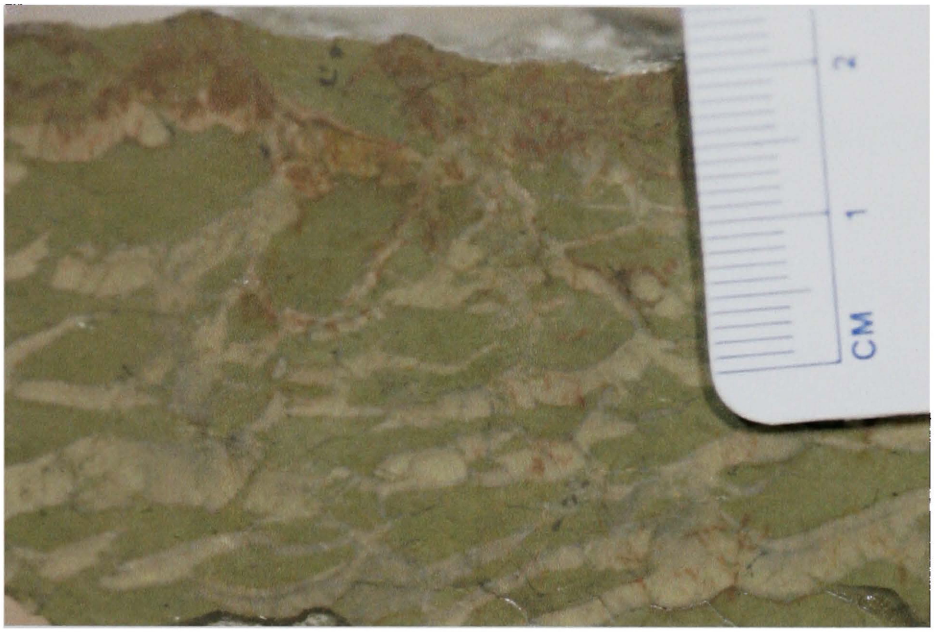
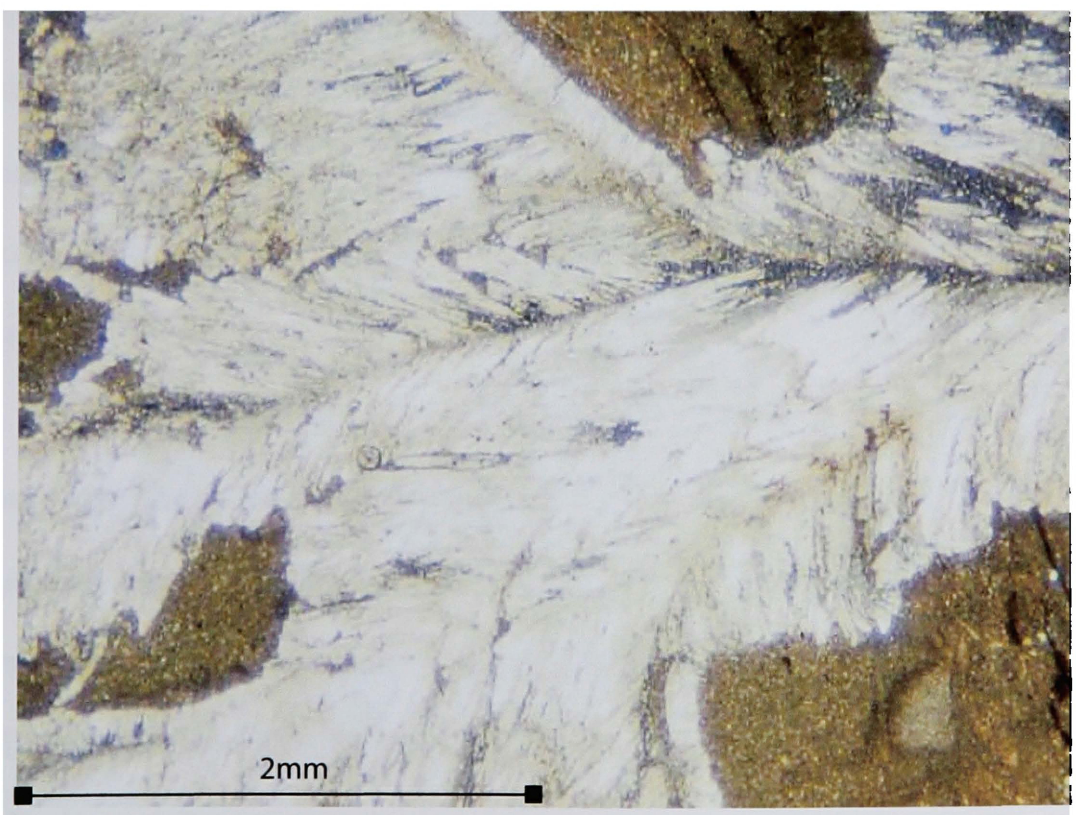



**Figure 27:** (above) Brecciated Dunkleberg Member (Kbld) bedrock along the K-T boundary in the Dunkleberg Creek locality. Red Hematite staining in top of photo and matrix composed of calcite. Unit is <20cm thick and is overlain by red kaolinitic clay (Tml) depicted in figure 11. (below) Photomicrograph of KT Breccia, matrix is calcite.

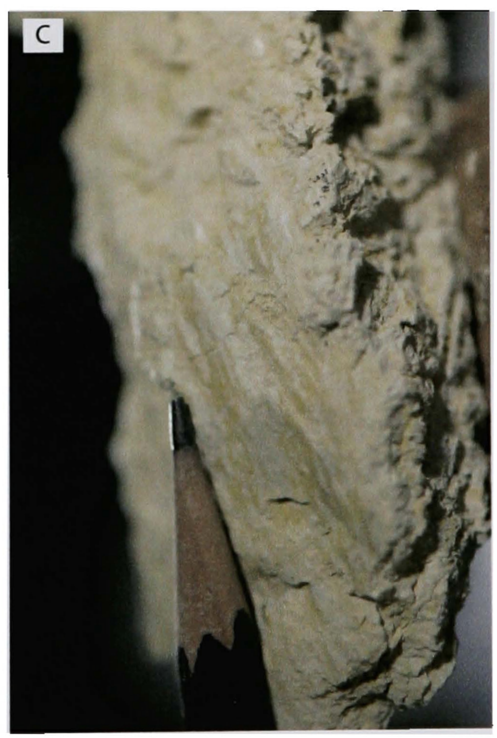


underlying strata and suggests pedogenic brecciation of underlying strata during Paleogene time.

Clay samples from two paleosols (facies **Fb**) of middle Cabbage Patch beds are dominated by interlayered smectite/illite clay with R0 reschvite ordering and expandabilites of greater than 80% (Figure 26). Root traces are the most common pedogenic feature in Cabbage Patch beds and tend to be bright yellow, orange and brown (Figure 28a). Burrow casts and molds are locally found and also suggest exposure of the parent materials to soil formation processes (Figure 28b). The burrows are typically much larger than the root traces and do not bifurcate downward. Slickensides are diagnostic of pedogenic processes (Figure 28c). Paleosols are typically orange brown, olive or yellow and commonly have reddish orange mottles. Paleosol profile horizonation is poorly developed, but is observed in measured section DNKB7b between units 9 and 15. **Cc** facies of that section are approximately 1-4 meters below a horizon of root traces and ferruginous mottling, here inferred to be the upper portion of a profile (Plate 3).

The uppermost meter of Cabbage Patch strata below the mid-Miocene unconformity **Gf** facies in the CBY section, is 99.9% smectite and illite clay (Figure 26). Ferruginous mottling is common in this unit and pedogenic slickens are present locally. A very dark brown irregularly laminated horizon (unit 3 CBYII) with horizontally bifurcating strings may represent a root mat (Figure 14c). Barite nodules (<3cm diameter) are scattered throughout an 11cm clay


**Figure 28:** Cabbage Patch beds paleosol features.
a. Ferriginous root traces collected from DNGWL 2b measured section.
b. Vertically elongate burrow mold, possibly from rodents (Rasmussen, pers. comm., 2004)
c. Pedogenic slicken sampled from DNGWL1b. Occurs as a result of expandable clay shrinking and swelling in well-drained soils.

horizon (unit 4 CBYII - III115.1) that is mottled and has a platy to blocky texture (Figure 14c; Figure 26; Appendix I). The nodules are crystalline masses with internal voids filled with clay parent material.

Destruction of bedding in facies **Fm** is typical of the Flint Creek beds and is suggestive of pedogenesis. Facies **Fm** is commonly interstratified with **Cc**. Irregularly shaped carbonate nodules tend to coalesce into massively indurated beds and form prominent outcrops (Figure 15). Clay types of calcrete host rocks are dominated by smectite with very minor amounts of kaolinite (Figure 26). Locally well preserved rhizoconcretions are also evident and typically preserved by calcite (Figure 29a). Large burrow molds are commonly preserved in $CaCO_3$ and are vertically elongate (Figure 29b, c). Uppermost **Fm** facies of the Flint Creek beds are mottled, relatively clay-rich and contain abundant root traces (unit 10 CBYIIb).

Kaolinite is a noticeable constituent in **Fm** facies of the Barnes Creek beds (Figure 26). Paleosols of the Barnes Creek beds occur as ocher red mudstones (**Fm**) that are interbedded with gravelly facies (**Gf**) (Figure 17b). These mudstones are commonly mottled, contain root traces and have rare carbonate nodules. Exposure quality is too poor to deduce horizonation.

### *Petrography*

Well-cemented sandstone samples from Bozeman Group strata are more common in **Sb** facies of lower Cabbage Patch strata. Therefore, petrographic

**Figure 29:** Pedogenic features of Fm and Cc facies of the Flint Creek beds.
a. Vertically elongate rhizoconcretion composed of carbonate
b. Vertically aligned burrow molds composed of carbonate
c. Calcrete unit showing basal burrow molds



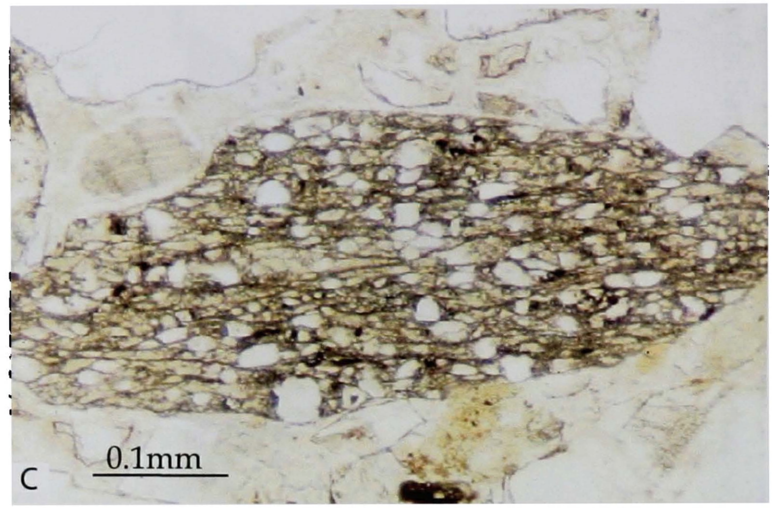
analysis of Tertiary strata in the field area is biased towards lower stratigraphic intervals. Silica cement (chalcedony and opal) prove to be a much better medium for sand grain point counting than calcite cement, because calcite replacement of numerous grains, particularly feldspars, rendered their identification impossible. Calcite cement is common in upper Cabbage Patch strata, basal Sixmile Creek Formation **Gf** bed matrix and to a lesser degree in the Barnes Creek beds. Because of the effects of calcite replacement, these samples were analyzed qualitatively. Silica cement was only common in lower and middle Cabbage Patch strata and shows several generations of growth (Figure 30a, b).

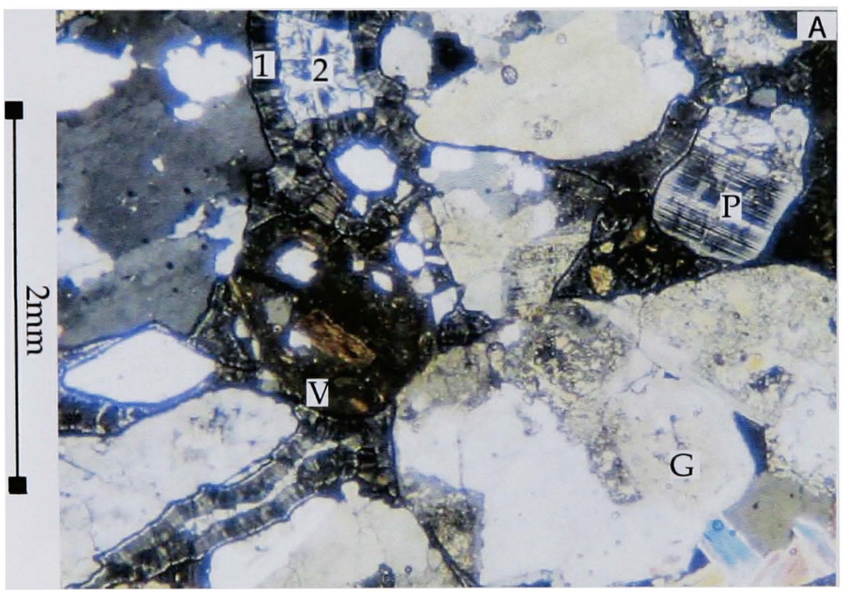
Gravel beds tend to occur with non-consolidated sand facies and are rarely cemented by calcite. Most gravel facies occur at higher stratigraphic levels with in the Sixmile Creek Formation. (Appendix J).

Upper Renova Formation - Cabbage Patch beds

Sandstone units from **Sb** facies are typically arkosic and texturally immature (Figure 31). They contain approximately 18% to 32% feldspar (Appendix K). Plagioclase is very often zoned and altered by sericite. A few grains exhibit myrmekitic texture (Figure 30b). Plutonic lithic grains make up 10% to 23% of samples and are more common in coarser samples (Figure 30a; Figure 31). Volcanic and sedimentary lithic grains were of about equal bulk percentages and sheared metamorphic fragments the least abundant (Figure 30a,c). In order of decreasing abundance biotite, muscovite and hornblende are

**Figure 30:** Sandstone samples from the Cabbage Patch beds
A. III27.1a - Two generations of silica cement (1 and 2). Volcanic lithic grain with biotite in middle of slide (V). Plutonic lithic with muscovite lower right and sericite covering plagioclase (G). Zoned plagiocalse grain upper right (P). Note the angular poorly sorted texture.
B. III27.1b-Myrmakitic texture of plagioclase grain in upper right corner (P). Volcanic lithic grain lower left (V).
C. II51.1a - Sedimentary metamorphic lithic grain.



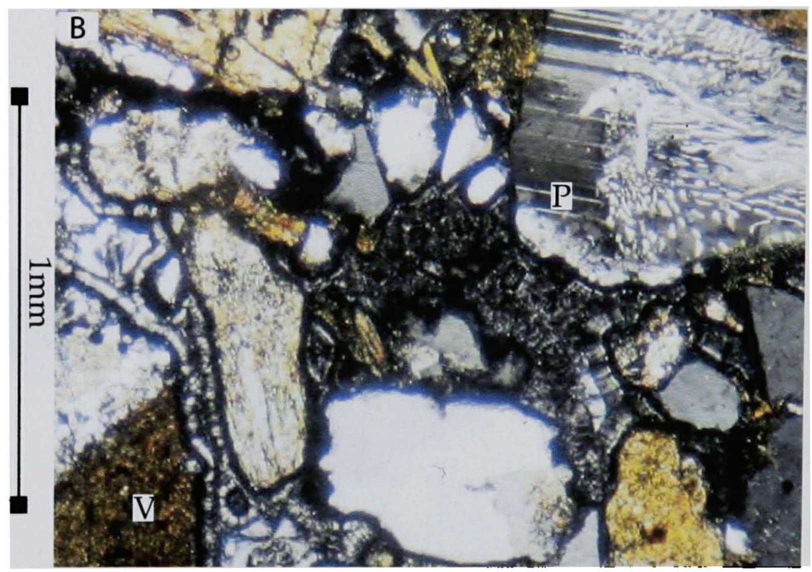
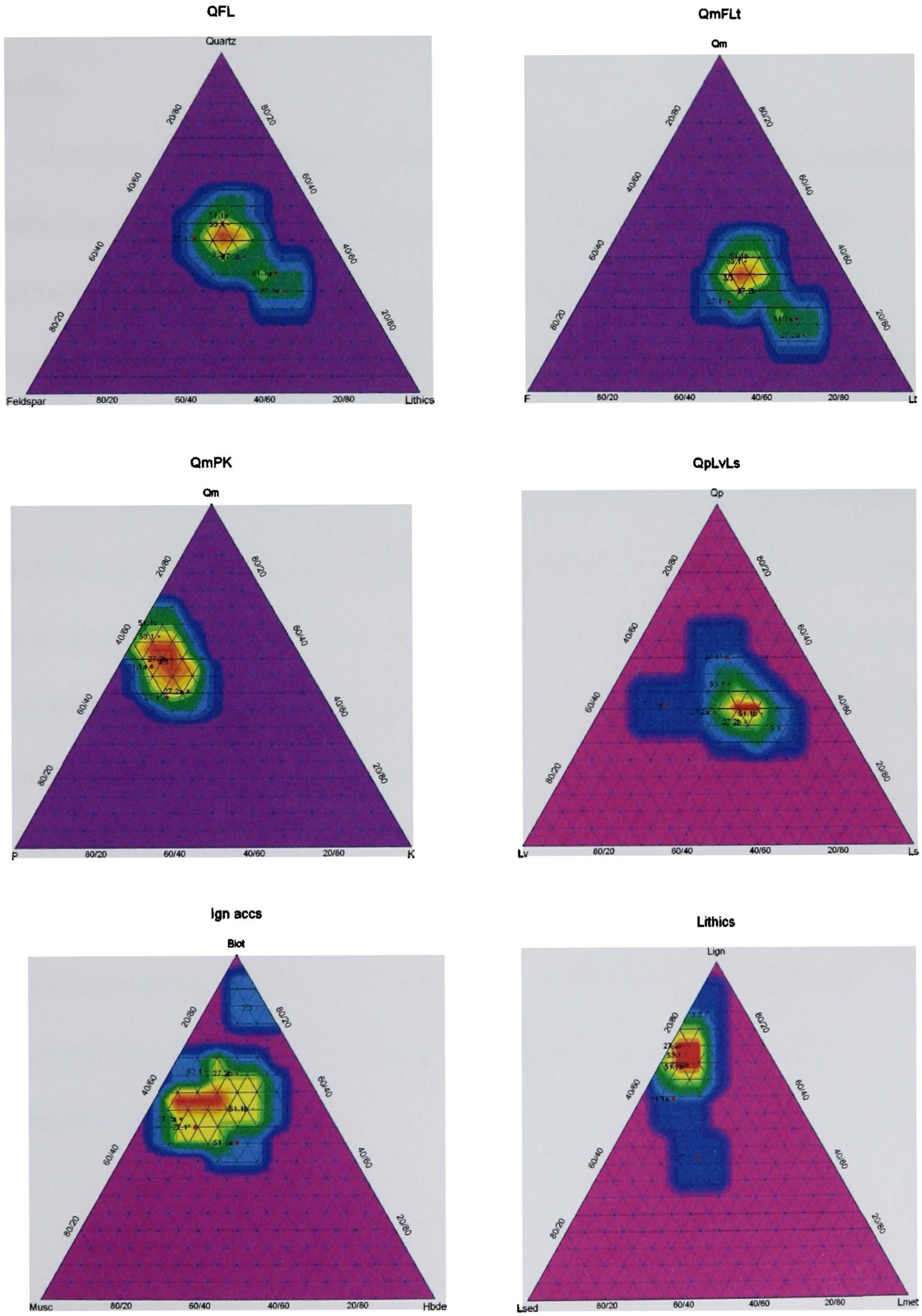



**Figure 31**: Ternary Diagrams of 7 sandstone samples from the Cabbage Patch beds. Sample grain size is portrayed by diameter of circle on ternary diagram.

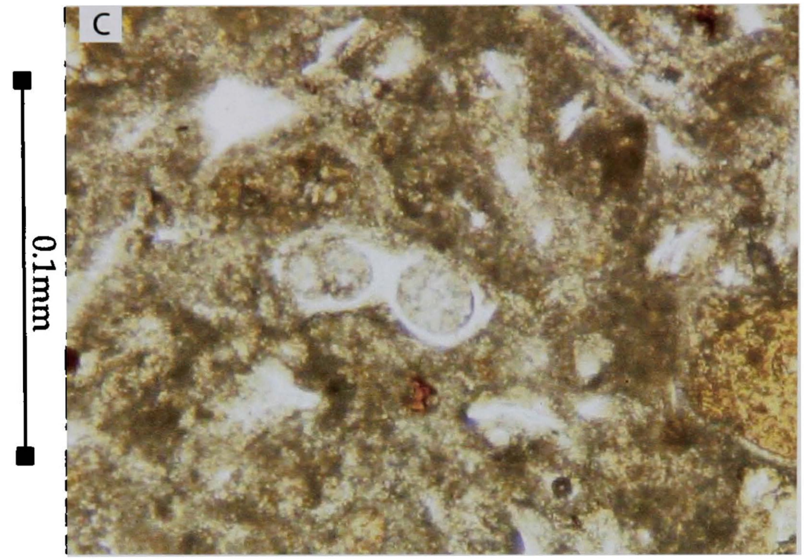


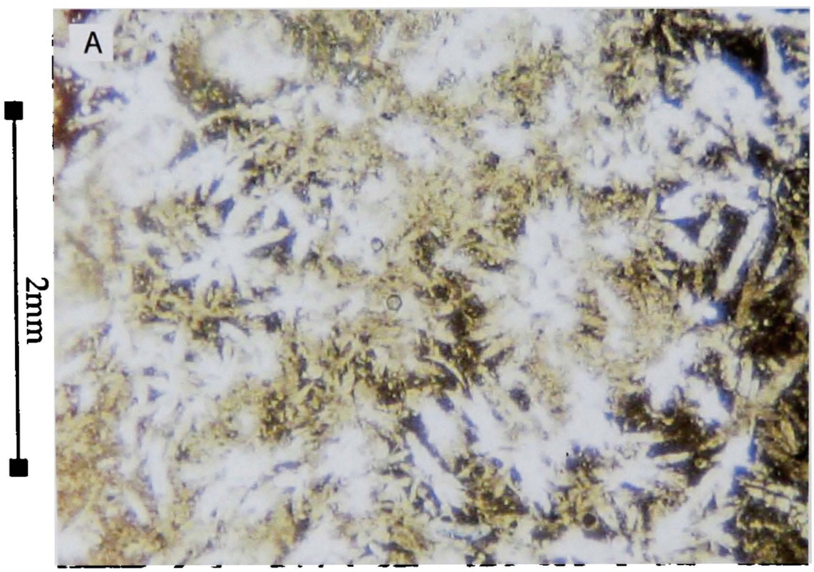
the most common accessory minerals. These minerals locally occur in high quantities. Biotite is most often altered to a chlorite group mineral compared to the very clean and euhedral muscovite. Sphene and zircon are common dense minerals.

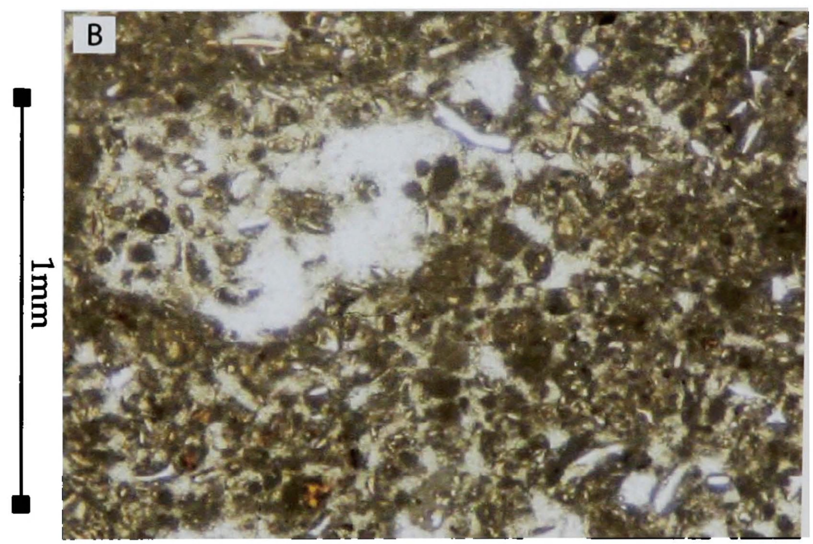
Conglomerate was a very minor component of Cabbage Patch exposures identified in this study. Monomict **Gm** facies were observed in DNGBG7 measured section proximal to the Dunkleberg fault. Clast lithologies are dominated by Cretaceous Dunkleberg member porcellanite that is exposed in the footwall of the Dunkleberg fault.

Carbonates from facies **Cm** are primarily micritic and contain molluscs, gastropods and ostracods (Figure 25a). Shell material is commonly composed of original aragonite. These units may be classified as bioclastic packestones after Folk (1962) and Dunham (1962). Sample III83.1 contains gastropods, algae, and root tubules (Figure 25a, b). This unit has 20%-50% sparry calcite that shows displacive growth (Figure 32a). A carbonate nodule from **Cc** facies exhibits a peloidal grainstone composition (sample - II19.1; Figure 32b). Micritic peloids are typically in a matrix of neospar to medium spar. This sample contains no macrofossils but does contain Charophyta, sponge spicules and possibly unidentified algae (Figure 32c).

**Figure 32:**
Carbonates sampled from the Cabbage Patch beds
A. III83.1 - Fossiliferous marlstone showing starlike displacive growth of secondary sparry calcite. Also see figure 25b.
B. II19.1 - Peloidal grainstone. Peloids are composed of micrite and set in a neospar matrix.
C. II19.1 - Charophyta fragment. Left pollup splitting into two pollups. Note scattered detrital clasts.



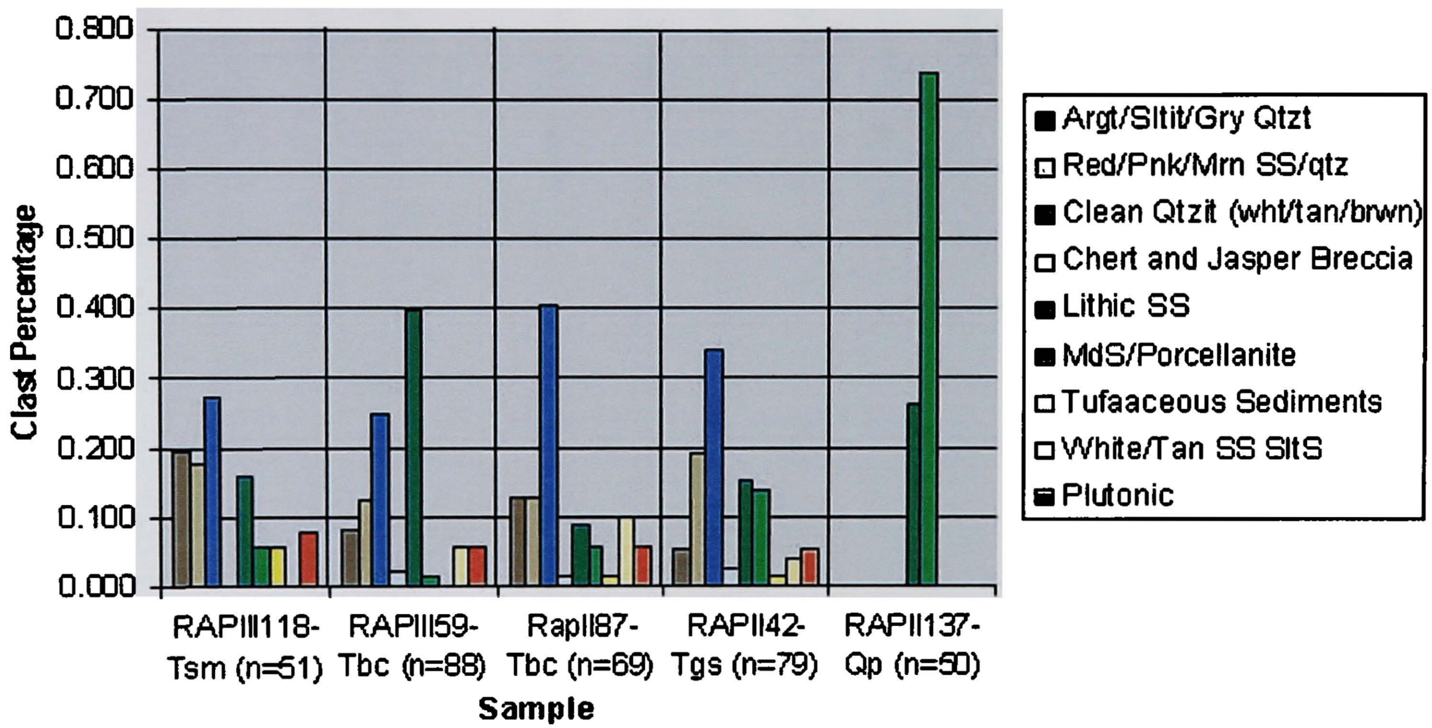
Sixmile Creek Formation

A tabular bed of imbricated polymictic **Gf** facies occurs along the mid-Miocene unconformity (Figure 14b). Boulders up to 0.8 meters across (longest axis) sit directly on the bed's sharp erosional basal contact. The base of the unit has poor framework support and contains the largest clast sizes. The largest boulders are tan quartzite and they tend to have numerous percussion marks (Figure 14c; Figure 33). Calcite cement is common throughout and sand matrix is very coarse, angular and poorly sorted.

Gravel facies of the Flint Creek beds are more common at higher stratigraphic levels. Monomictic **Gm** and **Sl** facies in the Flint Creek beds are dominated by very angular porcellanite clasts lithogically similar to porcellanite found in the Cretaceous Dunkleberg member. Clast sizes range from granule to pebble with the exception of a small boulder bed along Dunkleberg creek (Figure 22). An atypical exposure of **Gf** facies in the Flint Creek beds is present at the base of the BNC1a section. It is lithologically identical to gravel facies in the Barnes Creek beds (see below for description).

**Cc** facies of the Flint Creek beds are prolific and are a distinguishing feature of the unit (Figure15; Figure 29). Calcrete matrix lithologies are dominated by coarse spar and neospar. They contain abundant siltstone intraclasts, volcanic glass, fresh water sponge spicules and bioclasts. Small spherical grains of neospar with coarse spar void fillings are common throughout. They resemble root traces in thin section as described by Klappa

**Figure 33: Conglomerate clast counts samples collected above mid-Miocene unconformity**



(1980). Sample III63.8 contains numerous granule sized clasts of bedrock and intraclasts that are set in a neospar matrix (Figure 15b). Quartz sand, mica, chert and euhedral feldspar are common components of sample III63.8. These "clastic" calcretes are a diagnostic lithology of the Flint Creek beds.

Interstratified **Sb** and **Gf** facies of the polymict Barnes Creek beds are best recognized by a greenish hue common in many outcrops. Sandstone is generally more mature than underlying Cabbage Patch and Flint Creek beds. Mica is less common and the lithic component is considerably more subordinate. Most beds are poorly consolidated but some calcite cement is locally evident. Gravel is predominantly pebble- to cobble- sized, well sorted and well rounded. Average grain size increases toward the southern part of the basin. Quartzite is the dominant clast type (Figure 33). Rare plutonic clasts are commonly quartz monzonite and granodiorite in composition. Very few volcanic clasts were found.

Polymict **Gf** facies from the upper Sixmile Creek Formation (Tscgs in Figure 9) are lithologically similar to that found in the basal Sixmile Creek boulder bed (Tscfg in Figure 9). Clast types contain noticeably more tan, pink and maroon quartzite clasts than gravel in the stratigraphic equivalent Barnes Creek beds. The largest clasts in the basin are found in these beds; 60-70 cm sized clasts are not uncommon. Sand matrix is very coarse and angular. Monomictic **Gm** facies are more common toward the fringe of the basin and exhibited in measured sections of Douglas Creek. Approximately all clast types from the **Gm** facies (QTgrm on Plate 1) at the base of Douglas Mountain are tan quartzite and are lithologically similar to quartzite from the Pennsylvanian Quadrant Formation exposed on Douglas Mountain.

Quaternary Pediment

Very angular monomict **Gm** facies and loess unconformably overlie the upper Miocene Barnes Creek beds. Clast types are dominated by very angular clasts of the Cretaceous Dunkleberg member (Figure 33). Silt is the primary lithology of this unit and composes the gravel matrix.

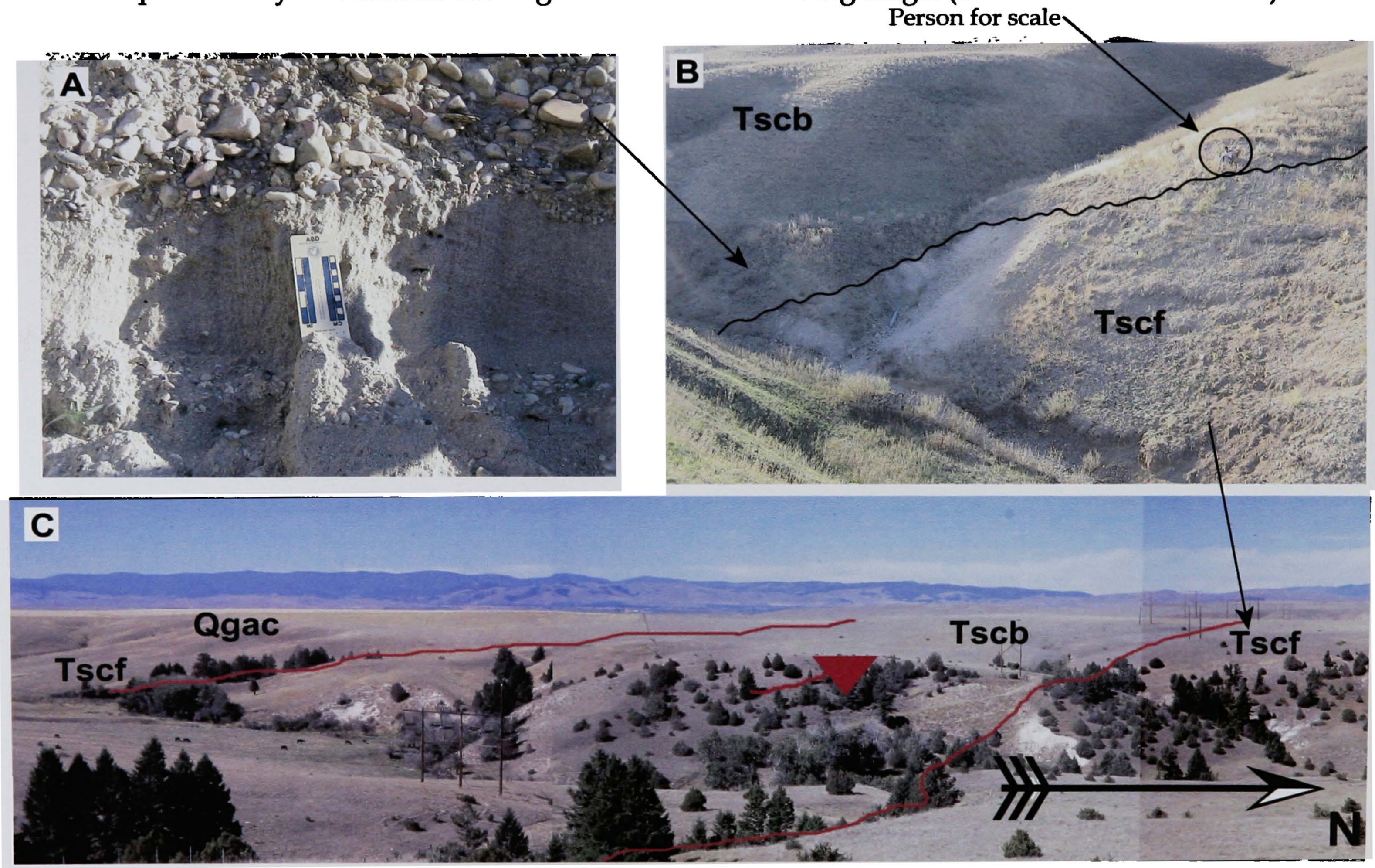
*Paleocurrent Indicators*

Paleocurrent indicators in the Cabbage Patch beds were measured from units in lower stratigraphic levels. Over 49 combined measurements from two outcrop localities in the Dunkleberg Creek drainage show a mean paleoflow direction of 303 and 319 degrees (sample II51.1 and III27.1 in Plate 1). This west to northwest directed paleoflow agrees with observations by Rasmussen (1977) of an eastward coarsening of Cabbage Patch conglomerate and sandstone beds into the adjacent Deer Lodge and Divide basins. Sparse paleocurrent indicators in strata west of Dunkleberg ridge also support a northwesterly flow. The ash bed identified at the base of the CBY2 has particularly well preserved ripple beds that also have a westerly orientation (Figure 21a, b).

Paleoflow inferred from clast imbrication of the basal Sixmile Creek Formation boulder bed (Tscfg - Figure 9) has a 91degree orientation (sample III117.1 in Plate 1). This easterly paleocurrent is in marked contrast to underlying and overlying strata. Paleocurrent indicators in the overlying Flint Creek beds are very sporadic and were taken from small discontinuous pebble units. They range from northerly in the southern part of the basin to westerly in the north part of the basin (Plate 1).

Well-preserved trough cross beds (**Sb** facies) and clast imbrication (**Gf** facies) in the Barnes Creek beds indicate a western paleoflow near the top of section CBY2 (Figure 34a). This orientation is parallel with an inferred channel margin cut into underlying strata of the Flint Creek beds (Figure 34b). Stratigraphically equivalent **Gf** facies (Tscgs) in the southern part of the basin contain imbricated clasts showing north to northeast transport direction (see arrow at mouth of Douglas Creek on Plate 1). Clast sizes of these units decrease to the north toward Barnes Creek bed facies.

**Figure34:** Barnes Creek paleovalley
a. Trough bedded sand and imbricated gravels of Tscb in CBY2
b. Basal erosion surface of horizontally bedded Tscb in CBY2. Tscf dips 9 degrees west
c. Inferred paleovalley orientation looking west from Dunkleberg ridge. (electric wires ~100ft tall)



## BASIN STRUCTURE

The largest exposed basin bounding normal fault is the east dipping Dunkleberg Fault, which was mapped along the eastern flank of Dunkleberg ridge and can be traced south into the Dunkleberg Creek drainage (Plate 1). Bedrock in the footwall of the fault is highly fractured and bedding can not be discerned. Possible fault plane travertine deposits have been reworked and redeposited in downstream Quaternary sediments. **Gm** facies of the Flint Creek beds have dips up to 50 degrees west into the fault. They are exposed in the hanging wall close to the inferred location of the fault. Balanced cross section C-C′ requires at least 300 (?) meters of throw on the Dunkleberg fault and associated imbricate splays (Plate 2).

On the west flank of Dunkleberg ridge, highly fractured and veined strata of the Dunkleberg member occur just west of Coberly Gulch and suggest the presence of a fault there. This is supported by the observed map pattern as well as gravity and seismic data collected by Stalker (2004). However, cross section C-C′ does not require a normal fault in the subsurface Cretaceous strata of Coberly Gulch (Plate 2).

High angle east dipping reverse faults in bedrock along the southern flank of the map area can be traced northward into the basin where they align with high angle east dipping normal faults (Plate 2 – cross section B). Large stratigraphic displacements of Tertiary strata are not observed. Correlation of the ripple bedded ash marker bed between CBYIa and CBYIb sections suggest approximately 30-50 meters of Cabbage Patch bed offset across the Coberly Gulch fault. Good exposure of the Barnes Creek fault in BNC2 demonstrates approximately 30 meters of displacement within strata of the Flint Creek beds (Figure 19).

Strata of the eastern Flint Creek basin dip to the west across the entire map area and toward easterly dipping normal faults. Dip of strata in the CBY section decreases up section from 11-16 degrees in Cabbage Patch strata, to 6-9 degrees in Flint Creek strata (Plate 1). Both of these units are overlain by the horizontal Barnes creek beds, which do not appear to be offset by the small normal faults mentioned above. Last movement on the small inter basin faults is constrained to be older than the late Miocene Barnes Creek beds and younger then the middle Miocene Flint Creek beds (>12 mya - Early Barstovian).

## DEPOSITIONAL ENVIRONMENTS

### *Eocene - Early Oligocene*

Carbonaceous pre-Cabbage Patch strata were referred to as Tertiary lacustrine beds in the driller's report of borehole Henderson-Lorensen well #2 (Appendix E). These beds are probable equivalents to carbonaceous sediments interbedded with the Eocene Garnet Range volcanic sequence (Carter, 1982). The presence of plant fossils, pelecypods, coal and lignite in these strata support a marshy lacustrine environment. This environment of deposition may have developed synchronous with hiatuses of Eocene volcanic activity in the western FCB. These strata are neither present at the surface nor in the subsurface in the eastern FCB, likely as a result of erosion or nondeposition.

### *Late Oligocene – Early Miocene*

Fluviatile, lacustrine and paludal environments of deposition were the main depositional settings for the tuffaceous sediments of the Cabbage Patch beds (Rasmussen, 1969, 1977, 1989). Aeolian derived volcanic ash fall beds are less common. Facies characteristic of these environments of deposition interfinger and change rapidly both laterally and vertically in measured sections.

A west- to northwest- flowing fluviatile system deposited arkosic **Sb** facies and correlative overbank deposits. Rasmussen (1977) showed that fluviatile overbank deposits make up 67% of the Cabbage Patch beds and that lacustrine facies are only apparent in upper strata. This abundance of overbank deposits attests to the aggradational nature of stream systems. Pedogenic modification occurred on exposed floodplains between aggradational events. A lack of good horizonation in paleosols suggests that they were poorly developed and represent a rapidly aggrading depositional setting (Kraus and Brown, 1986). A lack of gleyey color (gray and blue hue) and accumulation of ferric ($Fe^{3+}$) iron (red/orange root traces and mottles) suggest that soils were oxidized and well drained (Retallack, 2001a). The dominance of mud and silt, floodplain paleosols and a general lack of coarse conglomeratic detritus suggest that meandering stream systems were in operation. Trough cross beds and lesser amounts of planar cross beds evident in sandstone beds are indicative of lower flow regime fluvial processes.

Interstratified **Cm** facies, **Fb** facies, fissile shale (western FCB) and rare diatomite (unit 3 of measured section DNKB1) are representative of low energy lacustrine depositional environments. Mollusks collected from **Cm** facies are typical of fresh water lacustrine environments (Pierce and Rasmussen, 1992). Root tubules in a fossiliferous marlstone bed (unit 2 of measured section DNGWLIb), suggests water depth was shallow enough for plant colonization. Plant colonization could also have been from periodic exposure of carbonate mud flats, particularly along lake margins. This sub-aerial exposure would initiate pedogenic modification and be coincident with lowered lake levels. The presence of gypsum crystals observed in float of DNKB1 and bedded gypsum identified north of the field area by Rasmussen (1977), suggest lower lake levels and an evaporative basin of deposition.

Alonso-Zarza (2003) demonstrated that the gradual lateral lithologic change of lacustrine carbonate facies to pedogenic calcretes is dependent upon their proximity to the edge of a lake where oscillations in lake level are prevalent (Figure 35). Palustrine carbonates are defined as ephemeral carbonate lake margin facies (Freytet and Plaziat, 1982). The term is broadly equivalent to "paludal" or swampy and marshy (Platt, 1989). Rooted carbonate units and laterally equivalent calcareous nodule bearing paleosols such as those in the Dingwall section of the FCB share similarities with the palustrine depositional environment described by Alonso-Zarza (2003). Petrographically these palustrine carbonates show displacive growth by sparry calcite that appears to overprint the primary micritic mud (Figure 32a, ie. III17.2). This microtexture was not observed in the non-pedogenically altered **Cm** facies and is unique to the palustrine environment of deposition.

Ripley (1987) showed that at the boundary between fresh and alkaline water in Renova Formation depositional environments (lake margins?), dissolved silica could precipitate out of solution. This process formed the Tertiary porcellanites recognized in the Avon valley (known locally as the "Avon Valley Chert") northeast of the FCB (Ripley, 1987). Silicified wood and massive chert beds in the FCB laterally correlate across the width of an outcrop with identified north of the field area by Rasmussen (1977), suggest lower lake levels and an evaporative basin of deposition.

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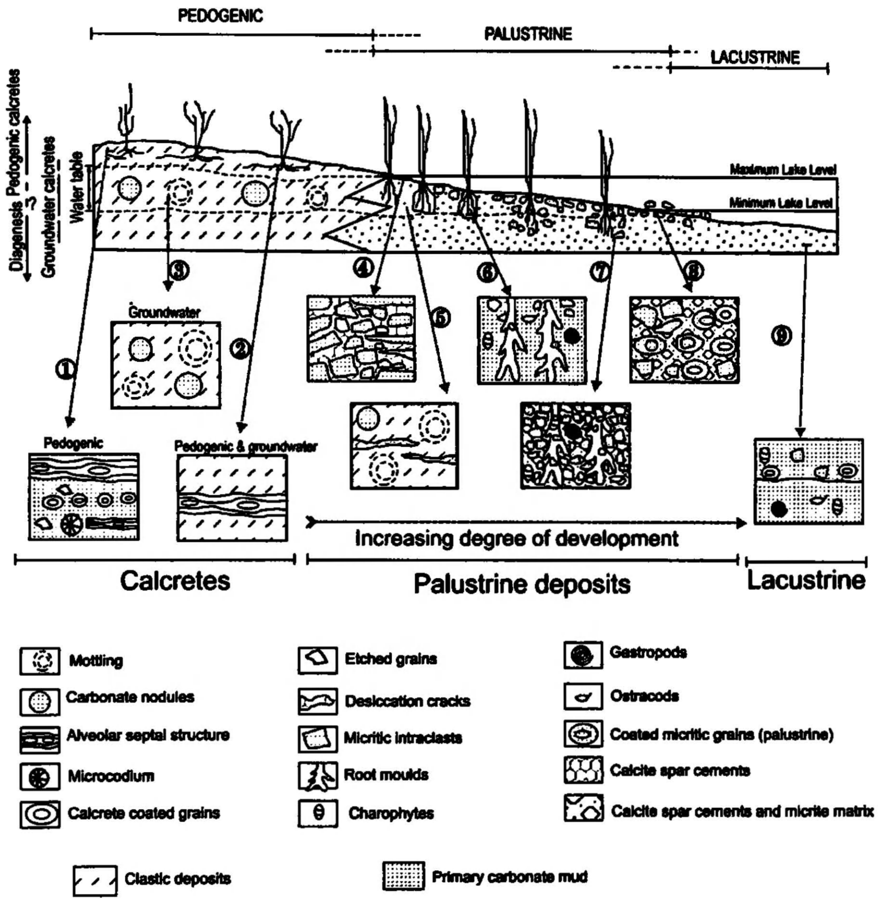


**Figure 35:** Schematic diagram of the lateral distribution of carbonate facies relative to a lake margin (taken from Alonso-Zarza, 2003).

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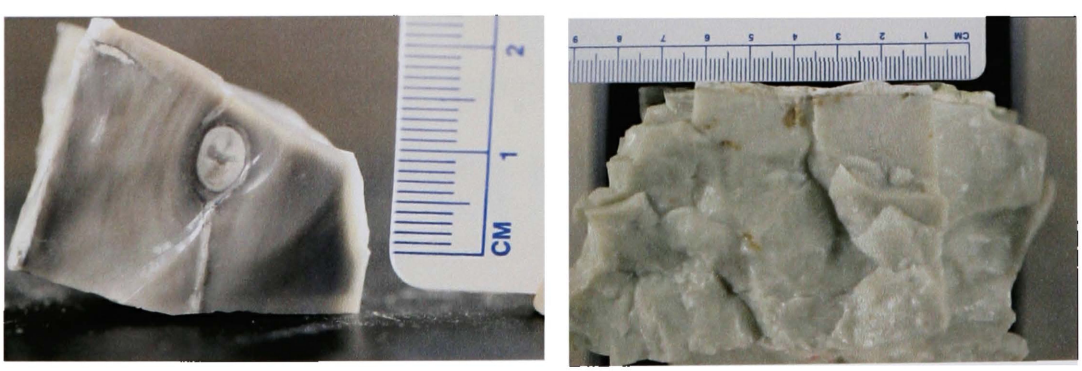
**Figure36:** SIlicified wood (left) and silicified mudstone (right) of the Cabbage Patch beds in DNKB sections.



fossiliferous mudstones. These localized beds probably formed along lake margins in a palustrine environment similar to that described by Ripley (1987) (Figure 36).

*Middle Miocene to Late Miocene*

Following a depositional hiatus and erosion during the later part of the Early Miocene, deposition in the FCB resumed with a pulse of very coarse boulder sized detritus (**Gf** facies) that flowed to the east. The boulder bed must have been deposited in an environment with enough energy to transport and round the durable quartzite boulders. The framework support, rounded clast texture, lack of mud, tabular geometry, percussion marks and well-developed imbrication of the unit suggest that high velocity fluid flow prevailed. Upper flow regime processes with a significant amount of reworking like that found in a sheet flood flow would provide the necessary energy to transport the large boulder detritus and form a laterally extensive bed. A mud-dominated debris flow deposit would have to be extensively reworked to produce such a mature lithology.

The thick succession of **Fm** facies that overlies the basal boulder bed (see CBY section) is lithologically similar to the floodplain deposits found in the basal Cabbage Patch beds. If these **Fm** facies represent overbank floodplain deposits their lateral channel complex equivalents are generally not exposed or not preserved. Alternatively, there may have been a lack of fluvial environments operating during deposition of the lower Flint Creek beds. The massive siltstones could have been deposited on a lake margin. Although evidence for a lacustrine environment does not exist in lower Sixmile strata of the FCB, McLeod (1987) and Sears and Ryan (2003) interpret a lacustrine environment of deposition in the adjacent Deerlodge basin.

A fluvial channel **Gf** facies was observed in the stratigraphically higher upper Flint Creek beds (unit 1 BNC1 and unit 5 BNC2). Adjacent to these gravels are **Fl** facies that are interstratified with **Fb** facies. This facies association is indicative of overbank levee and floodplain deposits laid down during flood stage of the fluvial system (DGC and BNC sections). Paleoflow indicators suggest flow toward the center of the basin and agree with intrabasinal composition of **Fl** facies.

Post depositional calcretes (**Cc** facies) commonly pervade many of the facies described above. Calcretes form in paleosols (pedogenic calcrete), within the vadose zone below the level of soil formation or at the capillary fringe zone below the water table (groundwater calcrete; Wright and Tucker, 1991). They are very common in alluvial and colluvial sequences where porous gravels serve as clast nucleation sites for calcium carbonate to precipitate on (Jimenez-Espinosa and Jimenez-Millan, 2003; Nash and Smith, 2003). Nodular calcretes that occur in sediments of the CBY and BNC sections resemble pedogenically- derived cornstones of the Middle Siwalik Group in India described by Tandon and Narayan (1981). Calcretes of the FCB and Siwalik group, both typically occur in fine-grained floodplain facies as bands of indurated fine-grained carbonate that exhibit floating detrital grains, displacive calcite growth and microspar. Coalesced carbonate nodules that form laterally continuous competent beds, such as those locally found in the Flint Creek beds, were observed by Gomez-Gras and Alonso-Zarza (2003) in discrete paleosol horizons of Spain. The lack of horizonation and sporadic distribution of the carbonate nodules in the Flint Creek beds suggest that paleosols are relatively immature. The apparently immature nature of paleosols makes the distinction between non-pedogenic and pedogenic calcretes difficult. Because calcretes of the Flint Creek beds occur in a floodplain environment, host rocks would have been frequently inundated during flood stage by rising groundwater tables. Fluctuation of a shallow water table in the floodplain would precipitate carbonate in the capillary fringe zone. Elongate calcrete nodules resemble molds of large vertical burrows (Figure 29b, c) that may have been created by Mylagaulid gophers (D. Rasmussen, pers. comm.., 2005). It is likely that both pedogenic and non-pedogenic carbonate replacement processes were acting on parent materials of the Flint Creek beds.

Polymict **Gf** and **Sb** facies of the Barnes Creek beds were deposited in a northwesterly flowing fluvial system that eroded underlying strata during an initial episode of degradation. Fluvial incision is demonstrated by a high angle basal erosion surface that cuts into Cretaceous strata east of Coberly Gulch and Flint Creek strata west of Coberly Gulch. This erosion was preceded by pedogenic modification of uppermost Flint Creek strata that is locally preserved below the erosion surface (unit 10 of CBYII). Once aggradational conditions were established, detritus was reworked and deposited in a westerly oriented paleovalley (Figure 34). **Fm** facies were deposited in an overbank environment during flood stage and subsequently pedogenically altered. The total percentage of mud and fine-grained detritus decreases to the south toward the apex of the basin. The predominance of coarse facies over fine facies and abundance of internal erosion surfaces suggest that braided fluvial systems were the dominant environment of deposition.

Polymict **Gf** facies in the southern part and flanks of the basin were deposited in a north flowing alluvial system. The coarse grain size, framework support, tabular geometry and general lack of mud typical of these facies suggest that they were deposited in braided fluvial and sheet flood environments. These observations imply that coarse **Gf** facies were deposited in a north dipping proximal to medial alluvial fan bajada complex that fed detritus to a west flowing axial Barnes Creek fluvial system. Northerly dip of the bajada surface can still be seen today in a dissected terrace evident in the southeast part of the basin. Matrix supported gravels that flank the basin and overlie the Barnes Creek beds represent debris flow deposits that blanketed the central basin facies. Similar facies relationships of the Sixmile Creek gravelly strata in southwest Montana were observed by Thomas et al. (1995), Sears et al. (1995) and Nielsen and Thomas (2004).

*Pleistocene to Holocene*

Quaternary time marked a period of loess deposition, reworking of intrabasinal detritus and accumulation of fluvial gravel. Pleistocene sediments were deposited on the flank of Glacial Lake Missoula (Figure 37). A debris flow carried granitic boulders from the mouth of Boulder Creek in the far southern part of Flint Creek Valley (near Maxville) up to at least the town of Hall ~20km north (Beatty, 1961). Rasmussen (1969) interpreted the Hoover Creek gravels as fluvial gravels of the ancestral Clark Fork River. The pronounced terraces seen today were formed during down-cutting by the ancestral and modern day Clark Fork River. Quaternary gravels are well exposed in some drainages and are primarily reworked Tertiary gravels.

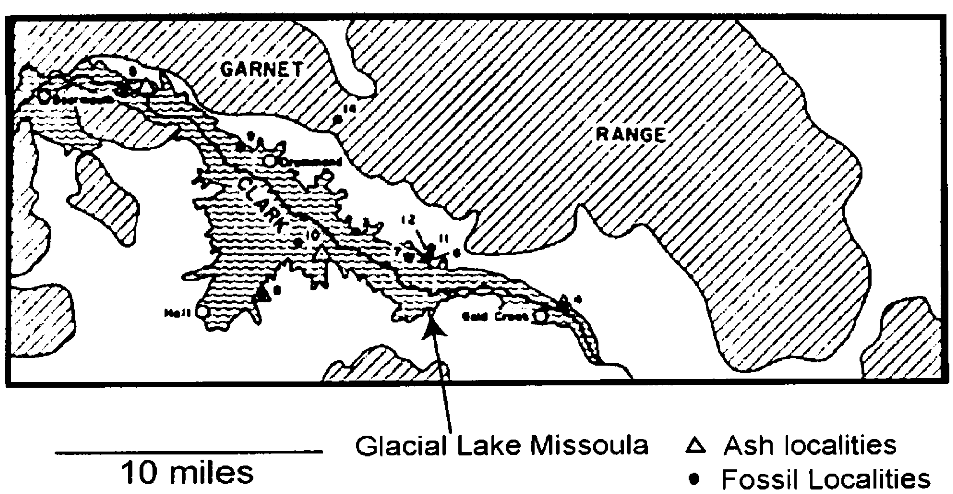



**Figure 37**: Eastern extent of glacial lake missoula in the vicinity of the FCB. Fossil control shown with dark dots.
(taken from Rasmussen, 1974)

## PALEOGEOGRAPHY AND PROVENANCE

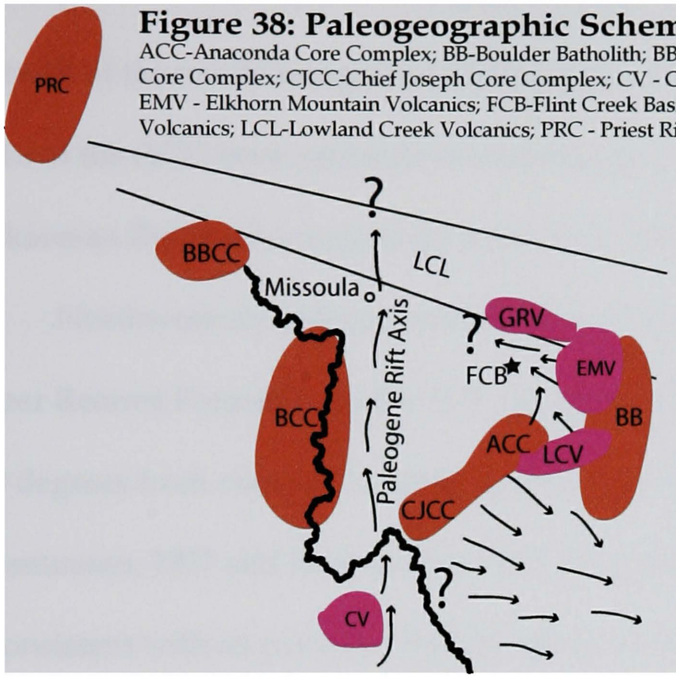
### *Pre-Renova Formation*

Sediments of the FCB were deposited on a paleoerosion surface created during Eocene time. Rasmussen (1977) showed that the ash flow tuff at the base of the Cabbage Patch beds was deposited in a paleovalley that ran southwest from a volcanic edifice in the Garnet Range. Nowhere does the ash flow tuff coexist with the basal red clay horizon observed elsewhere in the basin. Local **Gm** facies of the red clay horizon in the FCB are lithologically similar to red syntectonic conglomerates of the ACC hangingwall to the south (O'Neil pers. comm., 2004). Those facies may have been derived from unroofing of the ACC footwall.

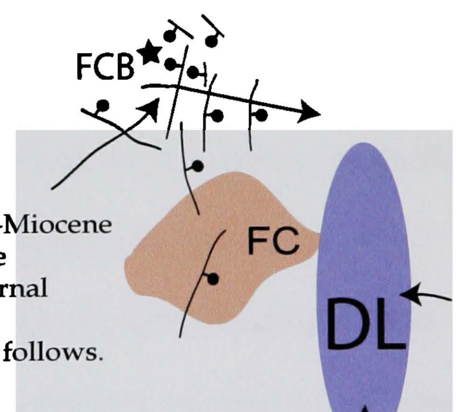
### *Renova Formation*

Cross-bedded fluviatile sandstone facies of the Arikareean (>27ma) Renova Formation in southwest Montana generally exhibit an east-directed paleoflow direction (Figure 38a; Thomas, 1995; Lofgren, 1985; Axelrod, 1984). Janecke (1994) suggested that fine detritus flowed east across the footwall shoulder of a Paleogene rift and into the Renova basin (Janecke, 1994). A two-mica granitic source for most Renova sandstone lithofacies is inferred from their arkosic composition and large flakes of both muscovite and biotite (see Thomas, 1995). Detrital zircon analysis of Arikareean aged (>27.7 Ma) 2-mica sandstones in the Grasshopper and Beaverhead basin (see Figure 4) contain 70 to 83 Ma

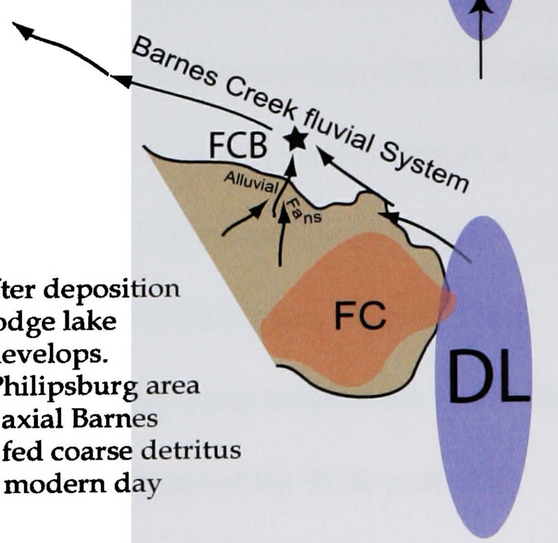
**Figure 38: Paleogeographic Schematic diagrams**
ACC-Anaconda Core Complex; BB-Boulder Batholith; BBCC-Boehls Butte Core Complex; BCC-Bitteroot Core Complex; CJCC-Chief Joseph Core Complex; CV - Challis Volcanics; DL - Deer Lodge lake; EMV - Elkhorn Mountain Volcanics; FCB-Flint Creek Basin; FC - Flint Creek range; GRV-Garnet Range Volcanics; LCL-Lowland Creek Volcanics; PRC - Priest River Core Complex.




a. Arikareean (~29.5ma - 20ma). Exhumation and unroofing of regional core complexes and volcanic edifice denudation, supplying 2-mica detritus souteastward into Renova basins of southwest Montana and northwestward into the Flint Creek and Deer Lodge basins




b. Hemingfordian-Early Barstovian (~17-13ma). Major uplift and normal faulting produce the mid-Miocene unconformity (17-15) ma. Onset of basin and range faulting in western Montana. Development of internal drainage, saline Deer Lodge lake basin (DL) and precipitation of Flint Creek (Tscf) calcretes shortly follows.




c. Late Barstovian (~13-6 ma). Fllowing a renewed period of faulting after deposition of the Flint Creek beds (Tscf) the Deer Lodge lake basin is filled and an external drainage develops. Large bajadas extended north from the Philipsburg area feeding coarse detritus to a NW flowing axial Barnes Creek fluvial system. Alluvial fans were fed coarse detritus from the upifting Flint Creek Range and modern day topography starts to develop.

grains (Link, et al. 2004). The two mica bearing Chief Joseph pluton in the footwall of the newly recognized Chief Joseph core complex and 2-mica footwall rocks of the ACC were probable sources for the granitic detritus of the Arikareean Renova Formation (Janecke et al., 2004; O'Niell et al., 2005).

Northwesterly paleocurrents for fluvial systems of the Arikareean aged upper Renova Formation in the FCB, Divide and Deer Lodge basins are nearly 180 degrees from correlative strata in southwest Montana mentioned above (Rasmussen, 1977 and Hanneman, 1989). West flowing fluvial systems are inconsistent with an easterly tilted rift shoulder model proposed by Janecke (1994) (Figure: 38a). Rasmussen (1977, p. 88) suggested that the Boulder batholith was a principal source for the arkosic composition of Cabbage Patch sandstones. Muscovite evident in Cabbage Patch sandstones likely was not derived from the muscovite-free Boulder batholith, however. In contrast, 2-mica granite of the Mount Powell batholith in the Flint Creek Range and possibly the Hearst Lake stock of the Anaconda Range, both to the south of the FCB, may have been other primary sources for granitic detritus in the FCB. Rapid unroofing of these 2-mica granites during exhumation of the Anaconda core complex would supply a granitic point source for northwesterly flowing streams into the FCB and southeasterly flowing streams to basins of southwest Montana (Figure: 38a). Foliated grains may have been derived from the mylonite zone of the ACC. The Elkhorn and Lowland Creek volcanics, both southeast of the FCB, probably covered much more of the Boulder batholith during Arikareean time and supplied the FCB with the abundant volcanic detritus observed in the 2-mica bearing sandstones. Unroofing of a thick wedge of folded and thrusted Proterozoic-Mesozoic rocks in ACC upper plate rocks of the Flint Creek Range supplied the FCB with sedimentary lithics. This provenance is reflected by sand compositions plotting between the magmatic arc and recycled orogen fields of Dickinson and Suscek (1979) (Figure 31).

### *Sixmile Creek Formation*

A significant change in sediment dispersal systems followed the mid-Miocene depositional hiatus and is represented by an increase in clast size, a decrease in granitic detritus, more quartzose sandstone compositions, and a change in depositional dip direction. Debris flows shed from a newly uplifted source to the west brought large metasedimentary clasts into the basin and deposited them on the mid-Miocene erosion surface. Depositional dip during this time was to the east toward the ancestral Deer Lodge lake basin (Figure 38b). Intrabasinal detritus filled the FCB and tuffaceous Cabbage Patch strata were reworked during deposition of the Flint Creek beds. A renewed period of uplift and faulting during Barstovian time deformed the Flint Creek beds and created an erosional surface upon which a westerly through flowing "Barnes Creek " fluvial system was established. Belt supergroup metasedimentary rocks are widespread to south and west of the FCB and would have shed detritus north and east via large alluvial fan complexes into the axial Barnes Creek fluvial system (Figure 38c).

Block faulting and uplift during mid-Miocene time introduced a considerable quantity of Belt Supergroup, Pennsylvanian Quadrant quartzite and Cretaceous aged detritus into the basin. Mature tan quartzite is a significant component of Sixmile Creek gravels and very large boulders were likely derived from nearby faulted folds of the Pennsylvanian Quadrant quartzite. The lack of Paleozoic limestone and dolomite detritus may be due to conditions that favored dissolution rather than physical transport. Dissolution of calcium carbonate may have precipitated into floodplain calcretes of the Flint Creek beds and locally cemented gravels and sands of the Sixmile Creek Formation. Lithic rich sandstone clasts were derived from Cretaceous sedimentary rocks, which make up the majority of the northern flank of the Flint creek range and hanging wall rocks of the ACC. Porcellanite from the Dunkleberg member of the Blackleaf Formation was a major contributor for intrabasinal detritus that is common in the Flint Creek beds and Quaternary pediment gravels.

## PALEOCLIMATE

### *Early-Middle Paleogene*

Soil clay mineralogy correlates with precipitation amounts and may be used to infer relative wet and dry environments for kaolinitic and smectitic clays respectively (Keller, 1965; Barshad, 1966). Red kaolinitic clays of the basal **Gm** facies (Tml on Plate 1) in the FCB have been observed in basins of southwest Montana where they represent early Paleogene lateritic weathering and development of oxisols during a wet tropical environment (Thompson et al., 1982). Iron rich claystone breccias referred to as detrital laterites are interbedded with kaolinitic ultisols and oxisols of late Eocene strata in Oregon (Bestland, 1996). The hematite rich claystone breccia and overlying kaolinitic oxisol along the K-T boundary in the FCB shares lithologic and mineralogic characteristics with the Oregon laterites. Both are indicative of the warm wet climate in which they were deposited. Correlative early Paleocene paleosols in eastern Montana are representative of waterlogged forest soils that formed in a humid climate with >1200 mm of annual rainfall (Fastovsky and McSweeney, 1987; Retallack, 1994).

### *Middle Paleogene - Early Miocene*

Accumulation of carbonate or alkaline earth minerals in paleosol profiles has been shown to be diagnostic of semiarid to arid climatic regimes (Wright and Tucker, 1991; Retallack, 2001a). Vertebrate faunal assemblages, calcic paleosols and clay mineralogies of basins in southwest Montana are indicative of a semiarid to arid paleoclimate (Thompson, et al. 1982; Fields, et al.; 1985, Ripley, 1987; Hanneman, 1989). A gradual shift from a humid and warm temperate Late Eocene climate to a dry semiarid Oligocene climate occurred during deposition of the Renova Formation and correlative sediments in South Dakota and Oregon (Retallack, 1983; Prothero, 1994; Retallack et al., 2004). A late Eocene (Chadronian NALMA) flora from the Douglas Creek basin just to the north of the FCB is characteristic of a cool temperate semi-humid paleoclimate and represents the climatic regime before deposition of the Cabbage Patch beds (Person, 1972). Rasmussen (1977) suggested that the Cabbage Patch beds were deposited in a subhumid environment based on *Sequoia* species (Appendix F). Good specimens of plant fossils in the FCB were not recovered in this study.

Smectitic clays and calcic paleosols common in the Cabbage Patch beds are more characteristic of a dry rather than humid environment of deposition. Preservation of caliche nodules less than 1 meter from the top of a soil is indicative of an aridisol and ~ <750 mm annual precipitation (Retallack, 1993). DNKB7 exhibits caliche nodules approximately 1 - 4 meters down from the inferred top of a paleosol. Paleosols in the DNKB section may be classified as calcic vertisols or calcisols, which are both indicative of a semi arid environment. The abundance of ferric Iron (warm colors) and absence of gley (dark colors) is characteristic of well-drained oxidized soils that would be expected in dryer conditions.

### *Later Early Miocene Unconformity*

A red kaolinitic horizon below the mid-Miocene unconformity is observed in basins of southwest Montana and correlates with warmer temperatures during a brief period in the later part of the Early Miocene (Thompson, et al., 1982). Laterite soils are also preserved in mid Miocene sedimentary interbeds of the 16.1-15 Ma Columbia River basalts (Smith and Gaylord, 2003). Thompson et al. (1982) suggested that this reflects a warm wet period that would have created a through flowing drainage that removed basin fill (erosion), and created the mid-Miocene unconformity. Fossil plant cuticle evidence and paleosols also are indicative of an unusual warm and wet period for western North America between 16 and 15 Ma (late Hemingfordian - early Barstovian) (Retallack, 2001b; Retallack, 2002).

Although lateritic paleosols have been observed below the "mid-Miocene" unconformity in west Montana, elsewhere, an apparent absence of kaolinite group mineral and lack of a red lateritic horizon is observed at this stratigraphic level (McLeod, 1987; Hanneman, 1989). Neither, a kaolinite group mineral or a red lateritic horizon is observed below the "mid-Miocene unconformity of the FCB. The non-uniform occurrence of lateritic soil development at a regional scale may be the product of paleotopographic variation (Bestland et al. 1996), poor exposure or non preservation.

The occurrence of barite (barium sulphate) nodules in paleosols below the mid-Miocene unconformity in the FCB has not been documented in Tertiary basins of western Montana and Idaho. Barite has been shown to occur below prominent discontinuities from pauses in sedimentation in marly sequences of France (Breheret and Brumsack, 2000). Barite has a very low solubility and occurs as microscopic euhedral lathes in hydromorphic soils associated with saline groundwater (Lynn et al., 1971; Stoops and Zavaleta, 1978; Darmody et al., 1989; McCarthy and Plint, 2003). Barite in the FCB may have formed authigenically from saline groundwater that extended up depositional dip from a saline lake environment in the adjacent Deer Lodge basin (Figure 38b).

*Middle Miocene – Late Miocene*

Calcretes prevalent throughout the Flint Creek beds and smectitic clay mineralogy of floodplain paleosols are suggestive of a semi-arid environment of deposition during Barstovian time (Wright and Tucker, 1991; Thompson et al. 1982). Geomyoid rodent vertebrate fossils in the Flint Creek beds are strongly indicative of a semiarid environment that was dryer than Arikareean time (Barnosky and Labar, 1989). *Waldemaria* and *Hendersonia* gastropods collected from the Flint Creek beds are indicative of cooler temperatures and more seasonality compared to invertebrate faunas from the Eocene-Oligocene of western North America (Pierce and Rasmussen, 1989). This cooling trend agrees with an increase in $\delta^{18}O$ levels (Figure 39).

Using clay mineralogy evidence cited above, the appearance of notable kaolinite clays in floodplain paleosols of the Barnes Creek beds would suggest a wetter climate than postulated for underlying Flint Creek beds paleosols. More likely, the kaolinite was eroded from the basal Tertiary laterite horizon (Tml on Plate 1). Rare caliche nodules do occur in Barnes Creek paleosols and would be more indicative of dryer conditions. Dryer soil conditions are supported by an absence gley and abundance of smectite clay. Vertebrate fossils, specifically *Geomyids* rodents, are similar to those found in the Flint Creek beds and comply with a semi-arid environment of deposition.

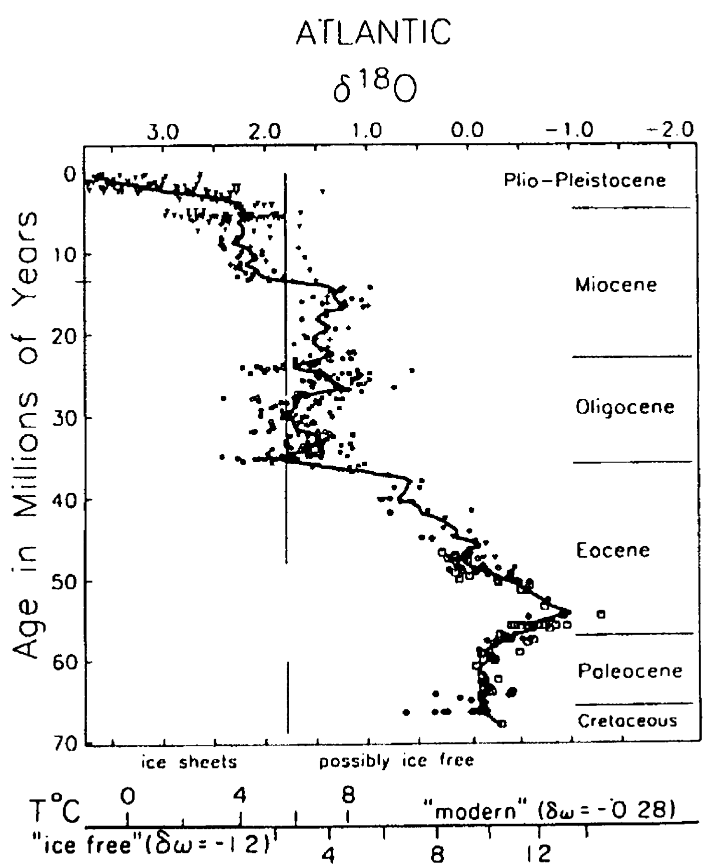



**Figure 39:** Oxygen isotope history for the Cenozoic. Dramatic cooling trend after the middle Miocene (taken from Prothero, 1994)

## REGIONAL STRATIGRAPHIC CORRELATION

### *Lithostratigraphy*

Many workers have used the Bozeman Group lithostratigraphic division of a coarser Sixmile Creek Formation erosionally overlying a finer grained Renova Formation (Dorr and Wheeler, 1948; Robinson, 1960; Kuenzi and Fields, 1971; Monroe, 1981; Fields et al., 1985; McLeod, 1987). This lithostratigraphic relationship has not been reported in adjacent basins in west-central Montana (Dunlap, 1982; Axelrod, 1984; Lofgren, 1985; Runkel, 1986; Hanneman and Wideman, 1991; Matoush, 2002). Hanneman and Wideman (1991) proposed that the mid-Miocene unconformity is smaller or absent in non-exposed central facies of the Jefferson, Beaverhead, Melrose and Divide basins. This may be a function of facies changes toward a finer lower Sixmile Creek Formation in the centers of the basins or a result of non-preservation along basin margins.

In the northern FCB Arikareean aged (Cabbage Patch beds) siltstone facies are overlain by lithologically similar Barstovian aged siltstone facies (Flint Creek beds) (Rasmussen, 1969). In the absence of the "mid-Miocene" unconformity boulder bed identified in this study, **Fb**, **Fm** and **Cm** facies of the upper Renova Formation underlie **Fm**, **Cc**, and **Fb** facies of the lower Sixmile Creek Formation. Runkel (1986) also did not observe an obvious lithologic break across the "mid-Miocene" unconformity in the Smith River basin to the east (basin 14 in Figure 4). This facies association of fine-grained Renova Formation strata overlain by fine-grained Sixmile Creek strata does not lend itself well to the Bozeman Group lithostratigraphic division described above. Despite this discrepancy, an upsection increase in the percentage of conglomerate within the Sixmile creek Formation, described by Kuenzi and Fields (1971), is evident in the FCB and is demonstrated by measured sections CBY2, BNC1 and BNC2.

*Sequence Stratigraphy*

Applying the sequence stratigraphic model proposed by Hanneman (1989) is difficult in the eastern FCB, because of the absence of exposed lower Renova Formation strata (sequence 2) and subdivision of the Sixmile Creek Formation (sequence 4) into 2 unconformity bounded units (Flint Creek and Barnes Creek beds respectively). Nevertheless, Rasmussen's (1969, 1977, and 2003) biostratigraphy defines the depositional sequences of the FCB and provides a framework for their correlation with Hanneman et al.'s (2003) sequences. Hanneman and Wideman (1991) proposed that a global fall of relative sea level during middle Oligocene time (~30Ma,) was responsible for formation of an extensive unconformity in the middle Renova Formation (sequence 2/3) that can be correlated throughout the Northern Rockies. Strata of the FCB do not consist of predictable repetitions of facies, lack laterally extensive genetic marker surfaces (i.e. flooding surfaces) and can not be directly tied to a correlative marine sequence. This nongenetic distribution of laterally discontinuous facies restricts their stratigraphic correlation with adjacent basins to large scale unconformities and regionally extensive tephra beds.

## BASIN FORMATION AND TECTONIC EVOLUTION

Gravity and seismic data supports a possible 600m of displacement on a set of west and south dipping normal faults buried in the center of the basin that initiated sometime during the Paleogene (Stalker and Sheriff, 2004; Stalker, 2004). Stalker (2004) suggested that these faults were the primary basin forming faults that were subsequently eroded and covered by Neogene strata. Movement of the down to the west basin bounding fault identified by Stalker (2004) may have preserved accommodation space for early Paleogene strata on the west side of the basin and subsequent erosion would explain the lack of correlative strata on the east side of the basin (Figure 40). Both the FCB and adjacent Missoula basin have trapdoor basin geometries with a down to the west normal fault on the east side and right-lateral fault component on the northern side. The northern faults in both basins are in structural line with the Lewis and Clark line (LCL; Evans, 1997; Stalker, 2004).

Initiation of extension in the FCB began in Eocene time with the extrusion of the Garnet Range volcanic sequence and exhumation of the ACC to the south (O'Neil et al., 2004). This time was also marked by dextral transtension on the LCL and exhumation of core complexes in the Northern Cordillera (O'Neill and Pavlis, 1988; Doughty and Sheriff, 1992; Foster and Fanning, 1997; Doughty, 2002; Doughty and Price, 2000; House et al., 2002; Foster, 2003; Sha, 2003; Vanderhaeghe et al., 2003). Transtension along the Lewis and Clark strike slip system is linked to extension of the Anaconda, Bitterroot, Priest River and Boehls

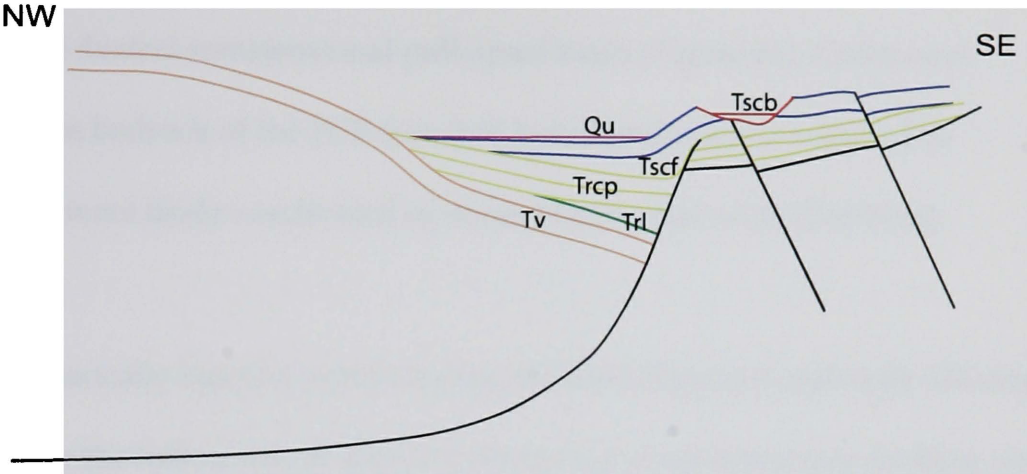



**Figure 40:** Hypothesized cross section of the Flint Creek basin.
Note angular relationships increase down section. Basinward dip on both sides of the basin require folding of strata over buried normal fault.
Tv - Eocene volcanics, Trl - Lower Renova Formation (not exposed),
Trcp - Cabbage Patch beds (Upper Renova Formation)
Tscf - Flint Creek beds of the Six Mile Creek Formation
Tscb - Barnes Creek beds of the Six Mile creek Formation
Qu - Quaternary sediments, undifferentiated

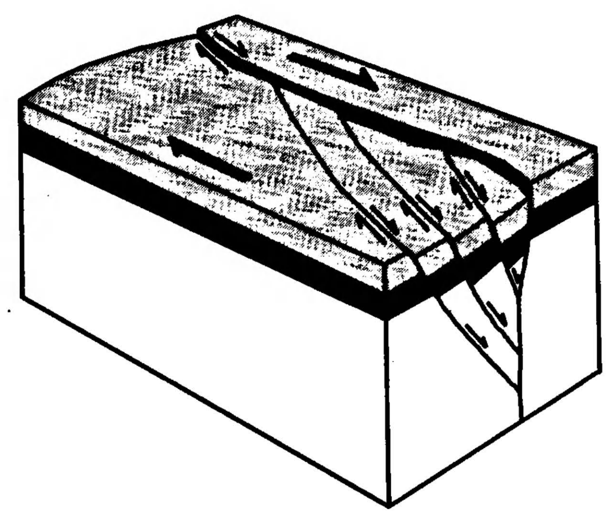


**Figure 41**: Schematic diagram of a dextral transtensional pull apart basin

Butte core complexes that abut the lineament (Foster, 2003). The FCB can thus be classified as a dextral transtensional pull-apart basin (Figure 41). Cretaceous thrust faults in bedrock of the FCB (see drill hole Henderson-Lorensen 2 in Appendix E) were likely reactivated as normal faults that controlled basin subsidence.

A tectonically inactive period during the late Oligocene and early Miocene is reflected by the lack of coarse detritus, absence of synsedimentary faulting and a ~1meter/1 thousand year deposition rate for the Cabbage Patch sedimentary sequence (using data from Rasmussen, 2003). Accommodation space for the Cabbage Patch beds was created by uninterrupted slow subsidence. A period of uplift and faulting during the mid-Miocene removed a significant portion of the Cabbage Path beds and reduced their original area of deposition to the present day extent of the FCB (Rasmussen, 1969).

Uplift and faulting during mid-Miocene time (~17-15 Ma) is widespread across the western Cordillera and marked by a shift from calc-alkalic to bimodal volcanism, extension in the Rio-Grande Rift, rapid slip on central basin and range faults, extrusion of the Columbia River flood basalts, initiation of the Yellowstone hotspot, and formation of an unconformity in western Montana (Fields et al. 1985; Pierce and Morgan, 1992; Miller, et al., 1999; Hooper et al., 2002; Miggins et al., 2002; Perkins and Nash, 2002). An angular relationship along the mid-Miocene unconformity in the FCB and other basins of western Montana suggest that the hiatus is a consequence of a tectonic pulse (Fritz and

Sears, 1993) and is coincident with a mid-Miocene thermal optimum (Thompson et al., 1982). A reworked boulder debris flow along the mid-Miocene unconformity marks the first flux of coarse clastics into the basin and represents such a tectonic pulse. This time marked the formation of the Deer Lodge lake basin. Uplift and erosion of bedrock strata in the surrounding Flint Creek, Sapphire and Garnet Ranges produced the coarse clastics that filled the FCB during later Miocene time (upper Sixmile Creek Formation). The present day geometry of the basin was beginning to take shape during this time.

Strata in the eastern FCB dip at lesser angles moving upsection. Bounding angular unconformities represent two periods of uplift and faulting during the mid-Miocene (Cabbage Patch/Flint Creek) and late-Miocene (Flint Creek/Barnes Creek). These observations are characteristic of growth strata over a long time span and elucidate renewed movement on a west dipping fault (identified by Stalker, 2004). Younger strata would be folded over the fault tip and older strata would be offset at depth in the central part of the basin (Figure 40). This interpretation agrees with eastern dipping (into the fault) Arikareean strata on the west side of the basin.

## CONCLUSIONS

Right-lateral transtensional stress along the Lewis and Clark line and relaxation of Cretaceous thrust faults were the main subsidence mechanisms for initial opening of the Flint Creek basin during middle Eocene time. This was concomitant with extrusion of the Garnet Range volcanic sequence and deposition of lacustrine sediments. Soils developed during this time were kaolinitic laterites and suggest a warm/wet paleoclimate.

Following the eruption of an ash flow tuff at 29.2 Ma, the upper Renova Formation (Cabbage Patch beds) was deposited in alluvial, lacustrine and palustrine depositional environments during a tectonically quiescent period. Facies associations suggest that perennial and ephemeral shallow alkaline- to fresh- water lakes existed between floodplains of meandering fresh water stream systems. Late Oligocene age arkosic sandstones with northwesterly paleocurrents have a 2-mica granitic source that likely was the Mount Powell batholith in the footwall of the Anaconda Metamorphic core complex to the south. Rapid exhumation of the core complex shed detritus in opposing directions to the northwest (FCB) and southeast (southwest MT). This westerly paleoflow direction in the FCB does not fit the rift shoulder model proposed by Janecke (1991) for the Renova Formation of southwest Montana.

The mid-Miocene angular unconformity (18-15ma) resulted from regional tectonic uplift and erosion. It is coincident with a warm wet thermal spike and may be related to initiation of the Yellowstone hotspot and extrusion of the

Columbia River basalts. Previously undocumented barite nodules were recovered from pedogenic clay horizons below the mid-Miocene unconformity. These nodules could have formed in a paleosol that formed up depositional dip from a saline Deer Lodge lake basin.

An imbricated boulder bed just above the unconformity at the base of the lower Sixmile Creek Formation (Flint Creek beds) indicates an easterly paleoflow toward the Deer Lodge lake basin. Calcrete facies that pervade alluvial siltstones and pebble sandstones of the Flint Creek beds may have been a result of oscillations in the paleowater table. The last evidence of faulting in the basin was prior to deposition of the upper Sixmile Creek Formation (Barnes Creek beds). These faults appear to be reactivated Cretaceous aged compressional structures. A paleovalley incised into Cretaceous bedrock and the Flint Creek beds accommodated a northwest flowing axial fluvial system. Large north dipping alluvial fans transported detritus from the uplifting Flint Creek and Sapphire ranges into the Barnes Creek fluvial system. Occurrence of calcrete, vertebrate fossil assemblages and clay mineralogy support a transition to a dryer and cooler Miocene climate.

The currently used lithostratigraphic subdivision of a dominantly fine-grained Renova Formation overlain by a dominantly coarse- grained Six Mile Creek Formation (with coarsening upward trend) may be applied to FCB Tertiary deposits, but should not be used in units immediately adjacent to the mid-Miocene unconformity. Genetic sequence stratigraphy is not advised in these deposits due to rapid lateral facies changes, local tectonic effects and lack of key regional marker beds. Tephra geochronology is beginning to allow correlation of finer subdivisions than the biostratigraphic subdivisions already set forth.

## FUTURE WORK

I recommend the following possibilities for future work that would build on the results presented in my thesis:

-Distribution and paleocurrent of 2-mica arkosic bedded sandstone facies of Arikareean age in basins north and west of the modern day continental divide; specifically in the Douglas and Blackfoot basins north of the FCB.

-Tephra geochronology and correlation of Bozeman Group strata between intermontane basins of Montana and Idaho (Hanneman and Wideman, 2004).

-Distribution of Barstovian aged calcretes (Flint Creek beds) in the northern Deer Lodge basin. Isotope analysis of calcretes would provide paleoclimate inferences.

-Bio- and litho- stratigraphic correlation of an upper Miocene unconformity within the Sixmile Creek Formation of Montana.

-Detailed gravity investigation of the major Flint Creek basin forming structure. Decipher the geometry of a west dipping reactivated thrust fault?

-Determine the duration of the mid-Miocene unconformity depositional hiatus in southwest Montana and whether it decreases north away from the initial outbreak position of the Yellowstone hotspot toward the FCB.

- Create a geologic map of the western side of the Flint Creek basin. Update the Belt Stratigraphic subdivisions on Maxwell's (1965) map and differentiate Cenozoic units using biostratigraphy.

-Genesis of the westward verging structures on the northern flank of the Flint Creek Range. Are they part of a Triangle zone?

-Determine the genesis and validity of the middle Renova Formation unconformity of Hanneman and Wideman, 2003.

-Perform a detailed paleopedologic study of Bozeman Group paleosols.

-Distribution, provenance and environment of deposition for basal Tertiary conglomerates and kaolinitic claystones flanking the Flint Creek Range (Anaconda beds of O'niell, 2004).

-Paleogeographic relationship between the Bitteroot, Missoula and Flathead basins with basins to the east and along the Lewis and Clark line.

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## APPENDIX-A

*Eastern FCB bedrock map unit descriptions*

**Cretaceous**

Ki **Intrusive, alkalic (~65 Ma, Sears and others (2000))**
Alkalic igneous sill (shonkinite) that is highly weathered to a medium grus. Commonly found along the Blackleaf-Coberly Formation contact and folded along parallel sedimentary bedding planes.

--Intrusive--

Kgs **Golden Spike Formation (Campanian-Maastrichian)**
Cobble to pebble conglomerate, matrix-supported, well-rounded and interbedded with sandstone. Clast composition dominated by chert. Sharp erosive basal contact. Locally well-exposed on north slope of Dunkleberg ridge. Regionally 5,000-8,000 feet thick (Gwinn, 1965); 10 feet exposed in field area.

--Unconformity--

Kcc **Carter Creek Formation (Coniacian-Santonian)**
Primarily sandstone, green siltstone, and mudstone. Sandstone beds have trough cross-sets, lateral accretionary surfaces and a continental-volcanic sedimentary source (Waddell, 1992). Volcanic clasts occur in local interstratified conglomerates. Regionally 4,500-6,000 ft thick (Gwinn, 1965).

Kj **Jens Formation (Turonian-Coniacian)**
Drab colored shales with minor siltstone and fine-grained sandstone with well-developed sandstone. Varicolored red/purple mudstone and siltstone in middle portion of unit. 1,000-1,500 feet thick (Gwinn, 1965).

Kc **Coberly Formation (Cenomanian-Turonian)**
Variegated green-brown mudstone and siltstone, local shaly lignite, fine-grained sandstone, and fossiliferous limestone. Limestone beds dark gray-brown with abundant large

gastropods, pelcypods, and oyster coquinas. Approximately 600 feet thick (Gwinn, 1965).

--Unconformity--

**Blackleaf Formation**

**Kbld** **Dunkleberg Member (Cenomanian)**
Salt and pepper colored, medium- to coarse-grained sandstone, light-green to dark greenish-brown, porcellanite and variegated red to purple mudstone in the uppermost portion of unit below the unconformity at the base of Coberly Formation. Six-foot-thick chert pebble conglomerate occurs toward base and middle of formation. 1500-1700 feet thick (Gwinn, 1965).

**Kblt** **Taft Hill Member (Albian)**
Thick- to medium-bedded, brownish-tan, fine- to medium-grained sandstone with abundant trough and planar cross stratification. Contains minor black shale interbeds. Basal contact with underlying black shale of Flood Member gradational. Approximately 900-1000 feet thick (Gwinn, 1965)

**Kblf** **Flood Member (Albian)**
Black fissile shale with local interbeds of very fine- to fine-grained sandstone. Two-foot-thick fine-grained sandstone commonly occurs at base of member. Approximately 700 ft thick (Gwinn, 1965).

**Kk** **Cretaceous Kootenai Formation (Neocomian-Albian)**
Upper and middle parts of the Formation consist of medium-gray limestone with abundant gastropods Limestone is interstratified with red-purple mudstone and local lenticular medium- to coarse-grained sandstone beds. 900-110 feet thick (Gwinn, 1965)

--Unconformity--

**Jurassic**

**Js** **Sedimentary rocks undivided, includes Morrison Formation and Ellis Group**

*Morrison Formation* – Poorly exposed brown-green mudstone and siltstone with interstratified salt-and-pepper sandstone locally.

**Ellis Group**

*Swift Fformation*– Chert pebble conglomerate and tan, medium- to coarse-grained sandstone.

*Reirdon Formation*- Tan-gray siltstone, shale, and local argillaceous limestone. Contains scattered invertebrate remains.

*Sawtooth Formation*- Dark-brown shale.

Approximately 900 feet thick (Gwinn, 1961)

--Unconformity--

**Permian and Pennsylvanian**

**PPpq** **Phosphoria and Quadrant Formations, undivided**

*Phosphoria*- Black-chert beds with interbedded dolomite and phosphorite. Poorly exposed aside from artificial mine and pit exposures. Thickness 0-50 feet (Gwinn, 1961).

*Quadrant Quartzite*- Well-sorted and very mature quartzite with meter-scale bedding. Very competent ridge-former that weathers reddish tan. Thickness 200-250 feet thick (Gwinn, 1961).

**Pennsylvanian**

**Pa** **Amsden Formation**

Very poorly exposed red siltstone, mudstone and dolomite. Forms red soil below Quadrant quartzite. Thickness 300-325 feet thick (Gwinn, 1961).

--Unconformity--

**Mississippian**

**Mm** **Madison Group, undivided**

Thick- to medium- bedded limestone with dolomite in uppermost beds. Contains scattered grey chert nodules. Only uppermost part of unit exposed in map area. Thickness approximately 1200 feet thick (Gwinn, 1961).

## APPENDIX-B

*Eastern FCB Cenozoic map unit descriptions*
*See Figure 9 for North American Land Mammal Ages*

**Quaternary**

| | |
|---|---|
| **ad** | **Anthropogenic Deposits (modern)**<br>Placer mine tailings, retention pond mud, and coarse, angular, exotic boulders deposited by human activity. Thickness 0-50 feet thick. |
| **Qal** | **Alluvium (Holocene)**<br>Unconsolidated to semi-consolidated stream and floodplain deposits exposed primarily along modern stream channels. Mostly coarse gravel and sand with local overbank brown mud deposits. Gravel is rounded and poorly sorted. Locally contains 1-ft-thick bed of volcanic ash. Less than 30 feet thick. |
| **Qaf** | **Alluvial fan (Holocene)**<br>Unconsolidated gravel and mud deposits at mouth of ephemeral drainages and along the edge of the Flint Creek and Clark Fork River floodplains. Well-developed fan-shaped geomorphology. Unit composed of locally derived, poorly sorted, angular clasts. Less than 15 feet thick. |
| **Qc** | **Colluvium (Holocene)**<br>Unconsolidated, very angular gravel, silt, and mud deposited at base of slopes. Gravel is moderately to well-sorted and primarily granule- to cobble-sized. Less than 10 feet thick. |
| **Qls** | **Landslide deposits (Holocene)**<br>Semi-consolidated sediment composed of locally derived source material. Identified by lobate and hummocky geomorphology. Tends to occur on steep slopes composed of Trcp and Tscf map units overlain by boulder-sized gravel. Less than 850 feet in diameter. |

--Unconformity--

**Qgrh** **Gravel deposit of Hoover Creek (Pleistocene)**
Poorly consolidated, well-rounded, poorly sorted pebble- to boulder- conglomerate with framework support. Discontinuous sand lenses are very fine- to medium-grained, micaceous and angular. Abundant volcanic clasts. Local deposit along northern margin of modern Clark Fork River. Age from Rasmussen, (1969). Less than 20 feet thick.

**Qlo** **Loess (Pleistocene)**
Loess, mud, and local deposits of unconsolidated angular gravel. Color medium-brown to buff-tan. Occurs locally on terrace surfaces. Gravel becomes finer-grained farther away from the Flint Creek Range. This unit probably was deposited contemporaneous with Glacial Lake Missoula sediments. Age from Rasmussen (1974). Less than 40 feet thick.

**Quaternary and Tertiary**

**QTgrm** **Gravel and mud (Pleistocene-Miocene?)**
Unconsolidated boulders, cobbles and pebbles in brown mud matrix support. Gravel ranges from very angular to rounded. Largest boulders characterized by compression marks and high sphericity. Probably deposited by debris flow processes along edge of basin. Less than 120 feet thick.

**QTgr** **Gravel undivided (Pleistocene-Miocene?)**
Unconsolidated boulder- to pebble-sized gravel with poor to well-rounded clasts in a sandy-mud matrix. Also includes undivided mud and silt deposits. Less than 240 feet thick.

**Tertiary**

**Sixmile Creek Formation**

**Tscgs** **Gravel and sand of Sixmile Creek Formation (Miocene, Hemphillian-Clarendonian?)**
Semi-consolidated, framework-supported boulders and cobbles with coarse angular sand matrix. Lacks bedding. Boulders well-rounded and imbricated to the N-NE at the mouth of Douglas Creek. Boulders up to 1 meter in diameter and predominantly composed of tan quartzite. Unit

commonly occurs on high terraces and along valley slopes. Locally contains brownish-red clay with caliche nodules. As mush as 400 feet thick in the southern Flint Creek Valley.

Tscb **Barnes Creek beds, informal of Sixmile Creek Formation (late Miocene, Clarendonian?-late Barstovian)**

Conglomerate facies (not mapped) typically have pebble to small cobble sized clasts with well-developed framework support. Pebbles are locally imbricated, well sorted, moderately well rounded and spherical. Intercalated sandstone lenses contain abundant tabular foresets and are commonly a greenish-pinkish hue. Sand matrix is angular, fine- to very coarse-grained and locally cemented with $CaCO_3$. Mudstone facies (not mapped) are commonly composed of variegated reddish-orange silty clay and poorly lithified. Contains scattered vertebrate bone fragments. Less then 240 feet thick.

--Unconformity--

Tscf **Flint Creek beds, informal of Sixmile Creek Formation (middle-late Miocene, early Barstovian)**
Calcrete facies consist of abundant irregular to tubular-shaped carbonate nodules within massive siltstone and mudstone. Local well-indurated tabular sheets of calcrete composed of floating angular granules. Unit tends to form prominent outcrops. Mudstone is yellow-tan (buff) colored throughout with large curve shaped fractures (pedogenic slickensides) and no stratification. Minor volcanic detritus commonly altered to smectite clay. Conglomerate and sandstone facies typically have lenticular geometries and internal scour surfaces. Clasts are granule to pebble-sized, very angular and lack imbrication. Sandstone units are fine- to coarse- grained and characterized by local mottling and preservation of root traces.Thin- to medium-bedded siltstone facies are more common in higher stratigraphic levels.Approximately 200 feet thick.

Tscfg **Gravel bed, informal at base of Flint Creek beds (early- middle Miocene, early Barstovian)**
Boulder- to pebble-sized conglomerate. Clasts are sub rounded to very rounded, moderately sorted,

framework supported, imbricated and locally $CaCO_3$ cemented. Sand matrix is medium- to very coarse-grained, poorly sorted and locally forms lensoidal beds. Unit as whole has a sharp erosive base and a crude fining upward profile. Unit occurs immediately above the regionally extensive late-early Miocene (Hemingfordian) unconformity, a regional extensive unconformity. Approximately 0-5 feet thick

--Unconformity--

**Renova Formation**

Trcp **Cabbage Patch beds, informal of Renova Formation (middle Oligocene through late-early Miocene, Arikareean - Upper Renova Formation equivalent)**

Sandstone facies are very coarse-grained, pebbly, wedge shaped interstratified with massive mudstone. Sandstone is poorly rounded to angular, arkosic, well-cemented and bedded on a decimeter scale. Sandstone contains internal fining-upward sequences and abundant tabular-trough cross beds. Mudstone is massive and buff-colored with scattered spherical $CaCO_3$ nodules. Bedded facies consist of laterally discontinuous beds of interstratified, locally tuffaceous sandstone, siltstone, mudstone, diatomite, chert and limestone with dispersed volcanic glass. Local tephra units are fine grained. Paleosols are common and characterized by abundant Fe-stained root traces, slickensides, mottling and $CaCO_3$ nodules. Limestone intervals are well-indurated with abundant shell debris including gastropods, ostracods and pelecypods. Sandstone beds are locally carbonate-cemented. Approximately 2,300 feet thick (Rasmussen, 2003).

Trt **Rhyolitic Tuff, welded (late Oligocene)**
Rhyolitic welded tuff with euhedral sanidine and smokey quartz grains. Very competent unit locally interstratified with basal Cabbage Patch units. 29.2 Ma zircon fission track age date by Rasmussen (1977). Approximately 100 feet thick at mouth of Coberly Gulch.

--Unconformity--

**Tv** **Volcanic rocks (Eocene)**

(Eocene, 0-600 ft thick in Garnet Range; Carter, 1982)
May include basalt, dacite, andesite, and rhyolite. Primarily mapped as basalt by Rasmussen (1969). Part of Garnet Range volcanic sequence in Bearmouth area (Carter, 1982). Very extensive in the western and northern parts of the Flint Creek basin. ~44-49 $\pm$ 2 Ma K-Ar dates by Williams (1976) and Carter (1982). 0-600 feet thick in Garnet Range

**Tml** **Mudstone, lateritic (Paleocene-Eocene?)**

Bright orange-red mudstone with local gravel lenses. Mud is primarily composed of kaolinite and interlayered smectite/illite clay. Poor exposures found locally along Cretaceous-Tertiary unconformity. Local occurrence of breccia with in uppermost 20 cm of Kbld along unconformity. Reddish staining is prominent in underlying Cretaceous units to a depth of about 25 feet and suggests a pedogenic laterite origin for this unit. 0-250 feet thick.

--Unconformity--

## APPENDIX C - Map Stations

| LATTITUDE | LONGITUDE | STRIKE | DIP | SAMPLE |
|---|---|---|---|---|
| 46.599417 | -113.056117 | 132 | 31 | |
| 46.587533 | -113.051917 | | | 19.01 |
| 46.58535 | -113.05735 | | | 19.02 |
| 46.5863 | -113.05866 | | | 21.01 |
| 46.584867 | -113.063867 | | | 23.01 |
| 46.578267 | -113.064823 | | | 25.01 |
| 46.576833 | -113.034417 | 202 | 74 | |
| 46.575583 | -113.03645 | 358 | 22 | |
| 46.575733 | -113.040817 | | | 29.01 |
| 46.57405 | -113.041917 | 352 | 19 | |
| 46.5741 | -113.042367 | 354 | 18 | |
| 46.574833 | -113.043367 | 345 | 21 | |
| 46.57515 | -113.043383 | | | 29.02 |
| 46.573233 | -113.045283 | 344 | 22 | |
| 46.580133 | -113.0469 | | | 33.01 |
| 46.609933 | -113.106 | | | 39.01 |
| 46.617133 | -113.102217 | 150 | 34 | |
| 46.608483 | -113.0998 | 8 | 20 | |
| 46.606617 | -113.098017 | 37 | 24 | |
| 46.605533 | -113.09515 | 28 | 16 | |
| 46.602567 | -113.090583 | 345 | 24 | |
| 46.59835 | -113.0956 | 334 | 24 | |
| 46.597283 | -113.099083 | 323 | 30 | |
| 46.595133 | -113.111483 | 0 | 0 | |
| 46.597733 | -113.062817 | 315 | 27 | 51.01 |
| 46.597717 | -113.063867 | 177 | 26 | |
| 46.59705 | -113.063967 | 324 | 10 | 53.01 |
| 46.596417 | -113.0635 | 275 | 3 | |
| 46.59905 | -113.069633 | 185 | 24 | |
| 46.603183 | -113.065417 | 207 | 10 | |
| 46.604 | -113.064117 | 192 | 19 | |
| 46.600567 | -113.060083 | 309 | 12 | |
| 46.588767 | -113.13985 | | | 63.01 |
| 46.587667 | -113.132283 | 189 | 16 | |
| 46.6048 | -113.140467 | | | 69.01 |
| 46.570017 | -113.259217 | | | 71.01 |
| 46.537683 | -113.310367 | | | 71.02 |
| 46.5273 | -113.27565 | | | 71.03 |
| 46.5359 | -113.199233 | 178 | 75 | |
| 46.5138 | -113.1798 | 200 | 81 | |
| 46.5157 | -113.180367 | 12 | 80 | |
| 46.5045 | -113.171033 | 357 | 56 | |
| 46.495967 | -113.1529 | 6 | 54 | |
| 46.495783 | -113.157017 | 355 | 25 | |
| 46.49065 | -113.15295 | 354 | 66 | |
| 46.485067 | -113.151633 | 5 | 85 | |
| 46.660433 | -113.15775 | 105 | 65 | |
| 46.549433 | -113.284733 | | | 80.01 |
| 46.552417 | -113.281467 | | | 83.01 |

| | | | | |
|---|---|---|---|---|
| 46.576867 | -113.1761 | | | 85.01 |
| 46.594333 | -113.1149 | 172 | 6 | |
| 46.59465 | -113.113983 | 175 | 9 | 89.01;89.02 |
| 46.595 | -113.1128 | 183 | 16 | |
| 46.595233 | -113.112183 | 262 | 19 | 93.01 |
| 46.596917 | -113.11245 | 145 | 11 | |
| 46.602117 | -113.118617 | 155 | 14 | 95.01 |
| 46.607617 | -113.119317 | 164 | 10 | |
| 46.607117 | -113.1068 | 173 | 18 | |
| 46.608983 | -113.10625 | 190 | 11 | |
| 46.593 | -113.113317 | 0 | 0 | |
| 46.586667 | -113.101467 | 120 | 28 | |
| 46.583517 | -113.0928 | 12 | 14 | |
| 46.588217 | -113.088317 | 75 | 15 | |
| 46.582133 | -113.093933 | 170 | 10 | |
| 46.5817 | -113.094967 | 320 | 10 | |
| 46.568683 | -113.072167 | | | 105.1 |
| 46.567733 | -113.079783 | 173 | 31 | |
| 46.572583 | -113.080783 | 190 | 56 | |
| 46.574317 | -113.089983 | 179 | 48 | |
| 46.600967 | -113.1288 | | | 109.1 |
| 46.603083 | -113.130217 | | | 111.01;111.0 |
| 46.588733 | -113.094583 | 318 | 24 | |
| 46.589383 | -113.087083 | | | 115.01 |
| 46.589017 | -113.087403 | 364 | 29 | |
| 46.58873 | -113.07737 | | | 119.01 |
| 46.592 | -113.07644 | 225 | 30 | |
| 46.59341 | -113.0772 | | | 121.01 |
| 46.59656 | -113.08557 | 220 | 19 | |
| 46.60042 | -113.08509 | 20 | 31 | |
| 46.60433 | -113.08212 | 157 | 49 | |
| 46.60827 | -113.07703 | 183 | 33 | |
| 46.59867 | -113.11037 | | | 127.01,.02 |
| 46.62598 | -113.12383 | 165 | 35 | |
| 46.5676 | -113.12539 | 15 | 65 | |
| 46.56771 | -113.12818 | 10 | 57 | |
| 46.55318 | -113.12762 | 355 | 65 | |
| 46.5514 | -113.12146 | 355 | 65 | |
| 46.5456 | -113.12452 | 175 | 60 | |
| 46.5424 | -113.12354 | 355 | 11 | |
| 46.5424 | -113.12356 | 160 | 70 | |
| 46.54511 | -113.12928 | 315 | 55 | |
| 46.53357 | -113.17425 | 310 | 70 | |
| 46.55579 | -113.16811 | 0 | 0 | 145.01 |
| 46.53814 | -113.16698 | 355 | 45 | |
| 46.5358 | -113.17048 | 340 | 50 | |
| 46.59718 | -113.09951 | 334 | 37 | |
| 46.59432 | -113.09943 | 0 | 40 | |
| 46.58482 | -113.1173 | 0 | 0 | 144.1 |

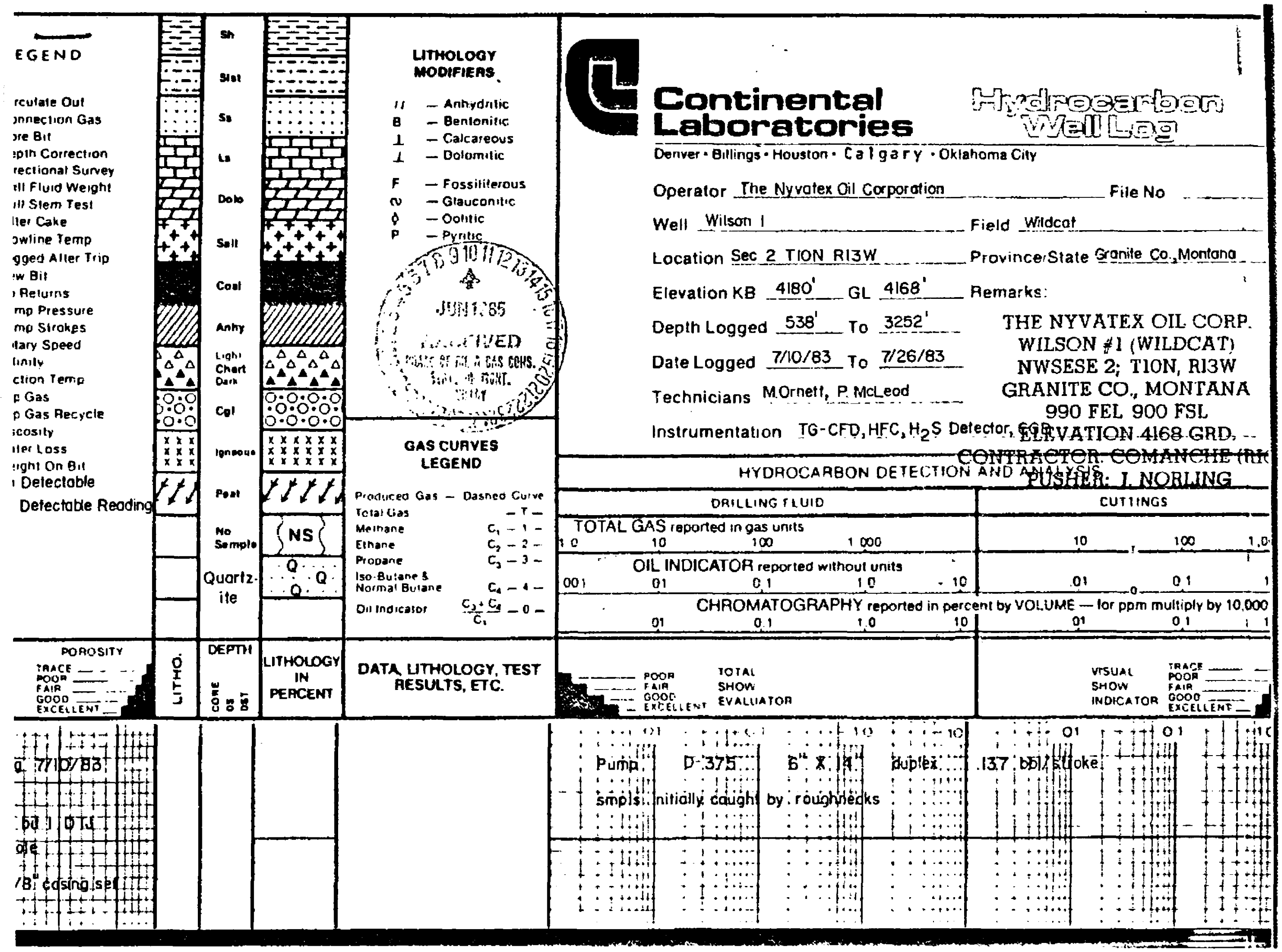
## APPENDIX D - Measured Sections

| SECTION | LATITUDE | LONGITUDE | ELV | STRIKE | DIP | SURFACE |
|---|---|---|---|---|---|---|
| BNC1A | 46.59021667 | -113.1316 | 4388 | 185 | 7 | bedding |
| BNC1B | 46.58895 | -113.1339167 | 4349 | 170 | 9 | bedding |
| BNC1C | 46.58716667 | -113.1367333 | 4325 | | | |
| BNC2A | 46.58728333 | -113.1345333 | 4345 | 157 | 52 | fault |
| BNC2B | 46.58676667 | -113.1360167 | 4323 | 195 | 15 | |
| BNC2C | 46.58765 | -113.1323 | 4337 | | | |
| BNCB | 46.58378333 | -113.1466333 | 3988 | | | |
| CBYB | 46.61986667 | -113.1041333 | 4092 | | | |
| CKFKB | 46.5995 | -113.0526667 | 4085 | | | |
| DGC1A | 46.53203333 | -113.1932333 | 4592 | 15 | 14 | bedding |
| DGC1B | 46.53205 | -113.1926333 | 4644 | | | |
| DGC2A | 46.52783333 | -113.1918 | 4636 | | | |
| DGC2B | 46.5276 | -113.19395 | 4635 | 0 | 0 | bedding |
| DGC3A | 46.52666667 | -113.1944 | 4630 | | | |
| DGC3B | 46.52633333 | -113.1939667 | 4682 | | | |
| DGC4A | 46.52111667 | -113.1938333 | 4706 | | | |
| DGC4B | 46.52208333 | -113.1941 | 4712 | | | |
| DGC5 | 46.51968333 | -113.1913333 | 4708 | 250 | 24 | bedding |
| DGLSCB | 46.52728333 | -113.1937333 | 4635 | | | |
| DNGB7C | 46.5765 | -113.06925 | 4434 | | | |
| DNGB8 | 46.57331667 | -113.0658 | 4402 | 253 | 21 | bedding |
| DNGWL1 | 46.61698333 | -113.1215167 | 4114 | 188 | 7 | |
| DNKB1 | 46.58696667 | -113.0249 | 4168 | 0 | 0 | bedding |
| DNKB2 | 46.5882 | -113.0367 | 4186 | 245 | 33 | bedding |
| DNKB3 | 46.5855 | -113.0440167 | 4199 | 320 | 22 | bedding |
| DNKB4 | 46.58696667 | -113.0483 | 4262 | | | |
| DNKB5 | 46.58543333 | -113.0596333 | 4386 | | | |
| DNKB6 | 46.58035 | -113.0549167 | 4305 | | | |
| DNKB7A | 46.57678333 | -113.0650167 | 4344 | | | |
| DNKB7B | 46.57656667 | -113.0665833 | 4365 | 0 | 0 | bedding |
| DNKBB | 46.5875 | -113.0387833 | 4180 | | | |
| DNGWL1b | 46.61868 | -113.12125 | 4098 | 282 | 12 | bedding |
| DNGWL2a | 46.61501667 | -113.1225 | 4150 | | | |
| CBY1a | 46.59865 | -113.11045 | 4218 | 0 | 0 | bedding |
| CBY1b(top) | 46.5969 | -113.11371 | 4330 | | | |
| CBY2 | 46.59465 | -113.113983 | 4306 | | | |

APPENDIX E: Borehole data

(See figure 2 for well locations)

Wilson 1


Continental Laboratories

Hydrocarbon Well Log

Denver • Billings • Houston • Calgary • Oklahoma City

Operator The Nyvatex Oil Corporation File No

Well Wilson 1 Field Wildcat

Location Sec 2 T10N R13W Province/State Granite Co., Montana

Elevation KB 4180' GL 4168' Remarks:

Depth Logged 538' To 3252'

Date Logged 7/10/83 To 7/26/83

Technicians M.Ornett, P. McLeod

Instrumentation TG-CFD, HFC, $H_2S$ Detector, CGR

THE NYVATEX OIL CORP.
WILSON #1 (WILDCAT)
NWSESE 2; T10N, R13W
GRANITE CO., MONTANA
990 FEL 900 FSL
ELEVATION 4168 GRD.
CONTRACTOR COMANCHE
PUSHER: J. NORLING

JUN 1985 RECEIVED

EGEND

rculate Out
onnection Gas
ore Bit
epth Correction
rectional Survey
ill Fluid Weight
ill Stem Test
lter Cake
owline Temp
gged After Trip
w Bit
Returns
mp Pressure
mp Strokes
tary Speed
linity
ction Temp
p Gas
p Gas Recycle
scosity
lter Loss
eight On Bit
Detectable
Detectable Reading

Sh, Silt, Ss, Ls, Dolo, Salt, Coal, Anhy, Light Chert Dark, Cgl, Igneous, Peat, No Sample, Quartzite

LITHOLOGY MODIFIERS
// — Anhydritic
B — Bentonitic
⊥ — Calcareous
⊥ — Dolomitic
F — Fossiliferous
ω — Glauconitic
◊ — Oolitic
P — Pyritic

GAS CURVES LEGEND
Produced Gas — Dashed Curve
Total Gas — T —
Methane $C_1$ — 1 —
Ethane $C_2$ — 2 —
Propane $C_3$ — 3 —
Iso-Butane & Normal Butane $C_4$ — 4 —
Oil Indicator $\frac{C_2+C_3}{C_1}$ — 0 —

HYDROCARBON DETECTION AND ANALYSIS

DRILLING FLUID | CUTTINGS

TOTAL GAS reported in gas units: 1.0, 10, 100, 1,000 | 10, 100, 1,000

OIL INDICATOR reported without units: .001, .01, 0.1, 1.0, 10 | .01, 0.1, 1

CHROMATOGRAPHY reported in percent by VOLUME — for ppm multiply by 10,000: .01, 0.1, 1.0, 10 | .01, 0.1, 1

POROSITY: TRACE, POOR, FAIR, GOOD, EXCELLENT

LITHO. | DEPTH (CORE, DS, DST) | LITHOLOGY IN PERCENT | DATA, LITHOLOGY, TEST RESULTS, ETC.

TOTAL SHOW EVALUATOR: POOR, FAIR, GOOD, EXCELLENT

VISUAL SHOW INDICATOR: TRACE, POOR, FAIR, GOOD, EXCELLENT

g. 7/10/83

50 ) DTJ

ole

/8" casing set

Pump D-375 6" X 14" duplex .137 bbl/stroke

smpls. initially caught by roughnecks

131

# Wilson 2-a

10N 13W
Sec 2
SW SE

API 21609 Wilson 2

## OPERATIONAL DISCUSSION

Normal drilling conditions were encountered from the surface to a depth of 780': At 780', an unconsolidated Quartzite gravel was encountered and continued to total depth (978'). While drilling this gravel, continuous lost circulation was encountered. This lost circulation varied from 30% to 80% of fluid circulation. At no time was circulation lost 100%. Despite a mud viscosity in excess of 100 sec./qt., the hole was continuously falling in causing periodically stuck drill pipe and very tight hole. From 750' to 900' the hole deviated 2 3/4 degrees (1 3/4° at 750'; 4½° at 900') indicating very steep dip or a fault plain was encountered. This deviation took place in spite of the fact that only 4,000 to 5,000 pounds of weight was run on the bit. At 978', the decision to plug and abandon the hole was made after duly considering the following factors:

1) The inability to control the hole sloughing with high viscosity drilling fluids.
2) Steady loss of drilling fluid
3) Stuck pipe and tight hole conditions due to sloughing formations
4) Crooked hole due to steep dips, despite running little weight
5) Due to the above factors, the liklihood of losing the drilling assembly and the hole appeared imminent, if drilling operations were to continue

## GEOLOGICAL SUMMARY

The well was spudded in a buff to white soft earthy mudstone with a variety of rocky inclusions. The surface exposure is probably a Tertiary wash. At approximately 110', a bedded green to bright green waxy bentonitic Shale, This Shale section was very soft and fairly uniform with localized thin stringers of low grade poorly developed limy mudstones. At 370', the shale section began varying in color (greens, greys, yellowish green) and thin inclusions of black carbonaceous material were noted. Thin low grade coal streaks were noted in the interval 430' to 510'. First Sandstone was noted at 538', and was hard and tite with no live shows. The section was interbedded Sandstones, Silts and Shales from 510' to 720'. Colors were green, grey, buff, tan and oxidized orange-yellow. A trace of orange red silt was noted at 690'. A dense grey shaly Dolomite bed was found from 720' to 740' and this was immediately underlain by bright red shales and silt. From 740' to 770', the section was a series of brightly colored silts and shales. A coarse conglomeritic Sandstone was found from 770' to 780'. A hard, sharp, unconsolidated Sandstone and Quartzite "gravel" was encountered at 780'. This section continued to total depth of 978' when hole was abandoned due to hole conditions. Residual asphaltic material was found in this section in the interval 800' to 820'. A subsequent drill stem test attempt of this interval was unsuccessful due to mechanical tool problems and poor hole conditions.

No attempt is being made to identify the beds penetrated in this hole, but it is believed that the majority of sediments drilled are Jurassic in age. The section penetrated in the No. 2 Wilson appears to be totally dis-similar to the section penetrated in the No. 1 Wilson, approximately 3/4 of one mile to the Southeast. Crooked hole caused by steep dips, and sloughing gravel beds (780'-978') forced the abandonment of the No. 2 Wilson at a total depth of 978'.

# Wilson 2-b

LITHOLOGY

Sample descriptions begin at 40'. Sample descriptions are corrected for drill time lag. Samples were examined both wet and dried, but described wet.

SAMPLES CAUGHT IN 10' INTERVALS:

| | |
|---|---|
| 40-50 | Shale, yellowish tan, pale lime green, tan, buff, generally soft, blocky, calcareous in part, gritty in part, has generalized oxidized/weathered appearance, some hairline black shale partings immbedded thruout; Dried sample is firm; trace buff marly limestone |
| 50-60 | No change from above |
| 60-70 | Shale, pale grey, greenish cast in part, some buff and tan, generally firm to soft, silty and gritty in part, chunky, noncalcareous, dense; some buff to pinkish white soft waxy textured bentonite |
| 70-80 | Mudstone, buff to lt grey, mottled yellow and dark gold, blocky, soft but firmer than above, gritty and calcareous in part, dense; trace bentonite as above |
| 80-90 | Mudstone as above; some clear Gypsum crystals; stringers of brindly brown limestone, pelletoid and marly, soft, dense |
| 90-100 | Mudstone, buff, tan, mottled, pinkish tan, much oxidized yellow-gold, blocky, firm, fairly sharp, calcareous, floating very fine clear quartz grains and reddish brown grains thruout, dense; Some pale yellowish green bentonitic shale |
| 100-10 | Mudstone, as above becoming increasingly firm and grading to a low grade subcrystalline limestone in part, shaly, silty, dirty, dense; Many loose clear Gypsum crystals |
| 110-20 | As above; Influx shale, dk green, greygreen, chunky, smooth textured, waxy and bentonitic in part, noncalcareous, dense |
| 120-30 | No change from above; dk green shale comprises approximately 15% of sample |
| 130-40 | Shale, dk green, bright green, chunky, lumpy, soft, smooth to subwaxy textured, may be bentonitic in part, noncalcareous, some gritty patches, dense; Much limy mudstone as above |
| 140-50 | Shale, green, as above; traces of soft blu-grey bentonitic shale |
| 150-60 | Shale, green, as above, waxy when wet, dries to a subearthy texture |
| 160-70 | Shale, green, as above |
| 170-80 | Shale, green, as above |

NOTE: 8 5/8" surface casing was set at 171' KBM: Hole size 7 7/8" from 180'

| | |
|---|---|
| 180-90 | No sample |

# Wilson 2-c

190 - BEGIN 30' SAMPLES - Very fast penetration rate.

| | |
|---|---|
| 190-220 | Shale, green, as before |
| 220-50 | Shale, green, as above, occasional gritty patches, some fine black carbonaceous shale inclusions |
| 250-80 | Shale, green as above |
| 280-310 | Shale, green, as above |
| 310-40 | Shale, green, as above; minor amounts of buff and white limestone, chalky to finely pelletoid, dense, no show |
| 340-70 | Shale, green, as above; much crystalline Gypsum |
| 370-400 | Shale, green as above; scattered thin stringers and laminations of black carbonaceous shale |
| 400-30 | Shale, pale yellowish green, chunky, soft, waxy and bentonitic, earthy textured when dried, noncalcareous, dense; trace black carbonaceous shale; trace loose fine pyrite |
| 430-60 | Shale, grey, dk grey, to greenish grey, chunky, soft, bentonitic, noncalcareous, waxy textured, earthy when dried, gritty in part, noncalcareous, dense; trace black coaly shale |
| 460-90 | Shale as above; some dk grey shale with fine black carbonized vegetation fragments imbedded thruout; trace black coaly shale; some thin coal beds |
| 490-510 | Shale, grey to dk grey to lt green, very soft, bentonitic, dense; trace black carbonaceous shale; trace loose pyrite clusters |
| 510-40 | Shale as above; Minor amounts of Sandstone, white, very fine grained to siltstone, quartzose, speckled with very fine pyrite, well sorted, well cemented, noncalcareous, silicious matrix, very dense, no show; trace sandy pyrite; trace coal |
| 540-70 | Sandstone, tan to buff to white, very fine to medium grained, quartzose and quartzitic, generally hard and sharp, very poorly sorted, well cemented, noncalcareous matrix material, appears silicious, sub-rounded to angular grains, isolated pyrite and glauconite specks, several clusters appear to have fair intergranular porosity, no staining, trace dull gold fluorescence in the denser sand, no cut in trichloroethane, no odor in wet sample, no show |
| 570-90 | Sandstone as above; Influx shale, medium grey, firm to soft, very silty and gritty, noncalcareous, dense; much lt grey, pale yellowish green soft bentonitic shale |

590 - BEGIN 10' SAMPLES - Penetration rate has slowed down

| | |
|---|---|
| 590-600 | Sandstone, white, clear, fine to medium grained, quartzose, unconsolidated in part, subangular to rounded clear and frosted grains, occasional fine pyrite specks, poor sorting, well cemented in part, questionable porosity, noncalcareous, no apparent show; much shale as above |

| | |
|---|---|
| 600-10 | Sandstone as above, no natural fluorescence, occasional specks of black organic bituminous material which gives off poor to fair cut when soaked in trichloroethane, no odor in wet sample, no live staining, does not appear to be oil show; Sample is predominantly green to greygreen soft bentonitic shale |
| 610-20 | Siltstone, oxidized rusty gold, firm, sharp, noncalcareous, dense, no show; Much sandstone and bentonitic shale as above |
| 620-30 | Siltstone, rusty gold, as above; Sandstone, cream to mottled lt brown, very fine to fine to medium grained, quartzose, occasional pyrite specks, fairly hard and sharp, poorly sorted, well cemented, non-calcareous, friable in part, some coarser pale brown quartz grains, trace poor to fair intergranular porosity, no apparent show; some green to greygreen bentonitic shales as before |
| 630-40 | Sandstone as above becoming generally finer grained, finely pyritic, dense, no show |
| 640-50 | Shale, dk grey, yellowish green, green, chunky, soft, bentonitic, non-calcareous, dense; minor amounts of sandstone as before |
| 650-60 | Shale and sandstone as above |
| 660-70 | Shale, medium grey, green, blu-green, yellowish green, chunky, soft, noncalcareous, bentonitic, dense; trace sandstone as before |
| 670-80 | Siltstone, grey, hard, sharp, very fine grained sandstone in part, quartzose, argillaceous, noncalcareous, hard, sharp, dense, no show; much shale as above |
| 680-90 | Shale, mustard yellow, very silty and sandy, siltstone in part, fairly hard and sharp, dense, moderately calcareous, no show; much pale green to green soft waxy shale; some sandstone, white, very fine grained, quartzitic, very dense, hard, sharp, and abrasive, no show |
| 690-700 | Shale, siltstone, and sandstone as above; some siltstone, bright orange-red, very shaly, hard, sharp, may be silicious in part, non-calcareous, very dense |
| 700-10 | Shale, lt grey, pale green, buff, generally very soft and earthy, finely silty and gritty in part, bentonitic, noncalcareous, dense; siltstone, dk golden yellow, glauconitic, finely sandy in part, fairly hard and sharp, noncalcareous, dense, no show; some dense mottled grey siltstone |
| 710-20 | Shale as above, very soft and earthy; much dk golden yellow siltstone as before; trace loose fine pyrite |
| 720-30 | Dolomite, grey, buff, lithographic, hard and sharp, argillaceous and gritty in part, very dense, no show; minor amounts of dk golden yellow siltstone as before |
| 730-40 | Dolomite as above; influx shale, bright reddish orange, chunky, firm to soft, mudstone textured, gritty in part, noncalcareous, dense |
| 740-50 | Siltstone, grey, very silicious, quartzitic, very hard, sharp and |

abrasive, very dense, no show; much grey to greybrown fractured chert and quartzite; minor amounts of dolomite as before

750-60 Siltstone, pale yellow, tan, greygreen, firm, occasionally glauconitic, fairly hard and sharp, calcareous, dense, very shaly in part, no show; much coarse fragmented chert and quartz

760-70 Shale, yellow, pinkish orange, grey, chunky, lumpy, soft, earthy textured, very silty and gritty in part, moderately calcareous, dense; much soft brick red muddy shale which washes out of sample

770-80 Sandstone, lt grey, fine to medium grained, coarse rounded black chert pebble inclusions, many black and grey broken chert pebbles, probably a conglomerate, well cemented, moderately calcareous, very dense, no show; some yellow and brick red shales as above

780-90 Sandstone, lt grey, pale green, white, very fine grained, quartzitic, appears to be orthoquartzite in part, occasional isolated glauconite and pyrite specks, very hard, sharp, and abrasive, very dense, no matrix porosity but may be fractured, hole is beginning to take fluid, moderate lost circulation, no staining, no fluorescence, no show, section is noncalcareous

790-800 No change from above

800-10 Sandstone as above; approximately 5% sandstone, lt grey to clear, very fine grained, quartzose, subangular to rounded grains, well sorted, well cemented, noncalcareous, questionable poor intergranular porosity, black pinpoint microspecks of asphaltic residue intercolated thruout, no live staining, no natural fluorescence but bright yellowgreen fluorescence and instant bright yellow cut when immersed in trichloroethane, no odor in wet sample, lt brown hydrocarbon ring in spot plate after solvent evaporates; still loosing fluid

810-20 No change from above; hole is very ratty; much difficulty making connection at 817'

820-30 Sandstone, cream, lt grey, lt blu-grey, very fine and fine grained, quartzitic, orthoquartzite in part, pyritic in part, very hard, sharp, and abrasive, noncalcareous, very dense, no staining, no fluorescence, no cut, no show; Hole still taking fluid

830-40 No change from above, section drills like it is highly fractured

840-60 No change from above, section appears to be mostly quartzite

860-80 Sandstone, lt blu-grey to white, very fine grained, very quartzitic, very hard, sharp, and abrasive, scattered black chert specks and fine pyrite imbedded thruout, noncalcareous, very dense, no shows, appears to be orthoquartzite in part

880-90 Quartzite, white, cream, pale bluish white, sandy in part, very hard, sharp, and abrasive, probably fractured, dense, no show; Hole is very ratty and tight, still loosing fluid while drilling

890-900 Quartzite as above, sandy in part, as above; some yellowish oxidation stain

# Wilson 2-f

| | |
|---|---|
| 900-10 | No sample |
| 910-20 | Sandstone, white, fine grained, quartzitic, fragmental, very hard, sharp and abrasive, very dense, some spotty yellowish oxidation stain; trace dk grey chert fragments |
| 920-30 | Sandstone, quartzitic and quartzite as before |
| 930-40 | As above, much yellowish oxidation stain; trace soft reddish orange earthy shale; trace fragments of dolomite, cream, microcrystalline, earthy textured in part, dense, no show |
| 940-50 | As above, many cavings after attempting DST No. 1: Many coarse dark grey chert fragments; some dolomite, cream, microcrystalline, earthy and very finely sandy in part, very dense, no show |
| 950-60 | Sandstone, quartzitic, and quartzite as before; much dk grey to black sharp chert; some dolomite, cream to lt grey, microcrystalline and microsucrosic, earthy in part, firm, very dense, no show |
| 960-70 | As above; trace sandstone, yellowish brown, fine grained, quartzose, very glauconitic, well rounded quartz grains, poor sorting, well cemented, slightly calcareous, dense, no show; quantity of dolomite may be increasing, samples are poor due to hole conditions and partial lost circulation; hole is sloughing badly |
| 970-78 | Quartzite, quartzitic sandstone, chert and minor amounts of dolomite as above; loosing circulation and hole beginning to cave in; very difficult to keep drill string unstuck; decision made to abandon hole. |

978' - Total depth by driller

LOCATE WELL CORRECTLY

(SUBMIT IN TRIPLICATE)
TO
BOARD OF OIL AND GAS CONSERVATION
OF THE STATE OF MONTANA
BILLINGS OR SHELBY

NOV 1982
RECEIVED
OIL & GAS CONS. COMM.
STATE OF MONT.
BILLINGS

Form No. 4
ARM 36.22.307
ARM 36.22.1011
ARM 36.22.1013

## COMPLETION REPORT

Company Trans-Texas Energy, Inc. Lease Henderson-Lorensen Well No. #2

Address 12201 Merit Dr. #1100, Dallas, TX 75251 Field (or Area) Wildcat

The well is located 1038 ft. from (S) line and 1153 ft. from (W) line of Sec. 33

Sec. 33 ; T. 11N ; R. 13W ; County Granite ; Elevation 4660' (G.L.)

Commenced drilling November 12, 1980 Completed October 28, 1982

The information given herewith is a complete and correct record of the well. The summary on this page is for the condition of the well at the above date.

Completed as Dry Hole (oil well, gas well, dry hole)

Signed [signature]

Title Vice President - Operations

API # 029 - 21007

Date November 4, 1982

### IMPORTANT ZONES OF POROSITY

(denote oil by O, gas by G, water by W; state formation if known)

From NONE to ______ From ______ to ______
From ______ to ______ From ______ to ______
From ______ to ______ From ______ to ______
From ______ to ______ From ______ to ______

### CASING RECORD

| Size Casing | Weight Per Ft. | Grade | Thread | Casing Set | From | To | Sack of Cement | Cut and Pulled from |
|---|---|---|---|---|---|---|---|---|
| 20" | 94# | J-55 | ST&C | 3761' | 0' | 3761' | 350 sx | N/A |
| 13 3/8" | 72# | N-80 | LT&C | 4215' | 0' | 4215' | 3500 sx | N/A |
| 9 5/8" | 47# | S-95 | BUTT | 12500' | 0' | 12500' | 1250 sx | 7815' |
| | | | | | | | | |

### TUBING RECORD

| Size Tubing | Weight Per Ft. | Grade | Thread | Amount | Perforations |
|---|---|---|---|---|---|
| NONE | | | | | |

### COMPLETION RECORD

Rotary tools were used from 0' to 17,375'
Cable tools were used from NONE to ______
Total depth 17,375' ft.; Plugged back to N/A T.D.; Open hole from 12,500' to 17,375'

| PERFORATIONS | | | ACIDIZED, SHOT, SAND FRACED, CEMENTED | | | |
|---|---|---|---|---|---|---|
| Interval From | Interval To | Number and Size and Type | Interval From | Interval To | Amount of Material Used | Pressure |
| NONE | | | 7750' | 7850' | 80 sx cmt plug | |
| | | | 4250' | 4350' | 80 sx cmt plug | |
| | | | 0' | 25' | 20 sx cmt plug | |
| | | | | | | |

(If P&A show plugs above)

### INITIAL PRODUCTION

Well is producing from N/A (pool) formation.

I.P. ______ barrels of oil per ______ hours ______ (pumping or flowing)

______ Mcf of gas per ______ hours.

______ barrels of water per ______ hours, or ______ % W.C.

(OVER)

# Henderson-Lorensen b

TRANS-TEXAS ENERGY, SUNMARK ET AL.

HENDERSON-LORENSEN UNIT No. 2
Granite County, Montana

STRATIGRAPHY AND FORMATION TOPS

| Elevation 4692' K. B. | Depth | Subsea | Structural relationship |
|---|---|---|---|
| TERTIARY | | | |
| Basalt flows (surface) | | | |
| Lacustrine beds | 400 | +4292 | Unconformity |
| PRECAMBRIAN (Beltian) | | | |
| Garnet Range Fm. | 500 | +4192 | Unconformity |
| McNamara Fm. | 1550 | +3142 | Normal sequence |
| Diabase-Gabbro sill | 2620 | +2072 | Intrusive contact |
| Garnet Range Fm. | 2800 | +1892 | Overthrust contact |
| MISSISSIPPIAN | | | |
| Madison (Lodgepole) | 3705 | +987 | Overthrust contact |
| PENNSYLVANIAN | | | |
| Amsden Fm. | 4070 | +622 | Overthrust contact |
| MISSISSIPPIAN | | | |
| Madison (Mission Canyon) | 4100 | +592 | Normal sequence |

From 4100' to 12500' the borehole penetrated numerous imbricated nappes which repeated the Madison section numerous times. Continuous monitoring by means of thin sections indicated that the entire section is Madison with the following exceptions: The intervals 6620'-6640', 6740'-6760', 7340'-7370', 8000'-8020' and 8070'-8110' contain a dense slightly calcareous black shale which has been assigned to the Sappington Formation on the basis of the palynomorph Vallatisporites sp. The aforementioned spore has a Late Devonian-Early Mississippian range. See Pl. 2 fig. 35.

| | | | |
|---|---|---|---|
| PENNSYLVANIAN | | | |
| Amsden Fm. | 12500 | -7808 | Overthrust contact |
| Quadrant Qtzite. | 12780 | -8098 | |
| | | | Overturned sequence |
| PERMIAN | | | |
| Phosphoria Fm. | 12860 | -8258 | |

The palynomorph Punctatisporites sp. was recovered from the interval 12950'-12960'. Pl. 2 fig. 48.

| | | | |
|---|---|---|---|
| CAMBRIAN | | | |
| Red Lion Fm. | 13060 | -8368 | Overthrust contact |
| Hasmark Fm. | 13120 | -8428 | Normal sequence |
| Red Lion Fm. | 13430 | -8738 | Overthrust contact |
| Hasmark Fm. | 13650 | -8958 | Normal sequence |
| Silver Hill Fm. | 14250 | -9558 | Normal sequence |
| Flathead Qtzite. | 14670 | -9978 | Normal sequence |
| PRECAMBRIAN (BELTIAN) | 14730 | -10038 | Normal sequence |
| Garnet Range Fm. | 14730 | -10038 | Normal sequence |
| McNamara Fm. | 14970 | -10278 | Normal sequence |
| Diabase-Gabbro sill | 15100 | -10408 | Intrusive contact |
| Garnet Range Fm. | 15150 | -10458 | Overthrust contact |
| McNamara Fm. | 15230 | -10538 | Normal sequence |
| Garnet Range | 16150 | -11458 | Overthrust contact |
| Garnet Range Fm. | 16870 | -12178 | Overthrust within Garnet Range Fm. |
| Total depth | 17379 | -12687 | No dipmeter data below 16870' |

# Henderson-Lorensen c

Trans-Texas Energy, Inc., - Summark et al.
Henderson - Lorensen No. 2
1038' FSL, 1153' FWL
Sec 33, T 11 N, R 13 W

DESCRIPTION OF CUTTINGS

| | |
|---|---|
| 0 - 65 | Conductor pipe. |
| 65 - 400 | Basalt to 400 feet. This unit crops out at the surface of location. This basalt of medium to dark gray to moderate brown color. Texture is aphanitic with sub-parallel oriented needles of dark greenish gray to black hornblende. Some dark gray chert and crystalline quartz occurs as fracture filling. This unit has been mapped in detail by Dr. John C. Maxwell and is reported in an unpublished map of the Southwest Drummond area. |
| 400 - 470 - 70 | No cuttings returned. Drilling in this interval was through Tertiary lacustrine beds. |
| 470 - 480 - 10 | Light gray slightly bentonitic clay, thin interbeds of lignite and carbonized wood, with scattered clusters of euhedral pyrite crystals. The pyrite is associate with the thin lignite layers. |
| 480 - 490 - 10 | Fine grained to coarse grained calcareous cemented sandstone with chips of glauconitic sandstone. The glauconitic chips are probably derived from boulders of Flathead Quartzite which crop out along the margin of the Tertiary basin. |
| 490 - 500 - 10 | As above with increased number of glauconitic sandstone chips. |

PRECAMBRIAN
MISSOULA GROUP
Garnet Range Formation

| | |
|---|---|
| 500 - 510 - 10 | Top of Garnet Range Formation, Missoula Group. Predominately moderate reddish brown to pale red pink fine to coarse grained orthoquartzitic sandstone. Some chips are slightly arkosic. Minor quantity of moderate reddish brown to dark reddish brown micaceous silty argillite. |
| 510 - 520 - 10 | Orthoquartzitic sandstone as above with 5% moderate reddish brown micaceous silty argillite. |
| 520 - 530 - 10 | As above. |
| 530 - 540 - 10 | Moderate reddish brown to dark reddish brown fine to coarse grained arkosic and micaceous orthoquartzitic sandstone. Several free granule size quartz particles are well rounded and frosted. |
| 540 - 580 - 40 | No sample recovery. |
| 580 - 590 - 10 | 90% Orthoquartzitic sandstone as above; 10% moderate reddish brown to dark reddish brown micaceous silty argillite. |
| 590 - 600 - 10 | 70% Orthoquartzitic sandstone as above; 30% argillite as above. Several chips of the orthoquartzite contained small clasts of reddish brown argillite. This suggests a fluviatile channel sandstone. |

## APPENDIX F:
## Faunal and Flora lists for the Arikareean Cabbage Patch beds: lower (l), middle (m), and upper (u) biostratigraphic divisions

(modified from Rasmussen 1977, 1989; Pierce and Rasmussen, 1992; Pierce, 1992, 1993; Pierce and Constenius, 2001; Henrici, 1994; Craig Christensen, written comm., 2005)

### PLANT GENERA

| | Cabbage Patch Beds | | |
|---|---|---|---|
| **Taxonomy** | **L** | **M** | **U** |
| Diatomophyceae (diatoms) | | | |
| Centrales | | | |
| ?Melosira | | | X |
| Pennales | | | |
| (several unidentified forms) | X | X | X |
| Algae (charophytes) | | | |
| Characeae | | | |
| (several unidentified forms) | X | X | X |
| Gymnospermae | | | |
| Pinaceae | | | |
| Pinus (pine) | X | X | X |
| Taxodiaceae | | | |
| Sequoia (sequoia) | X | X | X |
| Angiospermae | | | |
| Typhaceae | | | |
| Typha (cattail) | X | X | X |
| Fragaceae | | | |
| Quercus (oak) | X | X | X |

### INVERTEBRATE GENERA

| | Cabbage Patch Beds | | |
|---|---|---|---|
| **Taxonomy** | **L** | **M** | **U** |
| Demospongea (fresh water sponges) | | | |
| Monaxonida | | | |
| Spongillidae gen. sp. indet. | X | X | X |
| Gastropoda (aquatic and terrestrial) | | | |
| Oreohelicidae | | | |
| Oreohelix | X | X | X |
| Helminthoglyptidae | | | |
| Monadenia? | | X | |
| Valvatidae | | | |
| Valvata | X | X | |
| Viviparidae | | | |
| Viviparus | | X | |
| Lymnaeidae | | | |
| Lymnaea | X | X | X |
| Planorbidae | | | |
| Planorbula | X | X | |
| Biomphalaria | X | X | X |
| Pupillidae | | | |

| | | | |
|---|---|---|---|
| Gastrocopta | X | X | X |
| Vertigo | X | X | X |
| Pupoides | X | | X |
| Columella | | | X |
| Succineidae | | | |
| Catinella? | X | | X |
| Valloniidae | | | |
| Vallonia | X | X | X |
| Zonitidae | | | |
| Nesovitrea | X | | |
| Limacidae | | | |
| Deroceras | X | X | X |
| Punctidae | | | |
| Punctum | X | | |
| Ammonitellidae | | | |
| Polygyroidea | X | X | X |
| Pelecypoda (pelecypods) | | | |
| Sphaeriidae | | | |
| Sphaerium | | X | |
| Crustacea (ostracodes) | | | |
| Cyprididae | | | |
| Cypris | X | X | |
| Cyprinotus | X | X | X |
| Candona | X | X | X |
| Cyclosyprididae | | | |
| Cyclocypris | | | X |
| Cypria | | | X |
| Ilyocyprididae | | | |
| Ilyocypris | X | X | X |

## VERTEBRATE GENERA

| | Cabbage Patch Beds | | |
|---|---|---|---|
| **Taxonomy** | **L** | **M** | **U** |
| Pisces (Osteichthyes) | | | |
| Amiiformes | | | |
| Amia (bowfin) | X | X | X |
| Cypriniformes | | | |
| Gila (minnow) | X | X | X |
| Amyzon (sucker) | X | X | X |
| Perciformes | | | |
| Lepomis (sunfish) | X | X | X |
| Sciaenidae gen. sp. indet.(drum) | X | X | X |
| Amphibia | | | |
| Anura | | | |
| ?Ascaphus (tailed frog) | X | X | X |
| ?Scaphiopus (pelobatid toad) | X | X | X |
| Tephrodytes (pelodytid toad) | X | X | X |
| ?Rana (large frog) | X | X | X |
| Urodela | | | |
| Taricha (Palaeotaricha) (newt) | | X | |
| Plethodon | | | |

| | | | |
|---|---|---|---|
| (woodland salamander) | | | X |
| Reptilia | | | |
| Chelonia | | | |
| Testudo (tortoise) | X | X | X |
| Gen. sp. indet. (pond turtle) | | | X |
| Aves | | | |
| Galliformes | | | |
| Palaeonossax (cracid) | | X | |
| Charadriformes | | | |
| Gen. sp. indet. | | | |
| (large dowitcher) | | X | |
| Gen. sp. indet. (sandpiper) | X | | |
| Mammalia | | | |
| Marsupialia | | | |
| Herpetotherium | | | |
| (opossums, four sp.) | X | X | X |
| Peradectes | | | |
| (opossums, two sp.) | | X | X |
| Insectivora | | | |
| Ocajila (hedgehog) | X | X | |
| Stenoechinus (hedgehog) | | | X |
| Amphechinus (hedgehog) | | X | X |
| Parvericius (hedgehog) | | X | |
| Gen. sp. indet. (hedgehog) | | X | |
| Mystipterus (mole) | X | X | |
| Proscalops (moles, two sp.) | | X | X |
| Gen. sp. indet. | | | |
| (moles, two gen.) | X | | |
| Domnina (shrews, two sp.) | X | | X |
| Pseudotrimylus | | | |
| (giant shrews, two sp.) | X | | |
| Lagomorpha | | | |
| Palaeolagus (rabbit) | X | | |
| Archaeolagus (rabbit) | | X | |
| Megalagus (rabbit) | X | | |
| Desmatolagus (pika) | X | | |
| Gripholagomys (pika) | | | X |
| Rodentia | | | |
| Downsimus (aplodontid) | | X | |
| ?Allomys (aplodontid) | | X | |
| Niglarodon | | | |
| (aplodontids, three sp.) | X | X | X |
| Meniscomys (aplodontid) | | X | X |
| Gen. sp. indet. | | | |
| (aplodontid, new gen. A) | X | | |
| Gen. sp. indet. | | | |
| (aplodontid, new gen. B) | | X | |
| Gen. sp. indet. | | | |
| (aplodontid, new gen. C) | | X | |
| Gen. sp. indet. (squirrel) | X | X | X |
| Gen. sp. indet. (flying squirrel) | | X | |
| Pseudotheriodomys (eomyid) | X | X | X |

| | | | |
|---|---|---|---|
| Gen. sp. indet. (eomyids, four sp.) | X | X | X |
| Pleurolicus (gophers, three sp.) | | X | |
| Tenudomys (small gopher) | | X | X |
| Gregorymys (gophers, three sp.) | | | X |
| Entoptychus (gopher) | | | X |
| Mookomys (pocket mouse) | | | X |
| Agnotocastor (beaver) | X | | |
| Monosaulax (beavers, two sp.) | | X | X |
| ?Capatanka (beaver) | | X | |
| ?Euhapsis (beaver) | | | X |
| Eutypomys (beavers, two sp.) | X | X | |
| Gen. sp. indet. (new beaver) | X | X | |
| Leidymys (mice, two sp.) | X | X | X |
| Paciculus (mouse) | | X | X |
| Plesiosminthus (jumping mice, two sp.) | X | X | X |
| Parasminthus (jumping mice, two sp.) | X | X | X |
| Carnivora | | | |
| ?Cynodesmus (coyote-sized canid) | | X | |
| Gen. sp. indet. (small fox-sized canid) | X | X | X |
| Gen. sp. indet. (bobcat-sized felid) | | X | |
| Gen. sp. indet. (mink-sized mustelid) | X | | |
| Gen. sp. indet. (weasel-sized mustelid) | X | | |
| Perissodactyla | | | |
| Miohippus (three-toed horse) | | X | X |
| Parahippus? (three-toed horse) | | | X |
| Diceratherium (large rhinoceros) | X | X | |
| Gen. sp. indet. (Hyracodon-sized rhino) | | X | |
| Artiodactyla | | | |
| Gen. sp. indet. (peccary) | X | | |
| Daeodon (medium-sized entelodontid) | X | | |
| Kukusepasutanka (anthracothere) | X | | |
| Megoreodon (oreodontids, two sp.?) | X | X | |
| Desmatochoerus (oreodontids, three sp.?) | X | | |
| Gen. sp. indet. (small oreodontid) | | | X |
| Pronodens (small ruminants, two sp.) | X | X | X |

## APPENDIX G:
## Faunal list for the Barstovian Flint Creek Beds
(modified from Rasmussen, 1969, Craig Christensen, written comm., 2005)
*found during this study

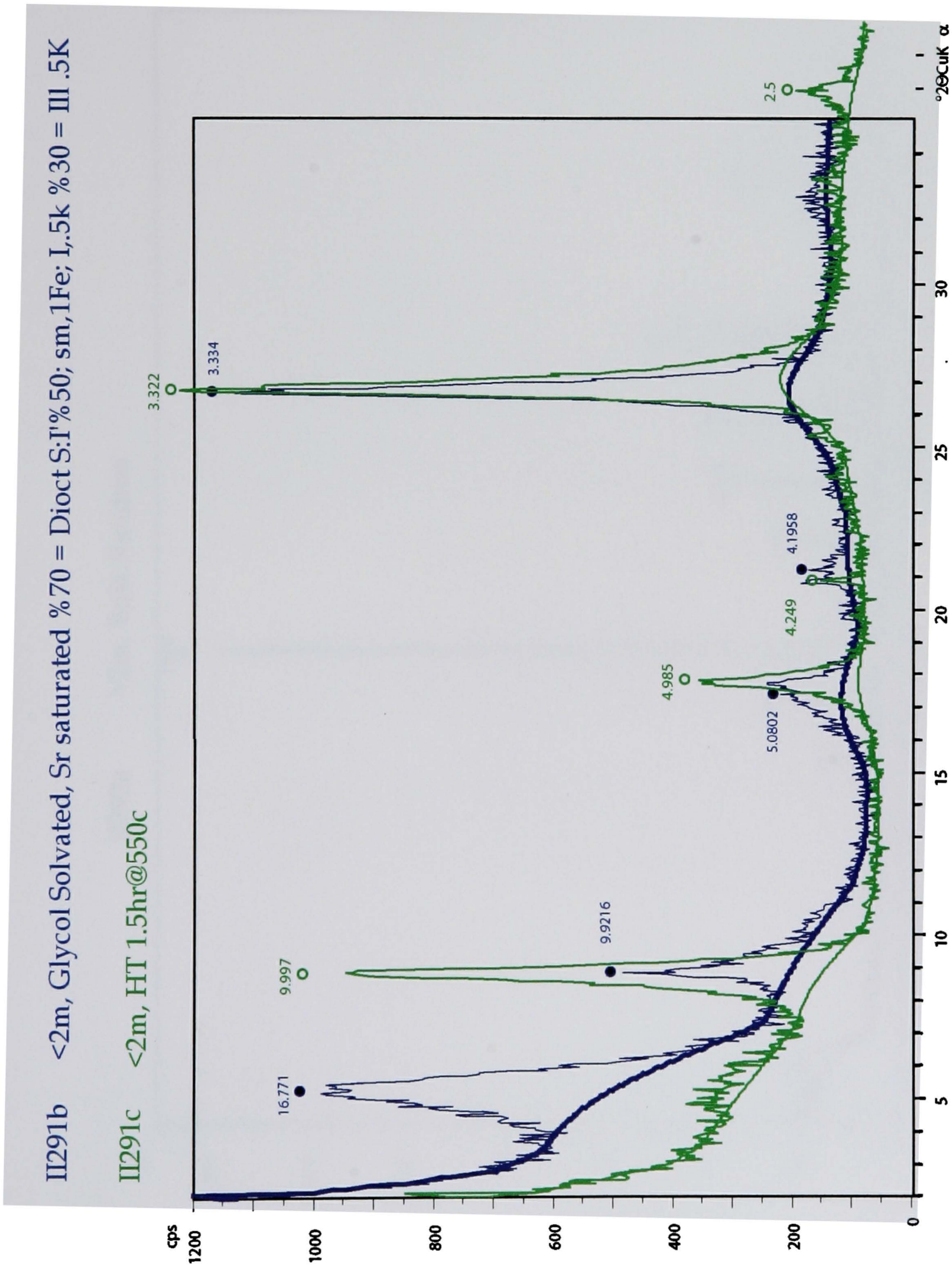
| Class | Order | Family | Genus- Species |
|---|---|---|---|
| Amphibia | | | |
| | Anura | | |
| | | Salienta | ? |
| Reptilia | | | |
| | Chelonia | | |
| | | Testudo | |
| | Squamata | | |
| | | Boidae | ? |
| Mammalia | | | |
| | Insectivora | | |
| | | Talipidae | ? |
| | Lagomorpha | | |
| | | Leporidae | *Hypolagus sp.* |
| | | | *Oreolagus sp.* |
| | Rodentia | | |
| | | *Sciuridae | *Citellus?* |
| | | Mylagaulidae | *Mylagaulus* |
| | | ?Geomyidae | |
| | Carnivora | | |
| | | ?Felidae | |
| | | Canidae | *Tomarctus cf. rurestris* |
| | Perissodactyla | | |
| | | *Equidae | *Merychippus sp.* |
| | | | *?Parahippus sp.* |
| | | | *Archaeohippus ultimus* |
| | | *Rhinoceratoidae | ? |
| | Artiodactyla | | |
| | | | *Dromomeryx borealis* |
| | | Antilocapridae | *Merycodus sp.* |
| | | Camelidae | ? |
| | | Merycoidodontidae | *Ticholeptus zygomaticus* |
| | | Oreodontid | ? |

## APPENDIX H:
## Faunal list for the Barstovian-Clarendonian Barnes Creek beds

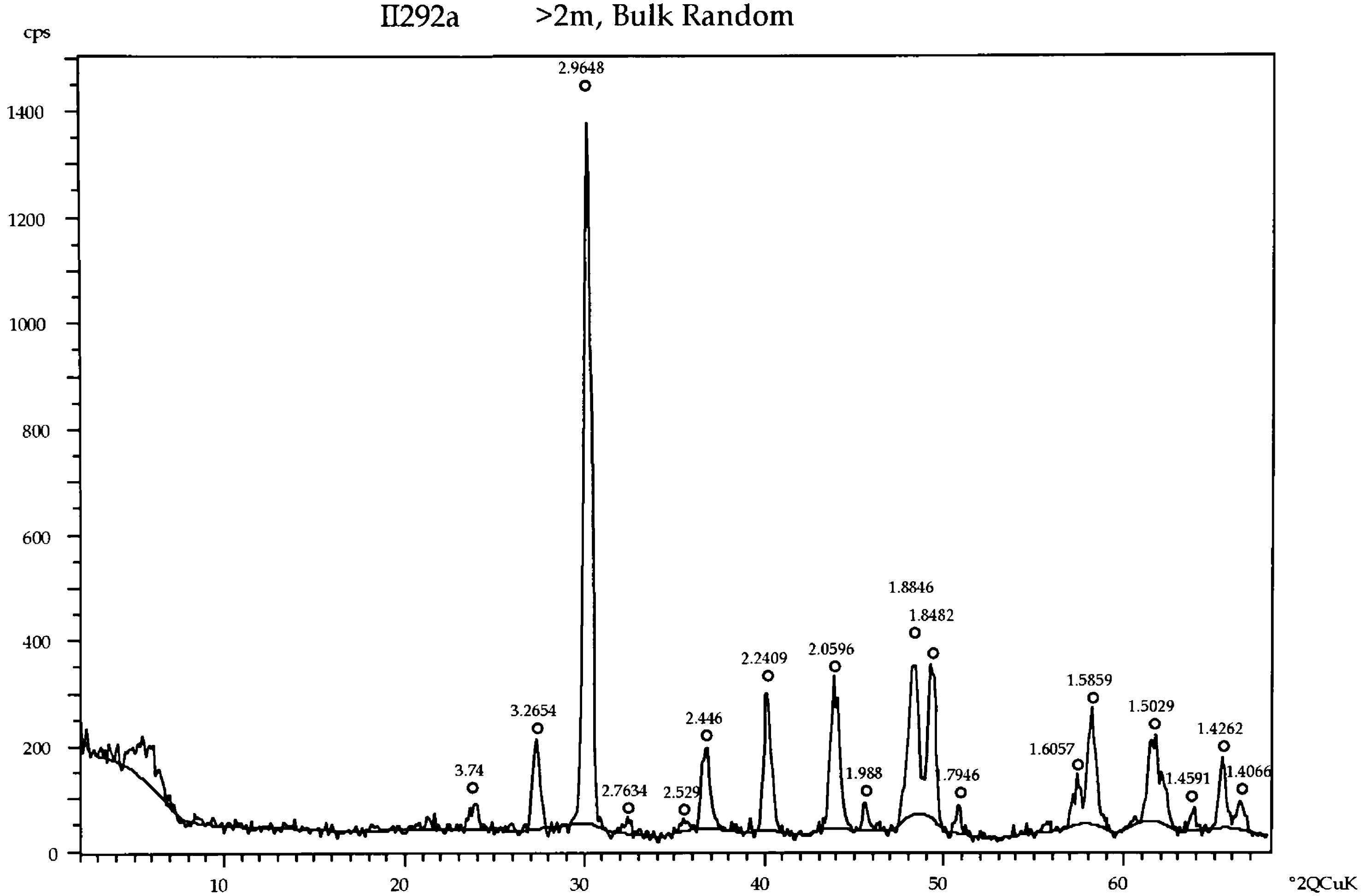
| Class | Order | Family | Genus- Species |
|---|---|---|---|
| Amphibia | | | |
| | Numerous unidentified frogs and salamanders | | |
| Reptilia | | | |
| | Numerous unidentified lizard and snake vertebrae | | |
| Aves | | | |
| | Several unidentified birds | | |
| Mammalia | | | |
| | Carnivora | | |
| | | Several unidentified teeth | |
| | Insectivora | | |
| | | Several unidentified moles and shrews | |
| | Lagomorpha | | |
| | | Leporidae | *?Hypolagus sp.* |
| | | | *Oreolagus sp.* |
| | Rodentia | | |
| | | Mylagaulids | |
| | | Sciurids | |
| | | Aplodontids | |
| | | Eomyids | |
| | | Cricetids | |
| | | Heteromyids | |
| | | Geomyids | |
| | Perissodactyla | | |
| | | Equidae | *Hypohippus sp.* (clarendonian) |
| | | | *Merychippus sp.* |
| | | | *Megahippus sp.* (clarendonian) |
| | | | *Pliohippus sp.* (clarendonian) |
| | | Rhinoceratoidae | ? |
| | Artiodactyla | | |
| | | | *?Blastomeryx* |
| | | | *?Dromomeryx sp.* |
| | | Antilocaparidae | *?Merycodus sp.* (clarendonian) |
| | | Camelidae | ? |
| Unidentified oreodontids | | | |
| | Salientia | ? | |
| | Proboscidea? | ? | |

# APPENDIX I: X-Ray Diffraction patterns

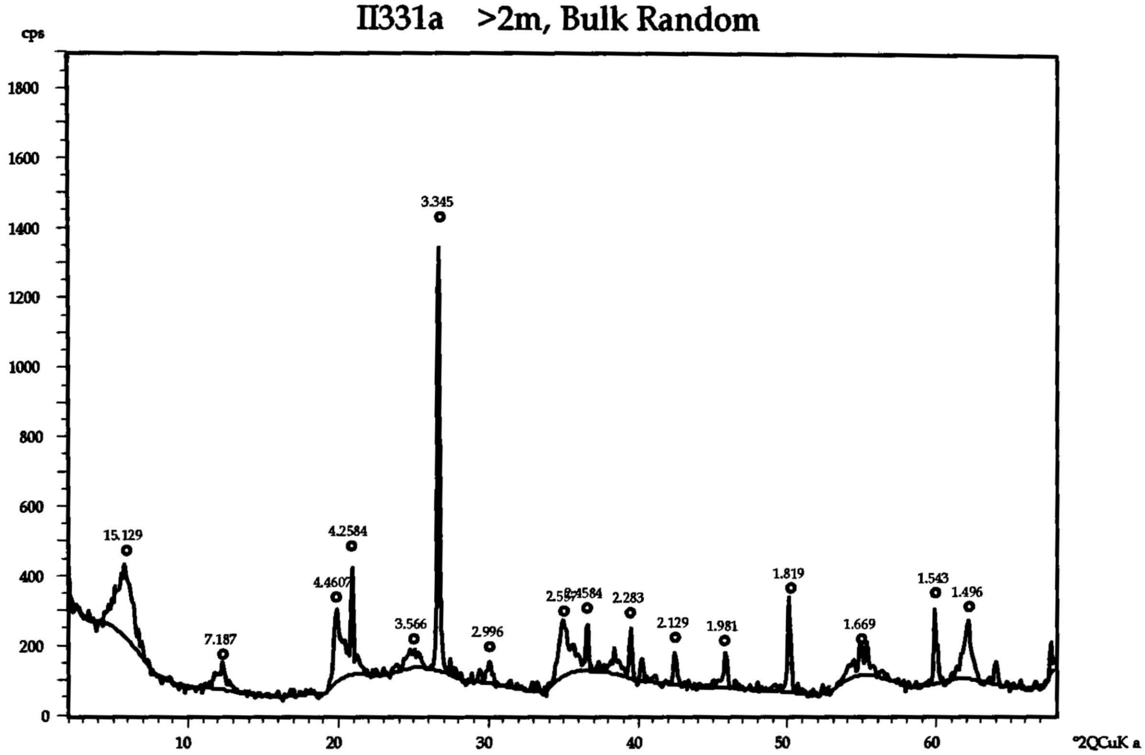
see Plate 1, Plate 3, figure 26, appendix C, appendix D for sample location.
peak values are in D-spacing; y-axis is in counts per second (cps);
x-axis in 2-theta



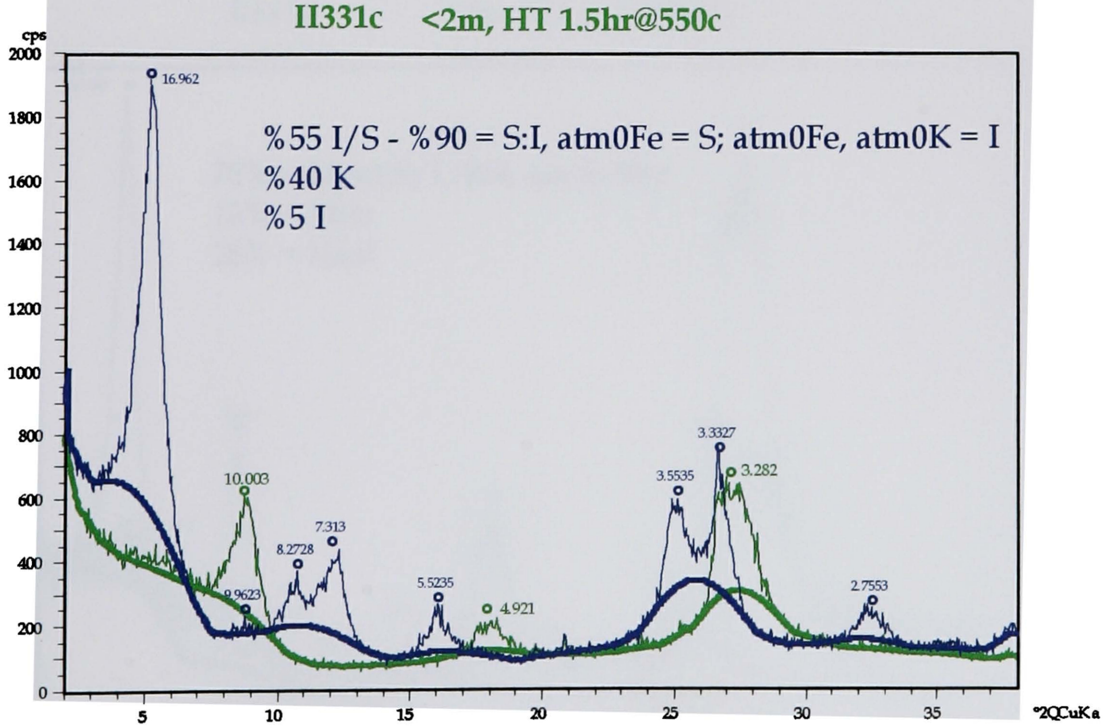
II292a >2m, Bulk Random



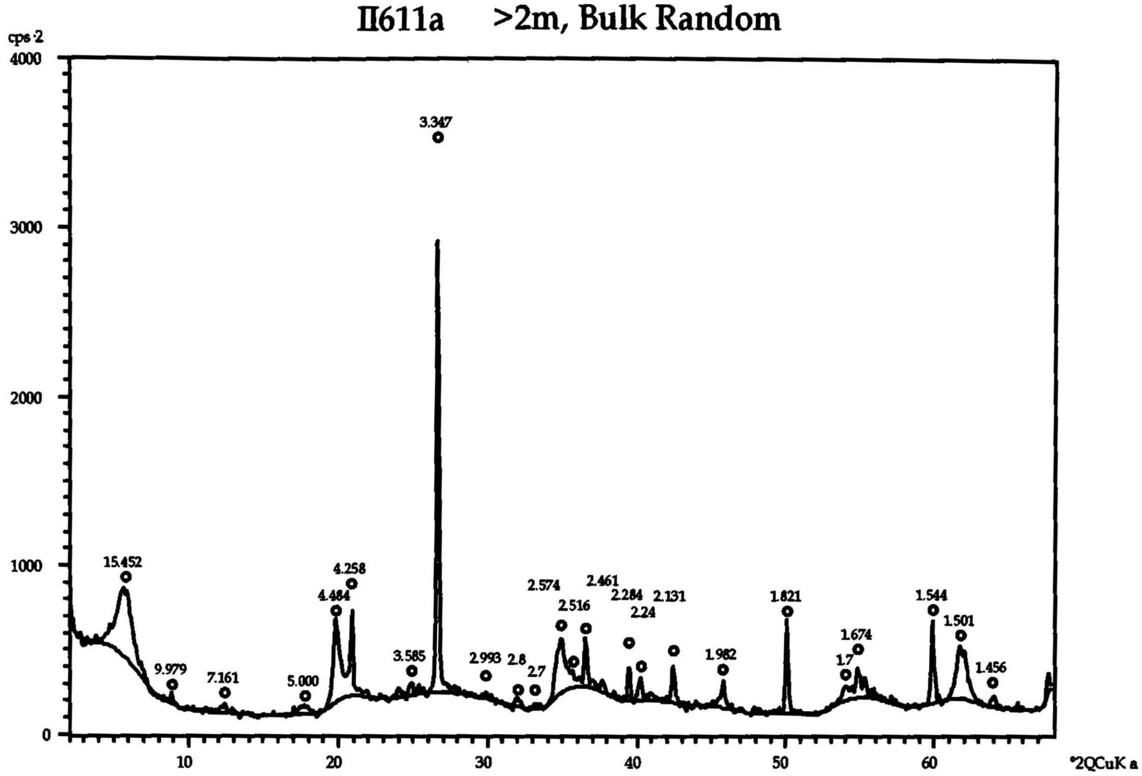
II331a >2m, Bulk Random

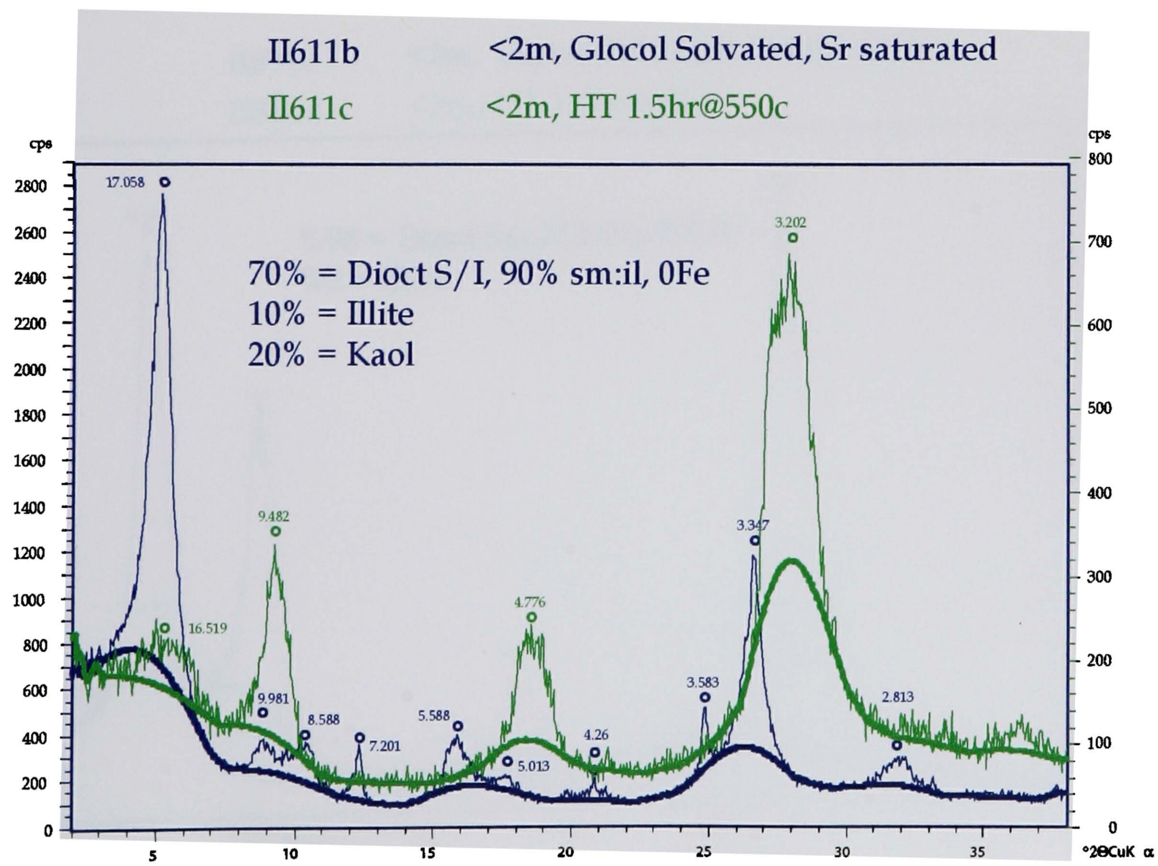


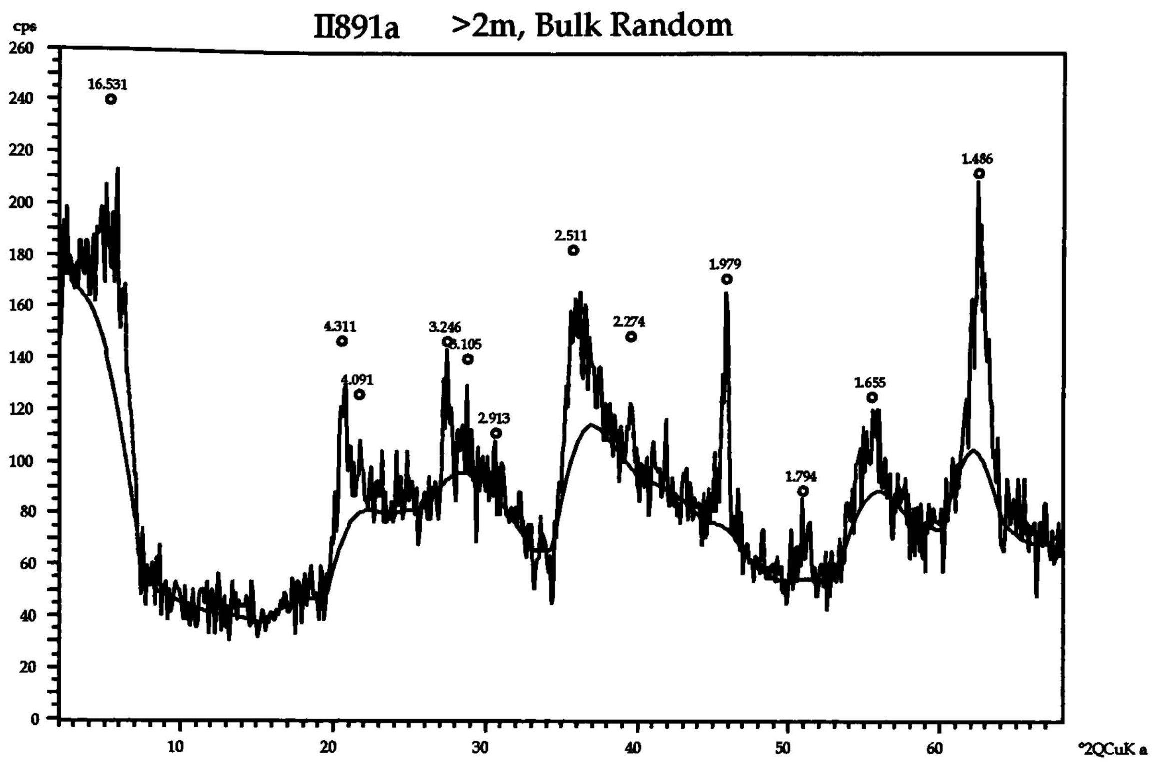

II331b <2m, Glycol Solvated, Sr Saturated
II331c <2m, HT 1.5hr@550c

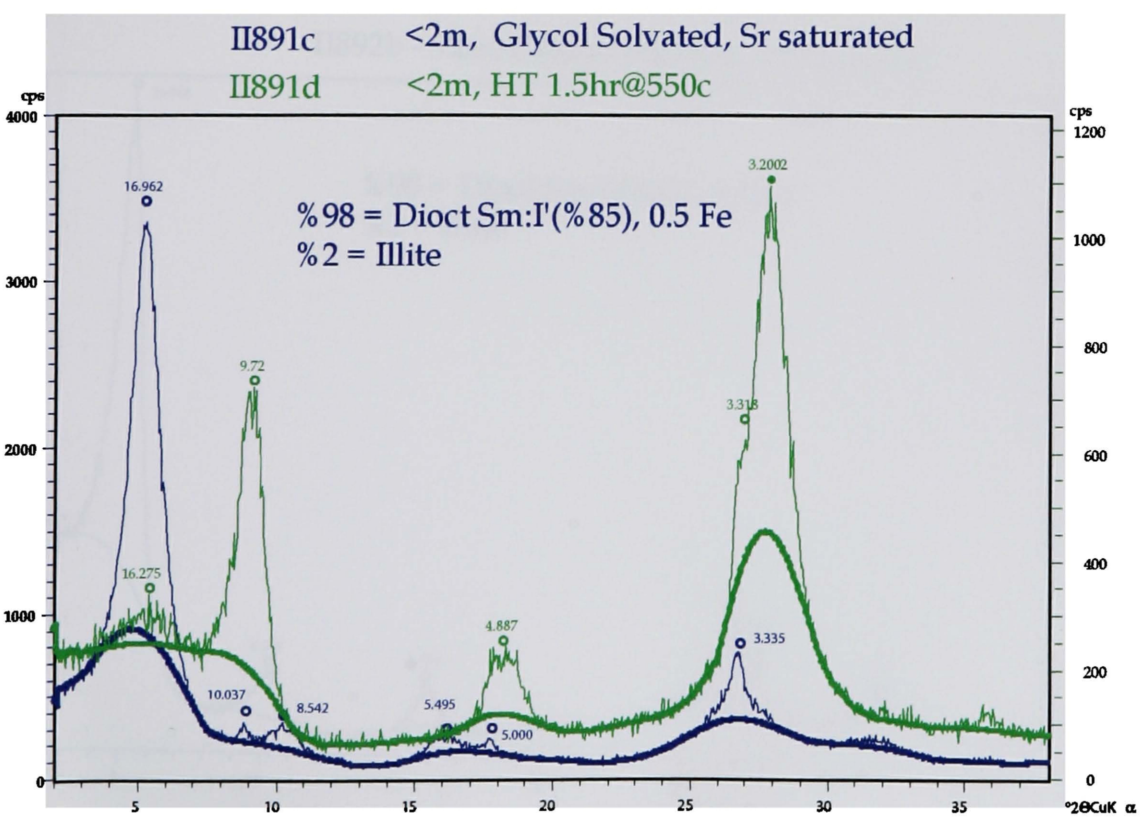


# II611a >2m, Bulk Random

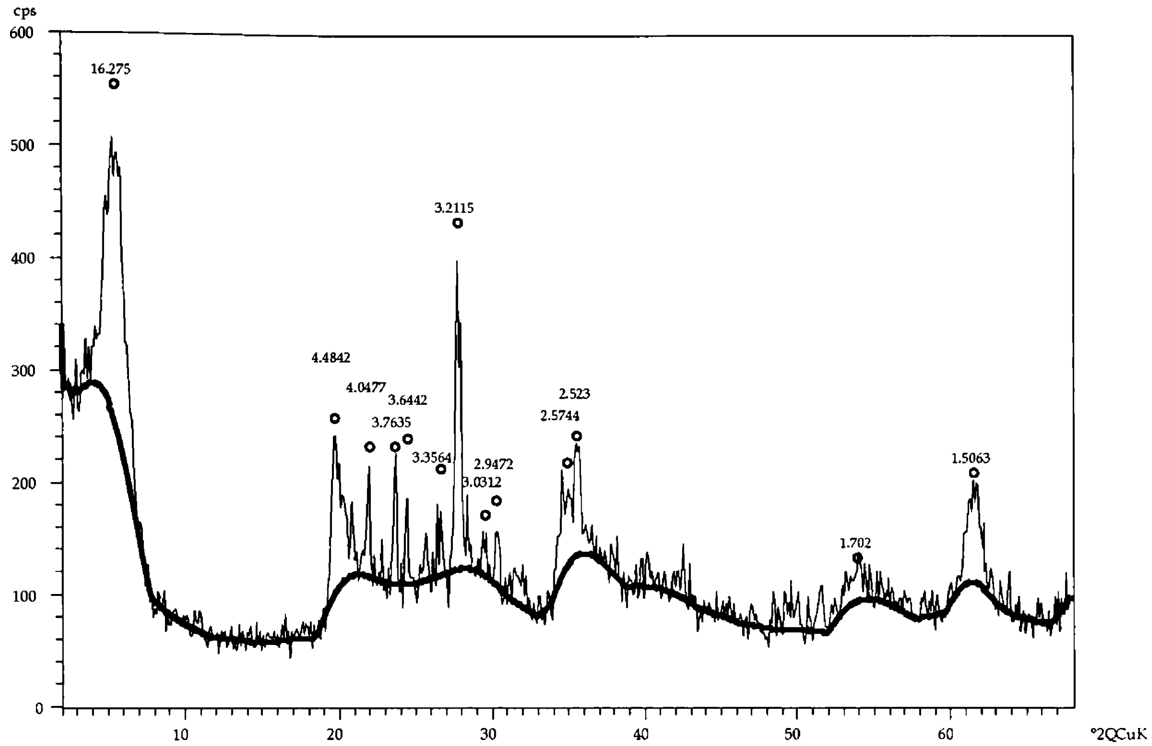


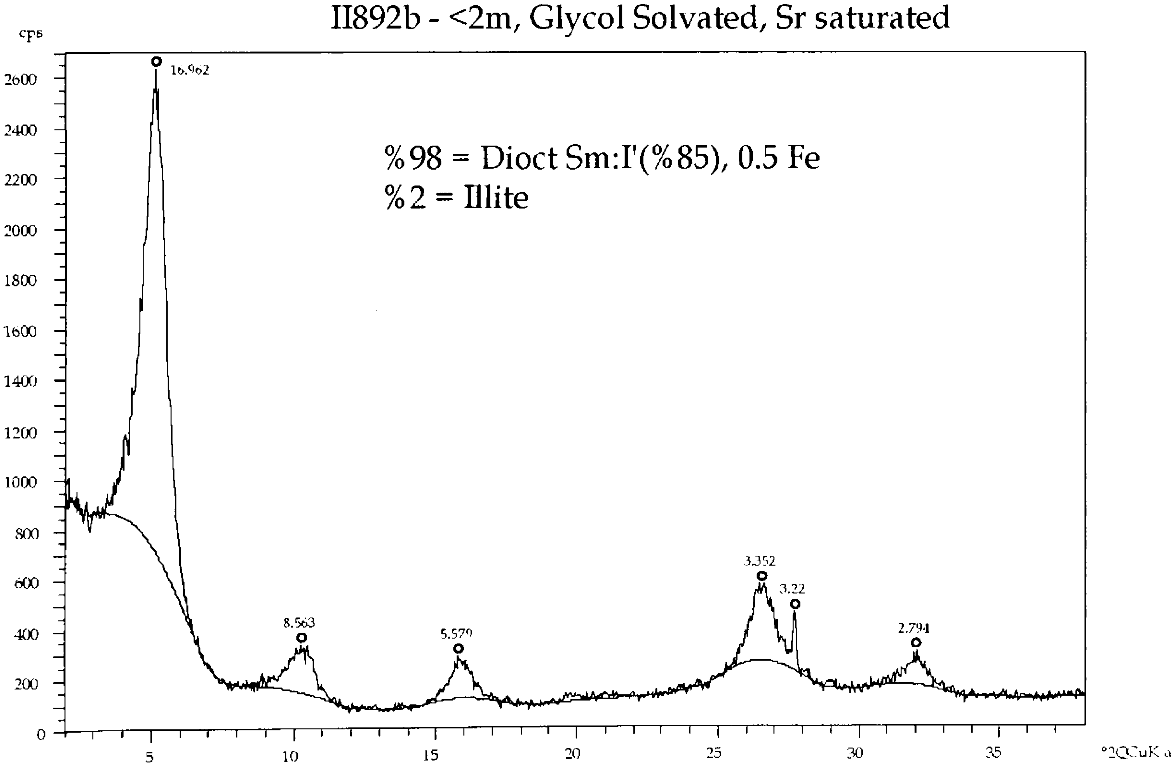

II891a >2m, Bulk Random
cps
260
240
220
200
180
160
140
120
100
80
60
40
20
0
16.531
4.311
4.091
3.246
3.105
2.913
2.511
2.274
1.979
1.794
1.655
1.486
10
20
30
40
50
60
°2QCuK a


II891c <2m, Glycol Solvated, Sr saturated
II891d <2m, HT 1.5hr@550c
%98 = Dioct Sm:I'(%85), 0.5 Fe
%2 = Illite
cps
4000
3000
2000
1000
0
cps
1200
1000
800
600
400
200
0
16.962
16.275
9.72
10.037
8.542
5.495
5.000
4.887
3.318
3.2002
3.335
5
10
15
20
25
30
35
°2θCuK α

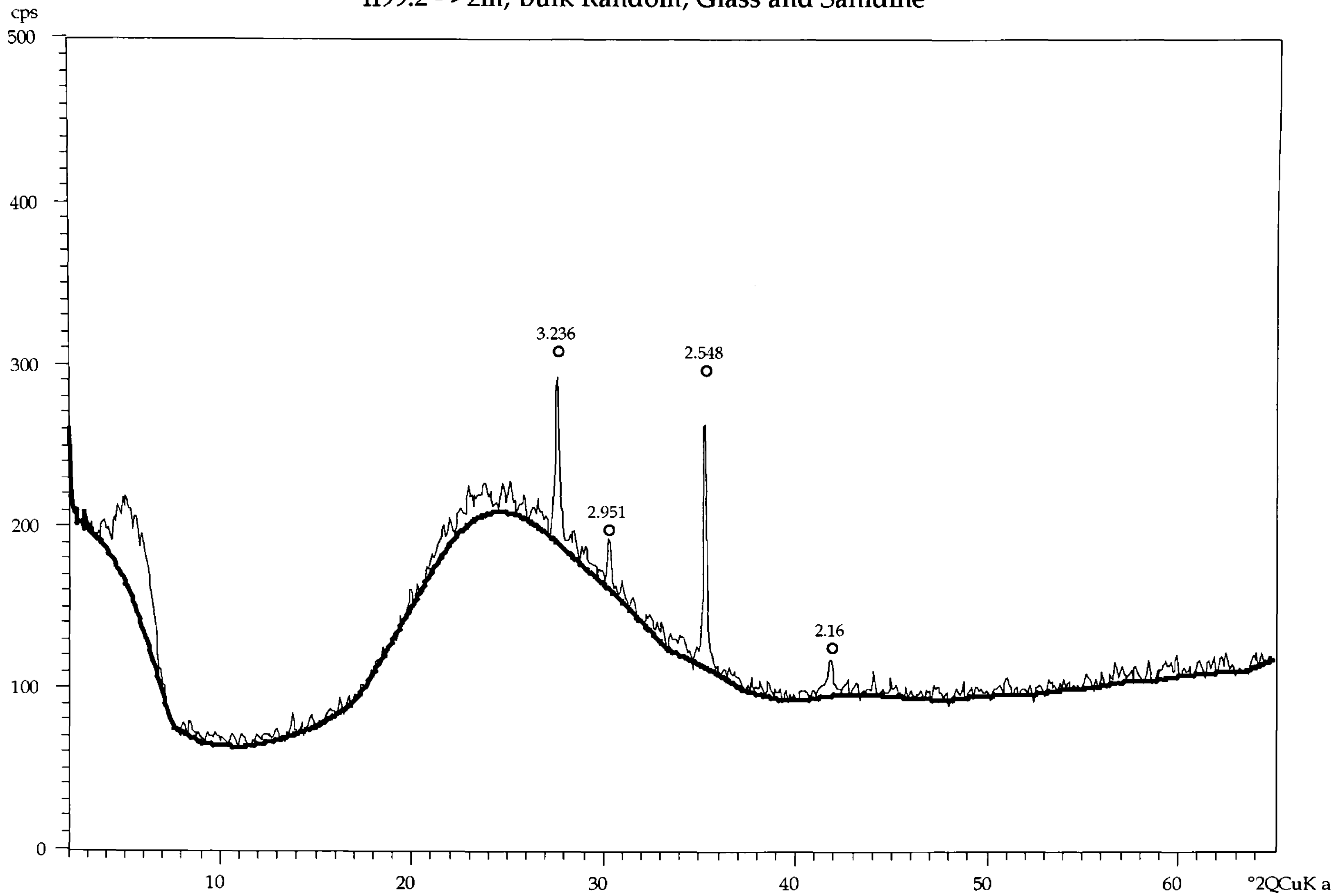
II892a - >2m, Bulk Random

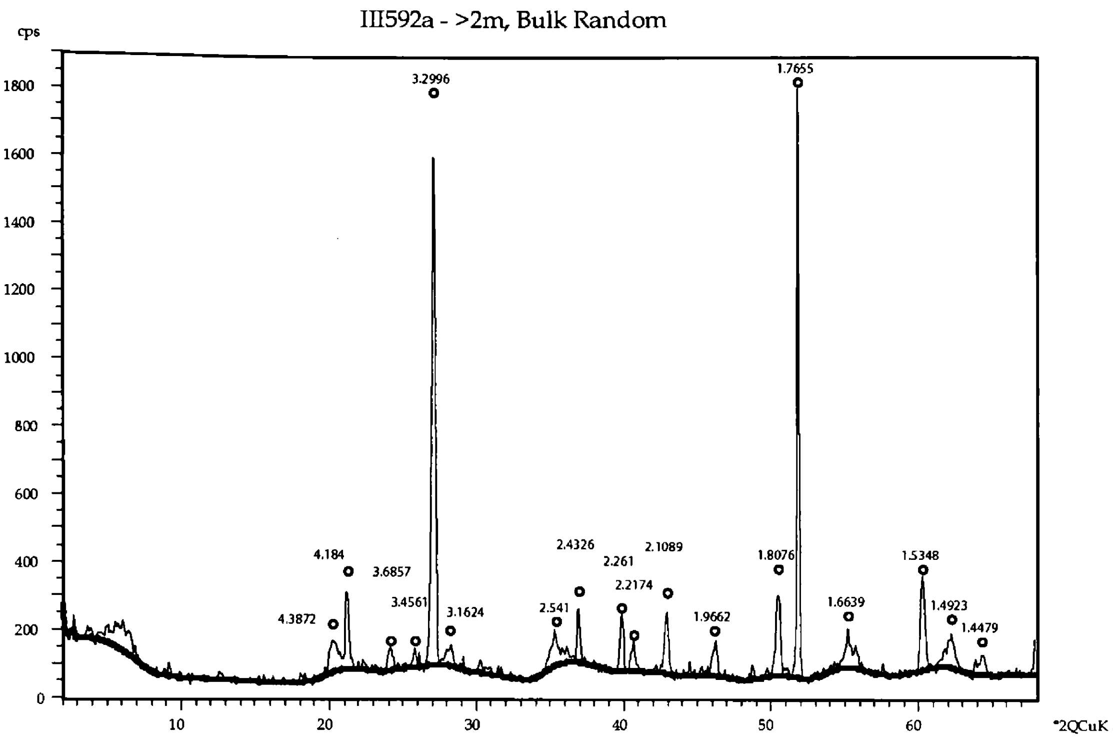


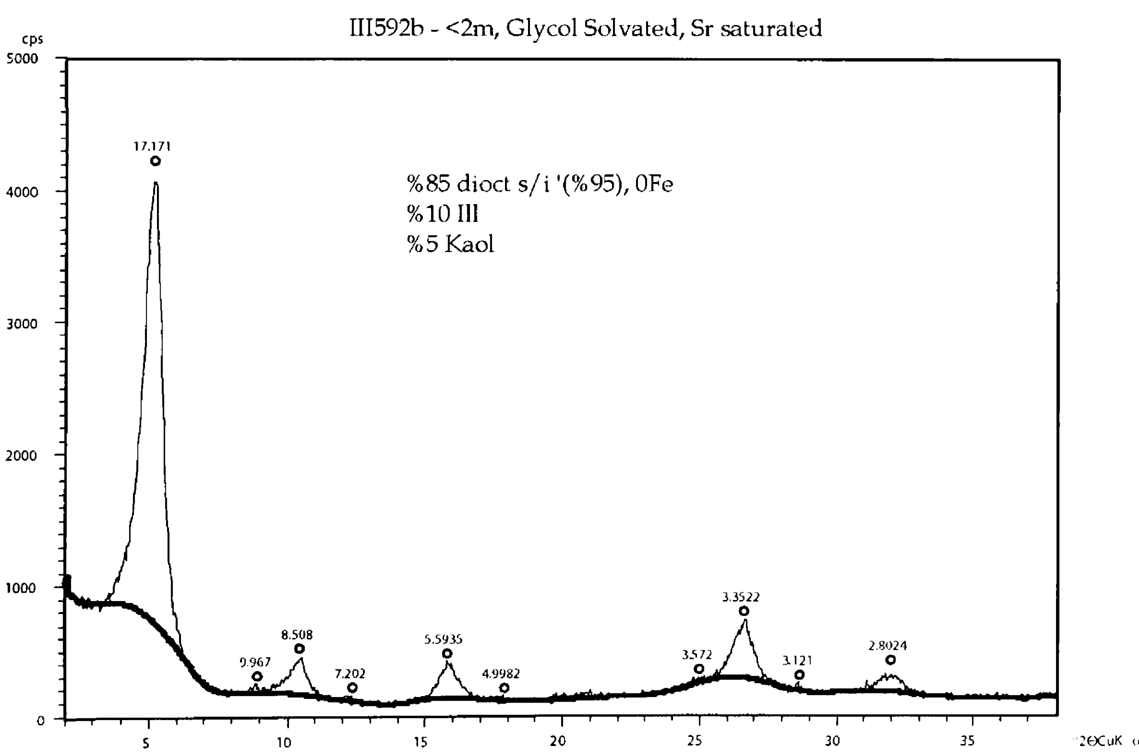

II892b - <2m, Glycol Solvated, Sr saturated



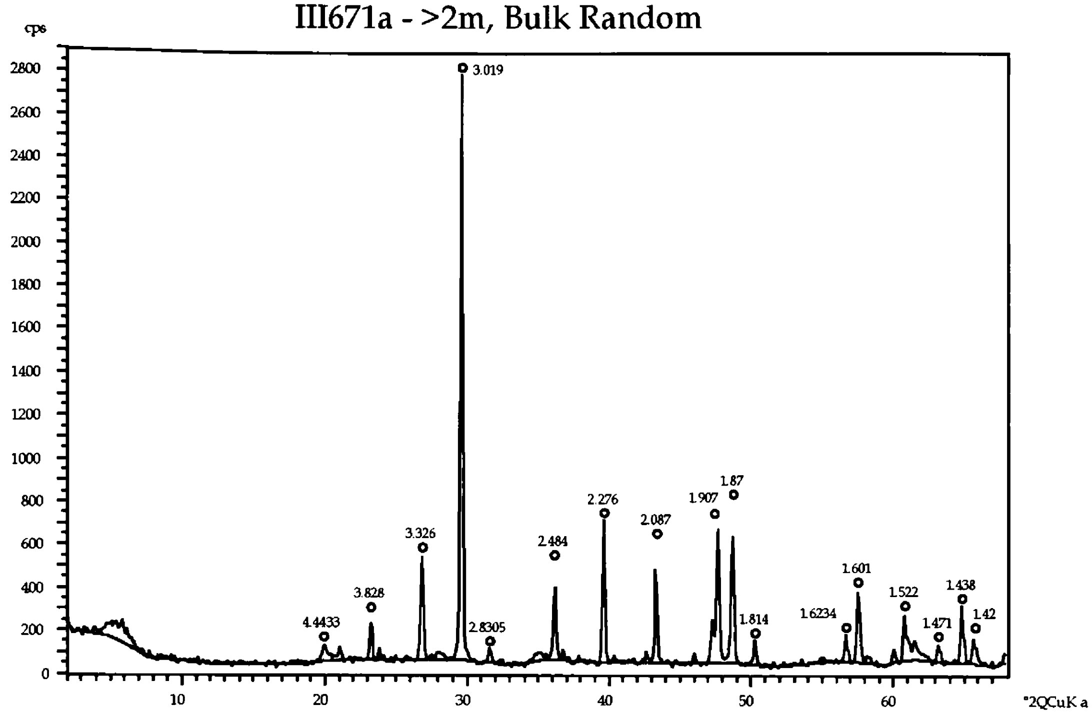
II99.2 - >2m, Bulk Random, Glass and Sanidine



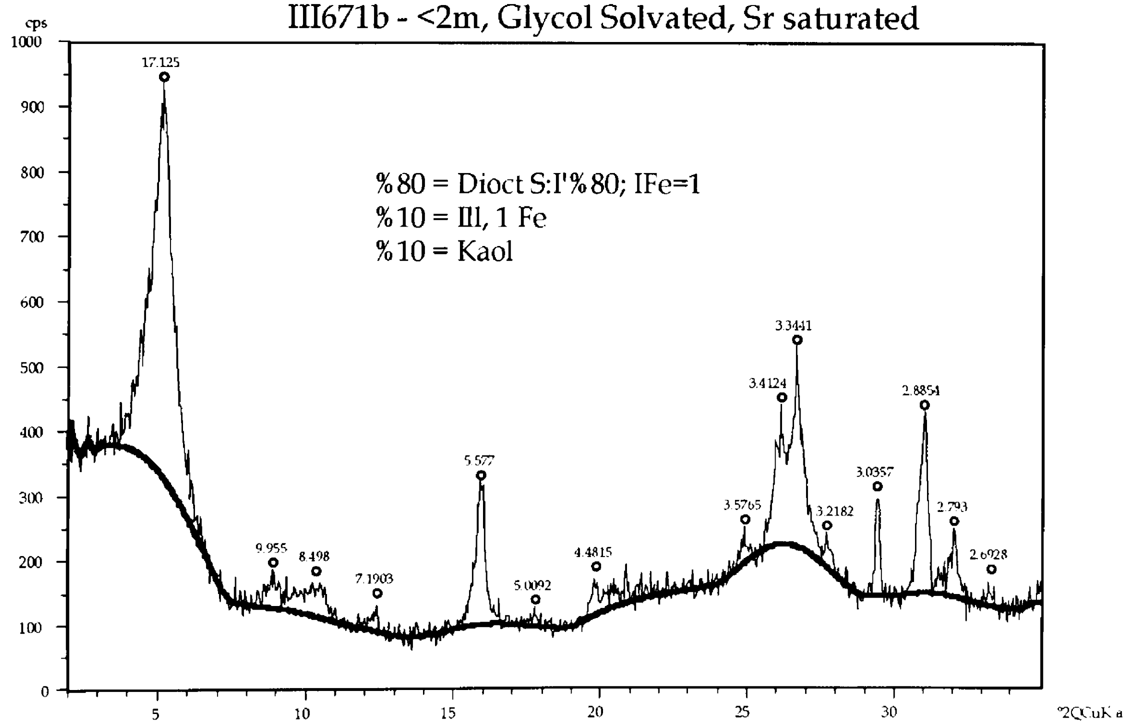

III592a - >2m, Bulk Random
cps
3.2996
1.7655
4.184
3.6857
4.3872
3.4561
3.1624
2.4326
2.261
2.1089
2.2174
2.541
1.9662
1.8076
1.6639
1.5348
1.4923
1.4479
°2QCuK a


III592b - <2m, Glycol Solvated, Sr saturated
cps
17.171
%85 dioct s/i '(%95), 0Fe
%10 Ill
%5 Kaol
9.967
8.508
7.202
5.5935
4.9982
3.572
3.3522
3.121
2.8024

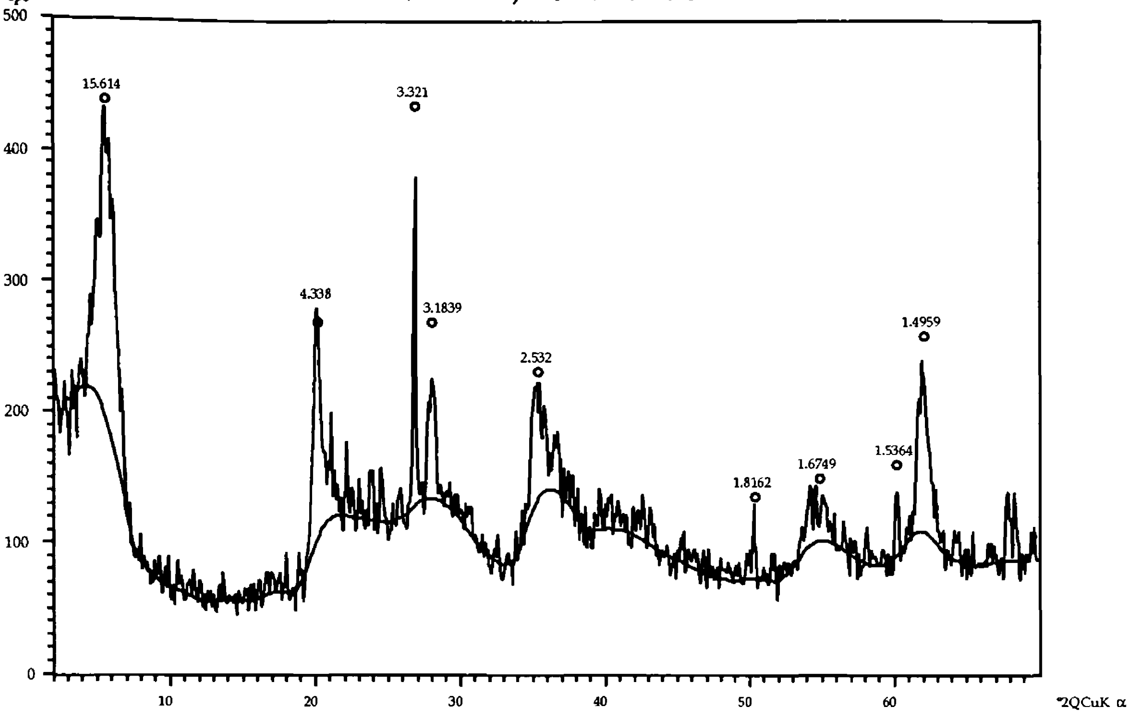
## III671a - >2m, Bulk Random



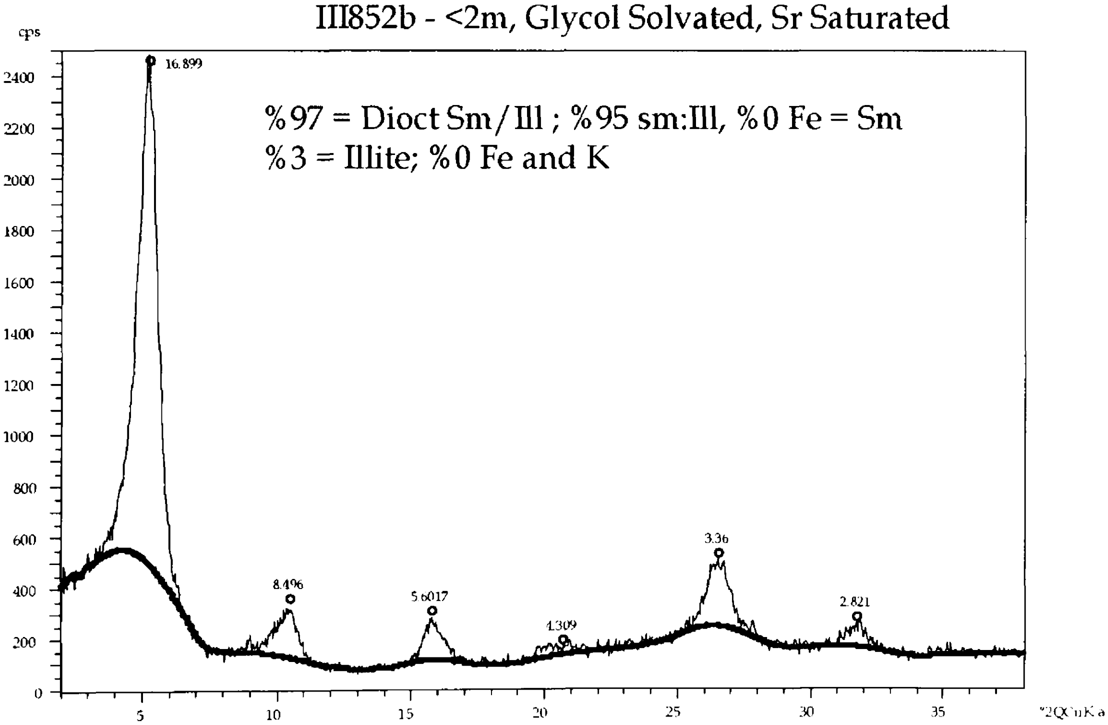

## III671b - <2m, Glycol Solvated, Sr saturated



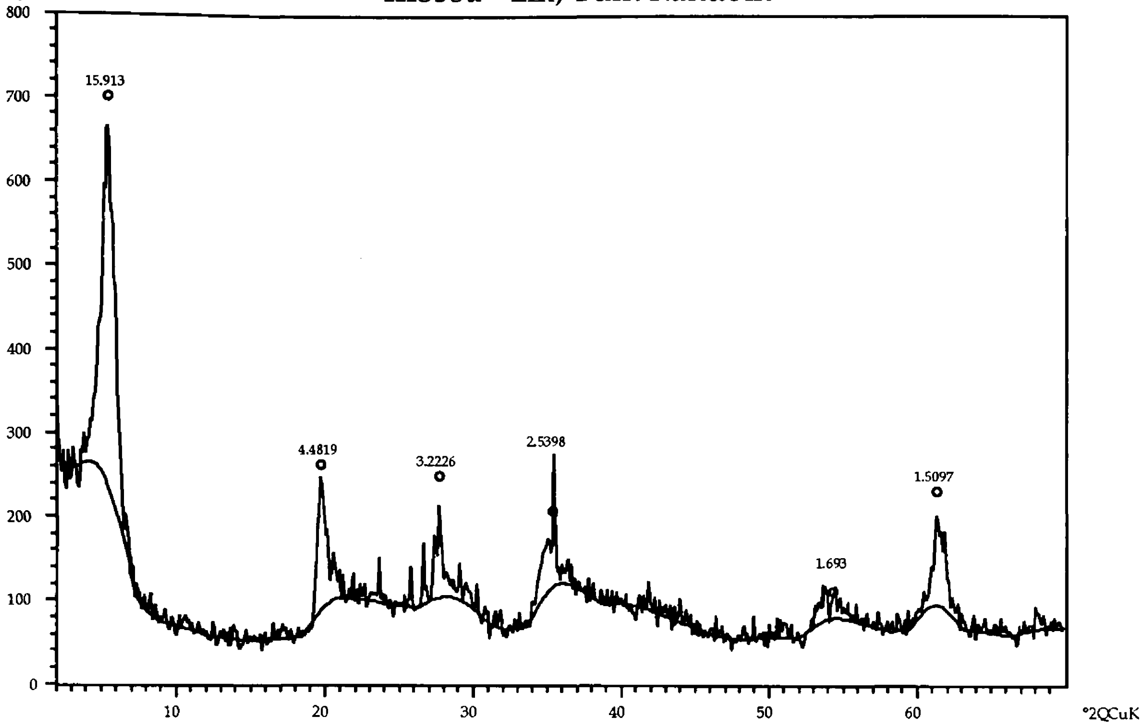
III852a - >2m, Bulk Random



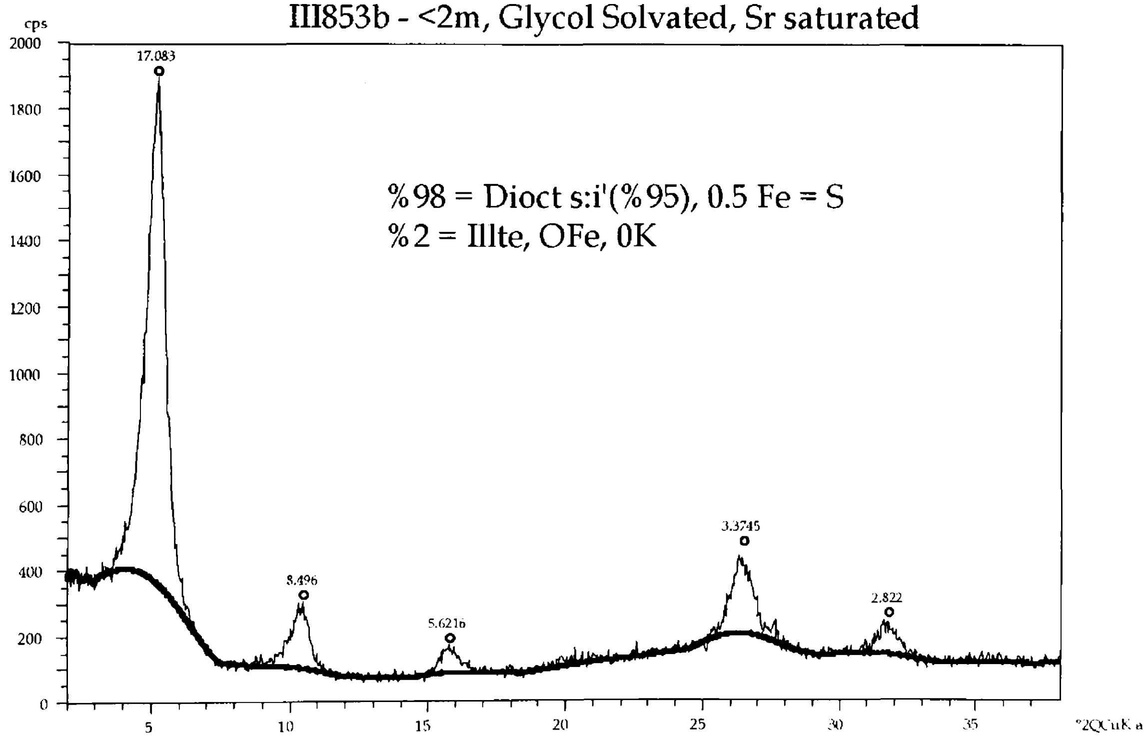

III852b - <2m, Glycol Solvated, Sr Saturated



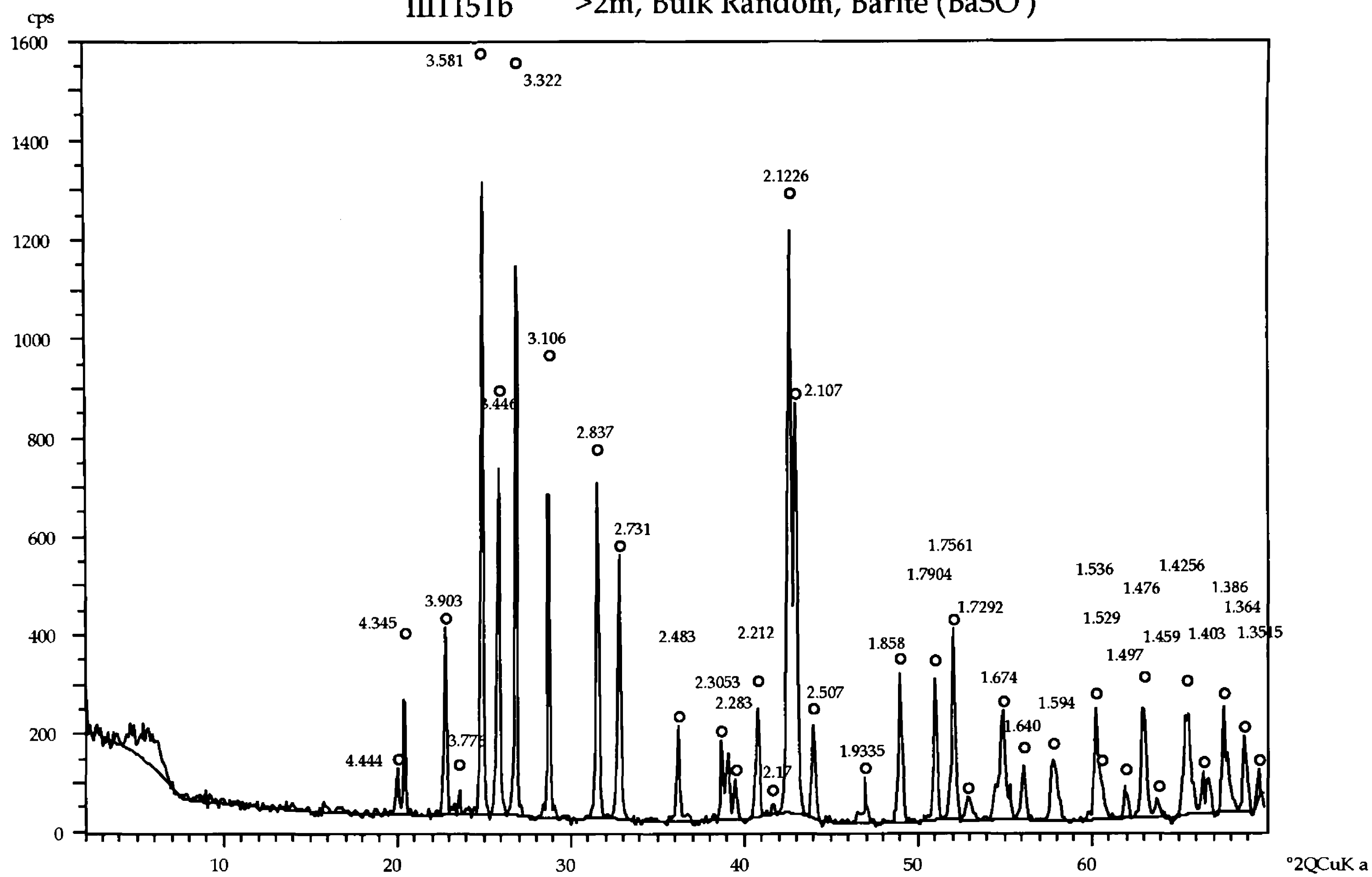
# III853a >2m, Bulk Random




# III853b - <2m, Glycol Solvated, Sr saturated



III1151b >2m, Bulk Random, Barite ($BaSO^4$)



| APPENDIX J: Clast count data from post mid-miocene unconformity strata | | | | | | |
|---|---|---|---|---|---|---|
| Provenance | Clast Lithology | Sample and Clast Percentages | | | | |
| | | RAPIII117<br>Tscfg | RAPIII59<br>Tscb | RapII87<br>Tscb | RAPII42<br>Tscgs | RAPII137<br>Qlo |
| Prot | Argt/Sltit/gy qtz | 19.61 | 7.95 | 13.04 | 5.06 | 0.00 |
| Prot | Red/Pink/Mrn SS/qtz | 17.65 | 12.50 | 13.04 | 18.99 | 0.00 |
| Pz | Qtz (white/tan/brown) | 27.45 | 25.00 | 40.58 | 34.18 | 0.00 |
| Mm-Pp | chert-chert breccia | 0.00 | 2.27 | 1.45 | 2.53 | 0.00 |
| Cret | Lithic SS | 15.69 | 39.77 | 8.70 | 15.19 | 26.00 |
| Mez | Mud/Porcl | 5.88 | 1.14 | 5.80 | 13.92 | 74.00 |
| Cnz | Tffcs Sed | 5.88 | 0.00 | 1.45 | 1.27 | 0.00 |
| ?? (Cz) | White/tan SS-slt | 0.00 | 5.68 | 10.14 | 3.80 | 0.00 |
| Ign | Plutonic | 7.84 | 5.68 | 5.80 | 5.06 | 0.00 |
| | total clasts | 51 | 88 | 69 | 79 | 50 |

Argt - Argillite
Sltit - Siltite
Qtz - Quartzite
SS - Sandstone
Mud - Mudstone
Porcl - Porcellanite
Sed - Sedimentary
Tffcs - Tuffaceous

Mrn - Maroon

| APPENDIX K: Point Count Data of Arikareean Trcp sandstones | | | | | | | |
|---|---|---|---|---|---|---|---|
| * Gazzi-Dickinson method used | | | | | | | |
| | II3.3-f,m | III27.2a-c | III27.2b-m | II51.1a-v.c | II51.1b-v. | II53.1-m | *III27.1a-v.c. |
| Qm | 30.8 | 15.6 | 27.4 | 20.4 | 36 | 31.8 | 24.6 |
| Qp | 6 | 10.8 | 8.2 | 11 | 10.2 | 8 | 17 |
| Chrt | 0.4 | 2 | 1.6 | 2.8 | 0.8 | 2 | 0.4 |
| Plg | 18.6 | 11.4 | 16.2 | 15 | 16.4 | 16.8 | 22.2 |
| Kspr | 7.4 | 7.2 | 6.2 | 3.2 | 2.6 | 3 | 9.4 |
| Prx | 0 | 0 | 0.8 | 0.2 | 0.6 | 0.6 | 0.2 |
| Musc | 0.2 | 1.6 | 1 | 0.6 | 1.4 | 3.2 | 2 |
| Biot | 6.6 | 2.2 | 3.8 | 1 | 4.2 | 8.6 | 2.8 |
| Hbde | 1 | 0.4 | 1 | 0.6 | 2 | 1.2 | 0.8 |
| Olv | 0 | 0 | 0 | 0.2 | 0 | 0.2 | 0.2 |
| Ls | 3 | 10.4 | 6.8 | 14.2 | 5.6 | 5 | 6.4 |
| Lv | 9.4 | 9.6 | 10.6 | 5.4 | 12 | 6.2 | 7.8 |
| Lp | 14.2 | 23.6 | 14.2 | 20.8 | 4.4 | 10 | 0 |
| Lm | 1.4 | 4.2 | 1.4 | 3.8 | 1.8 | 1.2 | 4.4 |
| Hvs | 0 | 0 | 0.2 | 0 | 0.4 | 0.2 | 0.6 |
| Opq | 0.4 | 0.2 | 0 | 0.2 | 1.6 | 0.6 | 0.4 |
| Chlr+altr | 0.6 | 0.8 | 0.6 | 0.6 | 0 | 1.4 | 0.8 |
| TOTAL | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| QFL - TOT | 91.2 | 94.8 | 92.6 | 96.6 | 89.8 | 84 | 92.2 |
| Q | 0.408 | 0.300 | 0.402 | 0.354 | 0.523 | 0.498 | 0.456 |
| F | 0.285 | 0.196 | 0.242 | 0.188 | 0.212 | 0.236 | 0.343 |
| L | 0.307 | 0.504 | 0.356 | 0.458 | 0.265 | 0.267 | 0.202 |
| Qm TOT | 90.8 | 92.8 | 91 | 93.8 | 89 | 82 | 91.8 |
| Qm | 0.339 | 0.168 | 0.301 | 0.217 | 0.404 | 0.388 | 0.268 |
| F | 0.286 | 0.200 | 0.246 | 0.194 | 0.213 | 0.241 | 0.344 |
| Lt | 0.374 | 0.631 | 0.453 | 0.588 | 0.382 | 0.371 | 0.388 |
| Orogen TOT | 18.8 | 32.8 | 27.2 | 33.4 | 28.6 | 21.2 | 31.6 |
| Qp | 0.340 | 0.390 | 0.360 | 0.413 | 0.385 | 0.472 | 0.551 |
| Lv | 0.500 | 0.293 | 0.390 | 0.162 | 0.420 | 0.292 | 0.247 |
| Ls | 0.160 | 0.317 | 0.250 | 0.425 | 0.196 | 0.236 | 0.203 |
| Granitic Maturity | 56.8 | 34.2 | 49.8 | 38.6 | 55 | 51.6 | 56.2 |
| Qm | 0.542 | 0.456 | 0.550 | 0.528 | 0.655 | 0.616 | 0.438 |
| P | 0.327 | 0.333 | 0.325 | 0.389 | 0.298 | 0.326 | 0.395 |
| K | 0.130 | 0.211 | 0.124 | 0.083 | 0.047 | 0.058 | 0.167 |
| Lithic-TOT | 28 | 47.8 | 33 | 44.2 | 23.8 | 22.4 | 18.6 |
| Ls | 0.107 | 0.218 | 0.206 | 0.321 | 0.235 | 0.223 | 0.344 |
| Lm | 0.050 | 0.088 | 0.042 | 0.086 | 0.076 | 0.054 | 0.237 |
| Lp+Lv | 0.843 | 0.695 | 0.752 | 0.593 | 0.689 | 0.723 | 0.419 |
| Ign-Accs | 7.8 | 4.2 | 5.8 | 2.2 | 7.6 | 13 | 5.6 |
| Biot | 0.846 | 0.524 | 0.655 | 0.455 | 0.553 | 0.662 | 0.500 |
| Musc | 0.026 | 0.381 | 0.172 | 0.273 | 0.184 | 0.246 | 0.357 |
| Hbde | 0.128 | 0.095 | 0.172 | 0.273 | 0.263 | 0.092 | 0.143 |