LARAMIDE SYNOROGENIC SEDIMENTATION IN SOUTH-CENTRAL NEW MEXICO: PETROLOGIC EVOLUTION OF THE MCRAE BASIN

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1986

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements of the degree of Master of Science (Geology).

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ABSTRACT

The McRae basin in Socorro and Sierra counties, New Mexico, contains up to 2500 m of Cretaceous and Tertiary(?) fill. Lithostratigraphic units include the Cretaceous Dakota and Mancos formations, the Mesaverde Group and the Cretaceous/Tertiary(?) McRae Formation.

Statistical analysis of detrital-mode ratios, determined from petrographic point-counting of specimens from these units, reveals the existence of five petrofacies (student's t-test, 95% confidence). Petrofacies are sedimentary units distinguished on the basis of detrital petrology and are related to distinct source terranes that provided detritus to the basin during its evolution:

1) The Dakota Formation, derived from distant erosion of non-volcanic supracrustal sediments and some plutonic and metamorphic basement rocks

2) The Mesaverde Group, derived from erosion of sedimentary terranes to the south and west during early stages, from sedimentary and volcanic terranes to the south and west during the middle to late stages, and finally from the Caballo uplift to the southeast and southwest (Ash Canyon Member)

3) The Jose Creek Member of the McRae Formation, derived almost exclusively from the petrologically similar Damsite intrusion on the southwestern margin of the basin

4) The Hall Lake Member of the McRae Formation, derived from an unlocated volcanic source west of the eastern margin of the Rio Grande rift and from the Fra Cristobal uplift to the north of the basin

5) The Fra Cristobal beds, derived from the Fra Cristobal uplift; this unit is present (without clear stratigraphic context) in a detachment fault-block in the Walnut Canyon area of the central Fra Cristobal Range and as an isolated outcrop at the northern end of the Fra Cristobal Range

The earliest evidence of basin subsidence is seen in the Mancos Formation (Cenomanian), which thickens along a trend subparallel to the basin's present structural axis. This structural trough persisted through Mesaverde time (Turonian-Campanian), and possibly into the Tertiary (Danian (?)).

Dakota and Mancos deposition were marine, as was the lower 40% of the Mesaverde Group. By mid-Mesaverde time, however, the Cretaceous interior seas had withdrawn from southern New Mexico, and the majority of the McRae basin Mesaverde was deposited in a deltaic and alluvial-plain environment. The last episode of Mesaverde deposition is recorded in the Ash Canyon Member, which was formed of sediments derived from erosion of the ancestral Caballo uplift to the south.

In Late Cretaceous (Campanian ?) time, an andesitic intrusive and extrusive center formed south of the present location of Elephant Butte Dam (Damsite intrusion). This intrusion was the primary source of sediment for the basal Jose Creek Member of the McRae Formation. The Jose Creek Member is composed almost exclusively of andesitic rock fragments and plagioclase, and locally interfingers with lahar and fanglomerate facies of the intrusion. The Damsite intrusion and the Jose Creek Member are locally very similar in composition and texture. Petrologic analysis shows that the two units are indistinguishable on the basis of major minerals and lithic fragments.

The Jose Creek Member is disconformably overlain by the Cretaceous/Tertiary (?) Hall Lake Member of the McRae Formation. The Hall Lake Member is much finer-grained, and is distinguished from the Jose Creek Member by increased quartz content, the first appearance of metamorphic lithic fragments, the appearance of potassium feldspar, and an overall reduction in the percentage of volcanic lithic fragments. Sedimentary lithic fragments are present in most specimens;

these are typically derived from older beds o the Hall Lake Member with some contributions from the Jose Creek Member and the Mesaverde Group.

Two isolated outcrop areas of fluvial sediments, similar in appearance and petrology to other McRae Formation lithologies, are found in the central and northern Fra Cristobal Range. On the basis of lithologic and petrologic similarities and paleocurrent trends, these outcrops appear to be remnants of a basin-marginal fluvial complex that carried sediment south into the McRae basin from the emerging Fra Cristobal Range to the north. The petrology of this unit of the McRae Formation (?), here named the "Fra Cristobal beds", is distinguished from the Hall Lake and Jose Creek members of the McRae Formation by higher ratios of modal quartz and metamorphic lithic fragments.

The stratigraphic record of the McRae basin shows evidence of two episodes of subsidence and two episodes of tectonic uplift in areas adjacent to the basin. Following the first period of subsidence during the deposition of the Mancos Formation and the lower Mesaverde Group, the Caballo uplift emerged to the south of the basin. This was followed by approximately 150 to 200 meters of relative subsidence during deposition of the Jose Creek Member of the McRae Formation and up to 800 meters of subsidence during deposition of the Hall Lake Member of the McRae Formation. The Fra Cristobal uplift emerged during deposition of the Hall Lake Member.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

ACKNOWLEDGEMENTS

I thank my thesis advisor, Dr. Eric Nelson, and committee members Drs. Keenan Lee and Karl Newman for their assistance in the preparation of this thesis. Invaluable assistance was provided by Tenneco Minerals, who granted access to the study area and also loaned many unique aerial photographs and maps. Tenneco geologists David Emmons, Jeffrey Wilson and Bruce VanAllan also provided much personal assistance. The Armendaris Corporation also granted access to their property. Plates and figures were prepared by Susan Hunter.

INTRODUCTION

LOCATION

The McRae basin, containing sediments of Cretaceous and Tertiary (?) ages, lies in a structural low between the Fra Cristobal and Caballo uplifts in Sierra and Socorro counties, New Mexico (Figure 1). This structural low, known as the Cutter Sag (Kelley and Silver, 1953), is a southeast-plunging syncline of late Laramide age. The term "McRae basin" refers to the *sedimentary* basin containing the Cretaceous and lower Tertiary (?) rocks that accumulated in the Cutter Sag (Plate 1). The Cutter Sag is a *structural* basin where Laramide deformation has affected rocks of Precambrian through Tertiary (?) ages (Plates 1 and 2).

The McRae basin is approximately 10 kilometers across and 35 kilometers long and contains rocks of the Cretaceous Dakota, Mancos, Mesaverde and lower McRae formations, Tertiary rocks of the upper McRae Formation, younger Tertiary deposits and volcanic rocks, and Quaternary sediments and basalts (Plate 3). The syncline is terminated on the west by west-dipping normal faults along the eastern boundary of the Tertiary-Quaternary Rio Grande rift, and on the southeast it merges into the much larger Jornada del Muerto basin, a large, north-trending syncline of Laramide (or possibly younger) age.

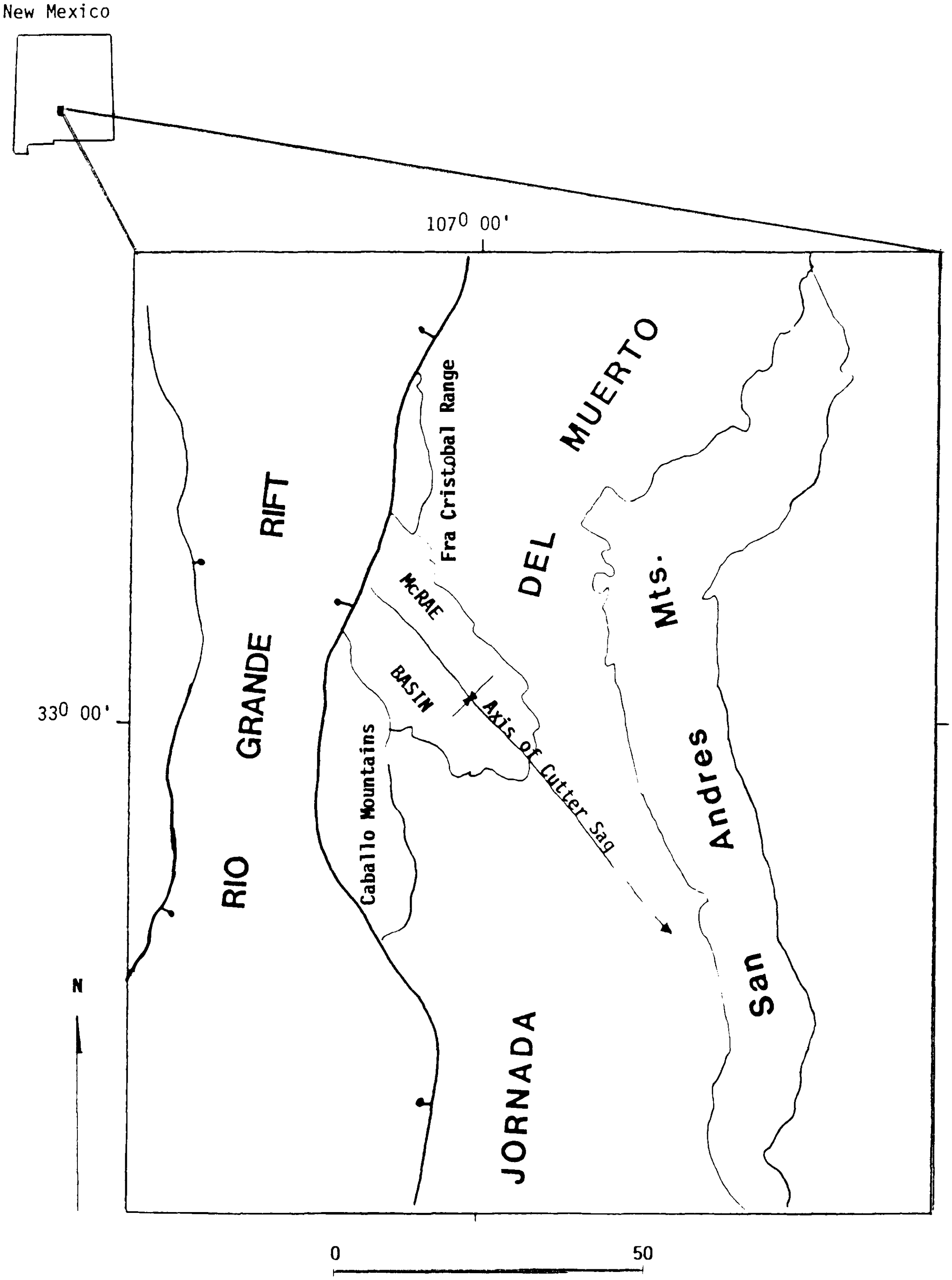


Figure 1: Location Map

PURPOSE

A stratigraphically and petrologically complex sequence of rocks accumulated in the McRae basin during the Cretaceous and Tertiary (?). Co-genetic with basin development was the establishment of a large Cretaceous and Tertiary paleodrainage along its axis, and the associated emergence of the ancestral Caballo and Fra Cristobal uplifts. Analysis of the detrital petrology, stratigraphy, facies relationships, and paleocurrent directions was undertaken to:

1) Identify source terranes for basin sediments by petrographic determination of mineral abundances and classification of lithic fragments in clastic sediments,

2) Correlate the lithologies of possible source terranes with material found in the synorogenic sediments,

3) Locate the source terranes by paleocurrent analysis and study of stratigraphy and facies relationships,

4) Determine the relative timing of episodes of subsidence, uplift and volcanism from the stratigraphy and petrology of the basin's sediments.

Understanding the nature, location and relative timing of the structural and volcanic events associated with Laramide orogenesis in central New Mexico is important for two principal reasons:

1) Regional studies of Laramide tectonics and sedimentation have shown that a variety of structural styles and depositional modes characterize basins of this age in New Mexico and Colorado, and this study would contribute to better understanding of basin evolution in Laramide time,

2) Uranium deposits have been found in the volcaniclastic rocks of the McRae basin and in lithologically similar rocks in the Laramide Galisteo basin in north-central New Mexico, and a more refined model of the development of these basins will aid future exploration efforts.

PREVIOUS WORK

Portions of the Cutter Sag area were first mapped in detail by Bushnell (1953). Subsequent work in this area has been published by Kelley and Silver (1953), Thompson (1955), Kelley and McCleary (1960), Hunter and Ingersoll (1979), Lozinski (1982) and Van Allen *et*. *al.* (1984).

STRATIGRAPHY

The stratigraphy of the study area was divided into Precambrian and Paleozoic rocks (Plate 1) and Mesozoic and younger rocks (Plate 2). The units described in Plate 2 include the preorogenic, synorogenic and postorogenic rocks which accumulated in the Cutter Sag/McRae basin.

Precambrian and Paleozoic Rocks

Precambrian basement is exposed along the western margins of the northern Fra Cristobal and central Caballo ranges (Plate 3 and Figure 2). Granitic and syenitic rocks of plutonic origin make up over 90% of the observed basement outcrops. The remainder is composed of aplites, pegmatites, quartz veins and several isolated roof pendants of highly deformed amphibolite. The granites are typically pink, coarse-grained rocks with abundant smokey quartz and microcline. These minerals are easily recognized in detrital rocks derived from erosion of the basement. Radiometric ages of 0.8 to 1.2 Ga are reported for similar rocks from nearby areas, along with detailed chemical analyses of the Fra Cristobal granite, in Van Allan _et_. _al_. (1984).

The basement is overlain by 1600 to 1800 m of Paleozoic strata, including deposits of the Cambrian, Ordovician, Pennsylvanian and Permian systems (Figure 3). The lower parts of this sequence are primarily lime-rich carbonates. Detrital and evaporitic rocks are more abundant in the uppermost Pennsylvanian and Permian deposits (Bushnell,

Figure 2: Outcrops of Precambrian basement (pC), northern Fra Cristobal Range, overlain by Paleozoic carbonates (Pz).

Figure 3: Lower Paleozoic section, Northern Fra Cristobal Range. Precambrian basement (pC) is in foreground; lowermost beds in upper center are Cambrian-Ordovician Bliss Formation (COb), overlain by the Ordovician El Paso Group (Oep). Cliff-forming carbonates are the Magdelena Group (Pm).

1953; Cserna, 1956; Jacobs, 1956; McCleary, 1960; Thompson, 1955; Hunter and Ingersoll, 1981). There are no known extrusive or intrusive rocks of Paleozoic age in this area, and there is no evidence for any significant deformational events prior to the Mesozoic.

The Cretaceous Dakota Formation unconformably overlies the Permian San Andres Formation (Figure 4). This unconformity represents a chronostratigraphic gap of over 125 million years. The unconformity is related to a regional uplift of Mesozoic age. The existence of this uplift was noted by Kelley and Silver (1953), who termed it the "Navajo High".

This regional unconformity is quite even and planar on the local scale, with only some minor karsting evident on the top of the San Andres Formation. Where seen in outcrop the angularity of the unconformity is only one or two degrees. The regional extent and planar geometry of this surface make it an excellent reference surface for mapping and analyzing younger structures.

Figure 4: Paleozoic-Mesozoic contact in Mescal Canyon, approximately three kilometers west of Damsite intrusion (Plate 5). Ridge on left is limestone of the San Andres Formation (Psa). Dipping beds in the lower center are the Dakota Formation (Kd), and Mancos Formation (Km) shale floors the valley. Beds in lower right foreground are the lower part of the Mesaverde Group (Kmv).

Mesozoic Preorogenic, Synorogenic and Postorogenic Stratigraphy

Plate 2 illustrates the ages and stratigraphy of the Mesozoic and younger deposits in the McRae basin. The preorogenic sequence began with the marine Dakota Formation. This was the first of a series of three cycles of transgression and regression during Cretaceous time (Hook, 1983; Molenar, 1983). The Dakota Formation is about 30 m thick, and grades upward into the pelagic, marine Mancos Formation. The Mancos varies in thickness from 50 to 80 m, and locally thickens in the McRae basin area.

The base of the overlying Mesaverde Group is marked by a thick and continuous bed of marine sandstone with abundant fossil shells. The Mesaverde Group is up to 1100 m thick in this area, but only the lower 200 m are of entirely marine origin. The majority of the Mesaverde Group was deposited under deltaic and coastal conditions.

The uppermost member of the Mesaverde Group, named the Ash Canyon Member by Bushnell (1953) is a coarse deposit of fluvial sandstones and conglomerates which are sharply scoured into the underlying Mesaverde (Figure 5). Petrologic and paleocurrent evidence indicates that this unit is the oldest Laramide synorogenic deposit in the McRae basin.

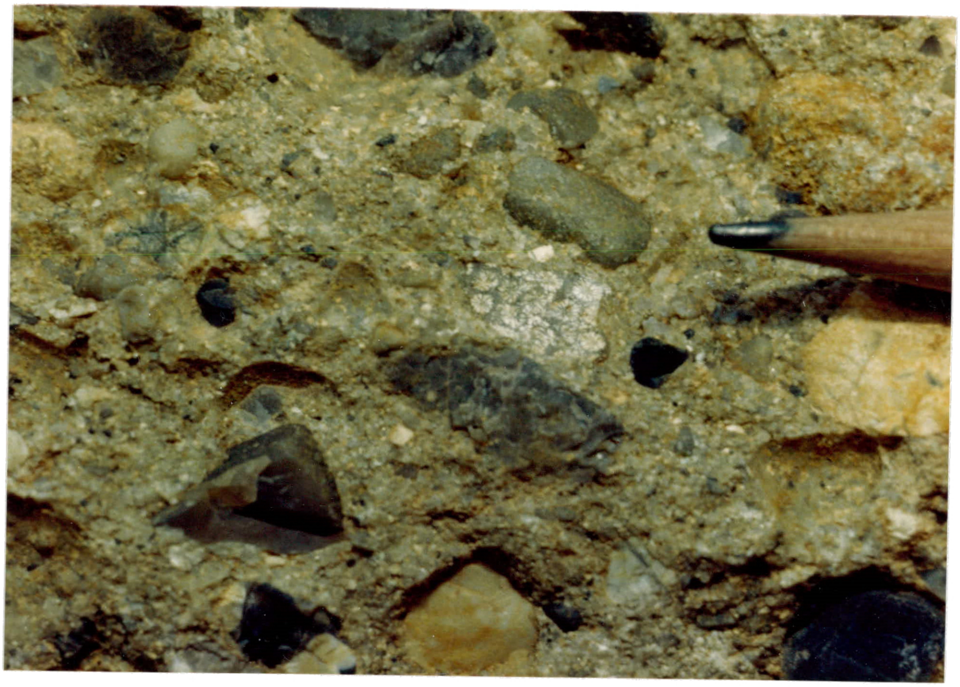


Figure 5: Outcrop of the Ash Canyon Member of the Mesaverde Group. Note chert pebble to left of pencil with coral (Hapsiphyllum); these are also found in the Magdelena Group (Pennsylvanian).

The major Laramide synorogenic deposit is the McRae Formation, first described by Bushnell (1953). This unit unconformably overlies the Mesaverde Group. Bushnell recognized two members of the McRae, the basal Jose Creek Member (Upper Cretaceous) and the Hall Lake Member (Upper Cretaceous-Lower Tertiary (?)). The McRae Formation is present only in the McRae basin, in parts of the Jornada del Muerto basin and in small outliers in the Fra Cristobal Range.

The basal Jose Creek Member of the McRae Formation disconformably overlies the eroded top of the Mesaverde Group. The arkosic, volcaniclastic sandstones of the Jose Creek Member are also of Cretaceous age, as indicated by _Tyrannosaurous_ _rex_ fossils found in outcrops near Elephant Butte Lake by Lozinski, _et_. _al_. (1984). The Jose Creek Member is almost entirely composed of detritus from andesitic volcanic centers located in the southern and western parts of the McRae basin. Lahars and alluvial-fan deposits composed of subrounded cobbles and boulders of andesite crop out near an andesitic breccia pipe south of Elephant Butte Dam (Figure 6). These facies grade northward into fluvial conglomerates and sandstones, which are also composed almost entirely of volcanic rock fragments and feldspars (Figure 7).

The Jose Creek Member is unconformably overlain by the Hall Lake Member of the McRae Formation. The Hall Lake Member includes an extensive basal sandstone and conglomerate bed that is locally rich in quartz and granitic rock fragments. The majority of this unit is composed of

Figure 6: Lithified fan deposit and/or mudflow on northern flank of Damsite intrusion (see Plate 5); this unit interfingers with the lower beds of the Jose Creek Member of the McRae Formation. Note large boulders of andesite; matrix is finer grained rock fragments and clay.

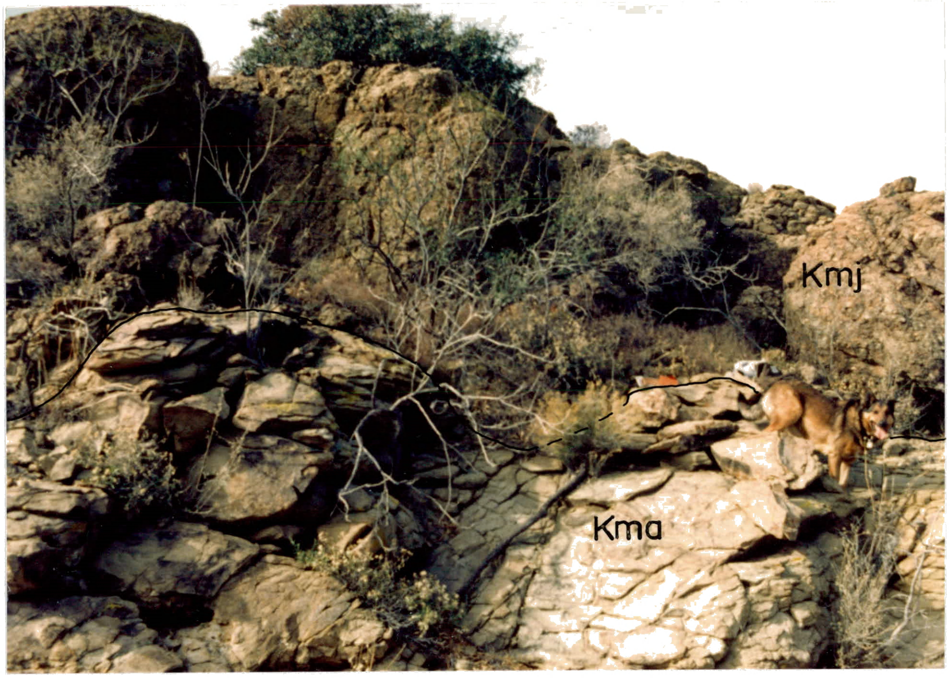


Figure 7: Jose Creek (McRae Formation)-Ash Canyon (Mesaverde Group) contact, southern edge of McRae basin. Jose Creek beds are the upper brown, massive conglomerate, Ash Canyon beds are medium-bedded, tan sandstone. Location is approximately three km northwest of Figure 6.

red and purple mudstones and shales with local interbeds of discontinuous, lenticular sandstones (Figure 8). This unit appears to represent deposition in generally lower-energy environments, as surrounding highlands eroded and the basin filled with sediments. Reports by Kelley and McLeary (1960) of Triceratops species and by Lozinsky, et. al. (1984) of Tyrannosarous rex fossils imply a Maastrichtian or Lancian age for the upper part of the Hall Lake Member.

Laramide basins in New Mexico and Colorado containing similar deposits been described by several authors. Baltz (1967) and Anderson (1970) have studied the Animas and Nacimiento formations (Cretaceous and Tertiary) in the San Juan Basin, Johnson (1978) has investigated the Baca Formation (Cretaceous/Tertiary (?)) of southwestern New Mexico, and Gorham and Ingersoll (1979) have described the Galisteo Formation (Tertiary) in north-central New Mexico. All of the units described by the above authors show some evidence of:

- Initiation of basin subsidence early in the Laramide period
- Detrital input from eroding basement-cored uplifts
- Volcaniclastic sediments from arc-type sources
- Some post-depositional deformation

Figure 8: Outcrop of Hall Lake Member of the McRae Formation. Thick, lenticular bed of volcaniclastic sandstone overlies purple mudstone.

Postorogenic Stratigraphy

The top of the McRae Formation is deeply eroded, and the base is covered by the waters of Elephant Butte Reservoir in most areas; therefore a complete section of this formation was not observed. A complex sequence of Tertiary and Quaternary deposits overlie the McRae, including the Santa Fe Group, which fills the Rio Grande rift, as well as Quaternary basalt flows and dikes, and Holocene alluvial and aeolian deposits. These units have been described in detail by Galusha and Blick (1971), Elston, _et_. _al_. (1976) and Lozinski (1982).

STRUCTURE

The Cutter Sag is a southeast-plunging syncline of Laramide age and is best defined by a structure contour map using the top of the Dakota as a datum (Plate 3). Earliest subsidence is seen in a thickening of the lower shale unit of the Mancos Formation which overlies the Dakota (Plate 4). The basin exhibits as much as 1500 m of structural relief in its central part (Plate 3), is approximately 10 km across, and extends 35 km along strike(N.45 E.). The limbs dip more steeply (30 to 40 degrees) in the older units, but dips shallow out to a minimum of 5 to 10 degrees in the upper McRae Formation beds. A similar trend of upsection shallowing of dip was observed in field reconnaissance of the larger Jornada del Muerto basin.

The term "Laramide" is used in this paper to refer to both tectonic styles and an orogenic period. Laramide structures in central New Mexico are typically basement-cored uplifts bounded by steep to low-angle reverse faults. Complex zones of folding and thrust faulting in the sedimentary rocks overlying the basement are commonly observed along the flanks of Laramide uplifts. Laramide deformation in south-central New Mexico began in latest Cretaceous time (Seager, 1983). Laramide thrust faulting was active into the Paleocene, when Laramide thrusts cut the 60 million-year old Hildago volcanics in southwest New Mexico (Loring and Loring, 1980).

Laramide tectonic styles are the result of both brittle and ductile strains in the upper crust. These strains are in part the result of Cretaceous and Tertiary subduction of parts of the Pacific plate under western North America (Atwater, 1970; Dickinson and Snyder, 1978). In New Mexico, Laramide structures are typically amagmatic, basement cored uplifts bounded by reverse faults. These faults may have various dips at depth in the crystalline basement rocks, but may assume subhorizontal attitudes in the shallower, more ductile Paleozoic and Mesozoic sedimentary cover (Sales, 1968; Anderson, 1970; Coney, 1972; Woodward, 1973; Armstrong, 1974; Tweto, 1975; Coney, 1976; Dickinson, 1976, Chapin and Cather, 1981; Molenar, 1983).

Both Armstrong (1974) and Dickinson and Snyder (1978) cite stratigraphic and geochronologic evidence for the spatial and temporal overlap of the Laramide and Sevier orogenies in the Montana-Wyoming foreland and the Mexican Cordillera. The Laramide exists as a separate entity only in the region between central Wyoming and the New Mexico-Texas border region.

The Cutter Sag area is now flanked by north-trending, basement-cored uplifts of post-Laramide ages (Fra Cristobal Range and Caballo Mountains). These mountains were apparently uplifted during the formation of the late Tertiary Rio Grande rift. In the Caballo and Fra Cristobal ranges, remnants of Laramide structures are exposed. These represent thrust fault and fold zones which were on the east flanks of the original Laramide uplifts.

Laramide faults in the Fra Cristobal and Caballo ranges are include low-angle thrusts and high-angle reverse faults that show a west-over-east, old-over-young geometry. Stacked thrust sheets are observed in the Fra Cristobal Range in Permian rocks, and the thrust plates are locally deformed into complex terranes of north-trending folds. Large-scale, upright to overturned, open to isoclinal folding and low-angle thrust faulting are observed in the Precambrian basement, the Paleozoic, and in some parts of the Cretaceous and Tertiary rocks (Hunter and Nelson, 1984).

Laramide structures are truncated by north-trending normal faults of the Rio Grande rift. These faults typically strike within 20 degrees of north, and dip 60 to 80 degrees west (Warren, 1978; Ander, 1980; Van Allen, _et_. _al_., 1984). Formation of the rift has removed large portions of the original Laramide highlands which existed to the west of the study area, leaving only the eastern flanks of these uplifts, with their foreland structures.

Based on studies of the complexly thrust-faulted and folded terranes preserved as tectonic remnants in the Socorro, New Mexico and Caballo Mountain areas, Kelly and Silver (1953) proposed the presence of the "Sierra Uplift". This uplift was a basement-cored Laramide structure which occupied the area to the west of the present eastern boundary of the younger Rio Grande rift. The compressional structures preserved in the mountains east of Socorro, the Fra Cristobal Range, and the Caballo Mountains are relict foreland structures of the much larger Sierra Uplift. The major part of this uplift has foundered in the rift, now lying beneath several thousand meters of Tertiary and Quaternary fill.

More recent work (Chapin and Cather, 1981; Seager, 1983) has focused on the interplay of both purely compressional and lateral-slip stress conditions. These authors cite evidence for right-lateral slip along, or subparallel to, the north and northeast-trending Laramide reverse-fault trends. This type of tectonic regime favors the formation of "transpressional" basins at oblique angles to the lateral-slip plane (Figure 9). Right-lateral slip along a north-trending fault zone, such as that bounding the McRae basin area, can cause the formation of a northwest-trending structural basin. Chapin and Cather (1981) have classified Laramide basins of transpressional origin as the "Echo Park" type, based on the Echo Park basin in southern Colorado, and include the McRae basin/Cutter Sag in that category.

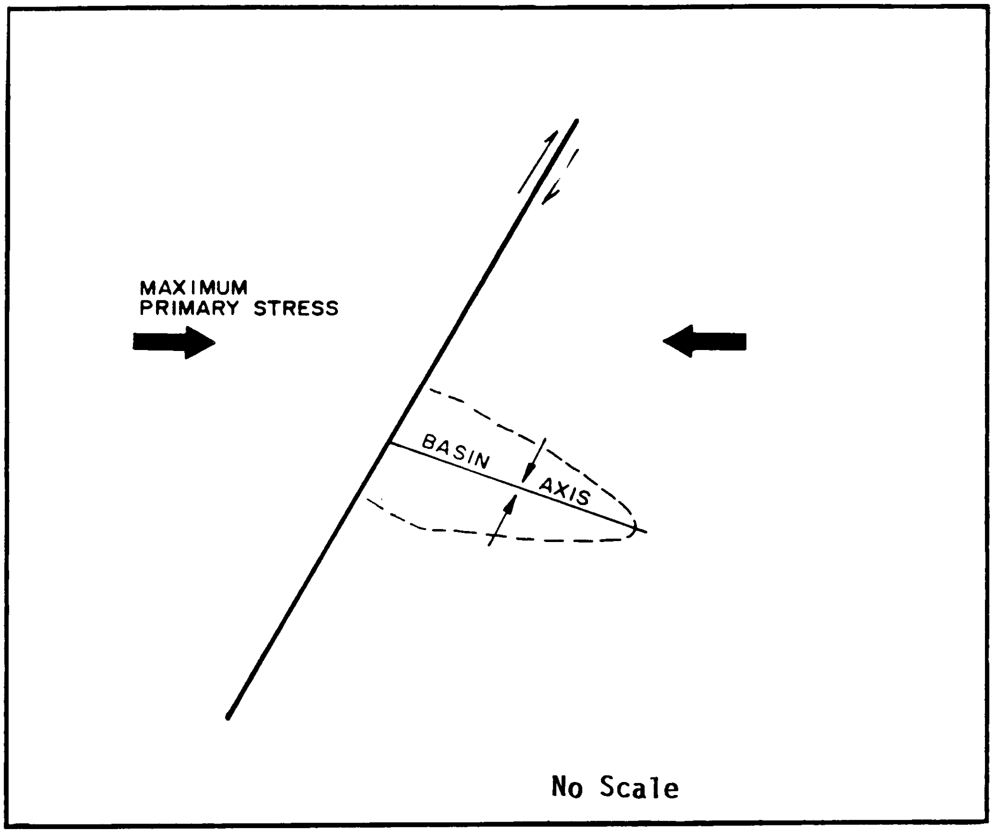


Figure 9: Schematic map of transpressional basin. Right-lateral shear on northeast-trending fault zone causes downwarping in basin to east of fault. Axis of basin is oblique to vertical plane of shear in the fault zone.

METHODS

Field data were collected by mapping on 1:12,000, 1:24,000 and 1:62,500 scale topographic maps and 1:24,000 aerial photographs. Stratigraphic sections were measured using measuring tapes, Brunton compass and hand levels. Samples for petrographic analysis were collected from key beds in these measured sections, and from other outcrops. Paleocurrent directions were determined by measurements of the orientations of cross-beds, trough sets and parting lineations. These measurements were stereonet corrected for structural dip. Cores from drill holes in the McRae Formation were made available by Tenneco Minerals, and regional stratigraphic and structural information was gathered from logs of deep oil-test wells located in the McRae and Jornada basins and from regional reconnaissance.

Samples for petrographic analysis were collected from the coarser, basal parts of selected beds, and an effort was made to collect the samples from relatively unweathered parts of the outcrops. The orientation of each sample was marked on the sample in the field, and thin-section slabs were cut perpendicular to bedding. Thirty thin sections were prepared, and were stained to discriminate feldspars.

Detrital modes were determined by point-counting approximately 500 points per specimen, according to methods described by Dickinson (1970), Ingersoll and Suzek (1979) and Hunter and Ingersoll (1979). These methods are designed to minimize the biases of chemical and mechanical weathering and maturation by counting discrete mineral grains in rock fragments as that mineral itself, rather than counting that point as a lithic fragment. Grains counted as lithic fragments include aphanitic or microlithic volcanic rocks (Lv), tectonites or metamorphicmineral aggregates (Lm), or carbonate, siltstone and claystone clasts (Ls).

Grains identified included:

1) Quartz (Q), as monocrystalline (Qm), polycrystalline (Qp), and chert (Qm),

2) Feldspars (F), as plagioclase (P), microcline or orthoclase (K), and undifferentiated (f),

3) Lithic fragments (L), as volcanic (Lv), metamorphic (Lm), and sedimentary (Ls),

4) Interstitial material (I), as orthomatrix, pseudomatrix, overgrowths and cements,

5) Accessory components such as monocrystalline phyllosilicates (Mp), mafic minerals (Mf) and miscellaneous grains (Mx) such as opaques and minor minerals.

These parameters are very sensitive to the type of source rocks from which the sediment was derived. The relationships of these constituent ratios were examined by standard statistical methods (Wonnacot and Wonnacot, 1977) and means, variances and 95% confidence intervals were calculated for the major constituent ratios of all formations and members.

The ratios of quartz, feldspars and lithic fragments to total QFL were calculated in two ways. First, chert was counted as a member of thee quartz set, resulting in the ratios cited as Q F L; secondly, chert was counted as a sedimentary lithic fragment, yielding ratios cited as Q' F L'. A similar method is used for the ratios of lithic fragments. Where chert is considered as a quartz species, lithics are cited as Lv Lm Ls; when chert is counted as a sedimentary lithic fragment, the ratio is given as Lv' Lm Ls'.

The first method emphasizes the bulk chemistry of the rock, while the second method reveals more about the sources of silica species and their provenance.

RESULTS

FIELD AND LABORATORY DATA

The results of mapping are presented in Plate 5, and in Figures 10 and 11. Plate 5 is a general geologic map of the McRae basin area. Figures 10 and 11 are detailed geologic maps of McRae Formation outliers in the Fra Cristobal Range. Figures 12, 13 and 14 are photographs of outcrops in these outlier areas. Measured sections and their locations are shown in Plate 6, and are correlated in Plate 7. Plate 8 shows the variations in detrital petrology through time of the units studied.

Rose diagrams of paleocurrent directions and their locations are shown in Figure 15. All paleocurrent data was corrected for structural attitude by stereonet rotation. The method of stereonet correction assumes that all post-depositional rotation of beds was around a single, horizontal axis. This assumption may be somewhat suspect in the case of the Walnut Canyon beds, where low-angle detachment faulting may have rotated the beds around more than one spatial axis.

Figure 16 shows a cross-section of the basin, which was constructed from field observations, core logs, and deep oil-test logs.

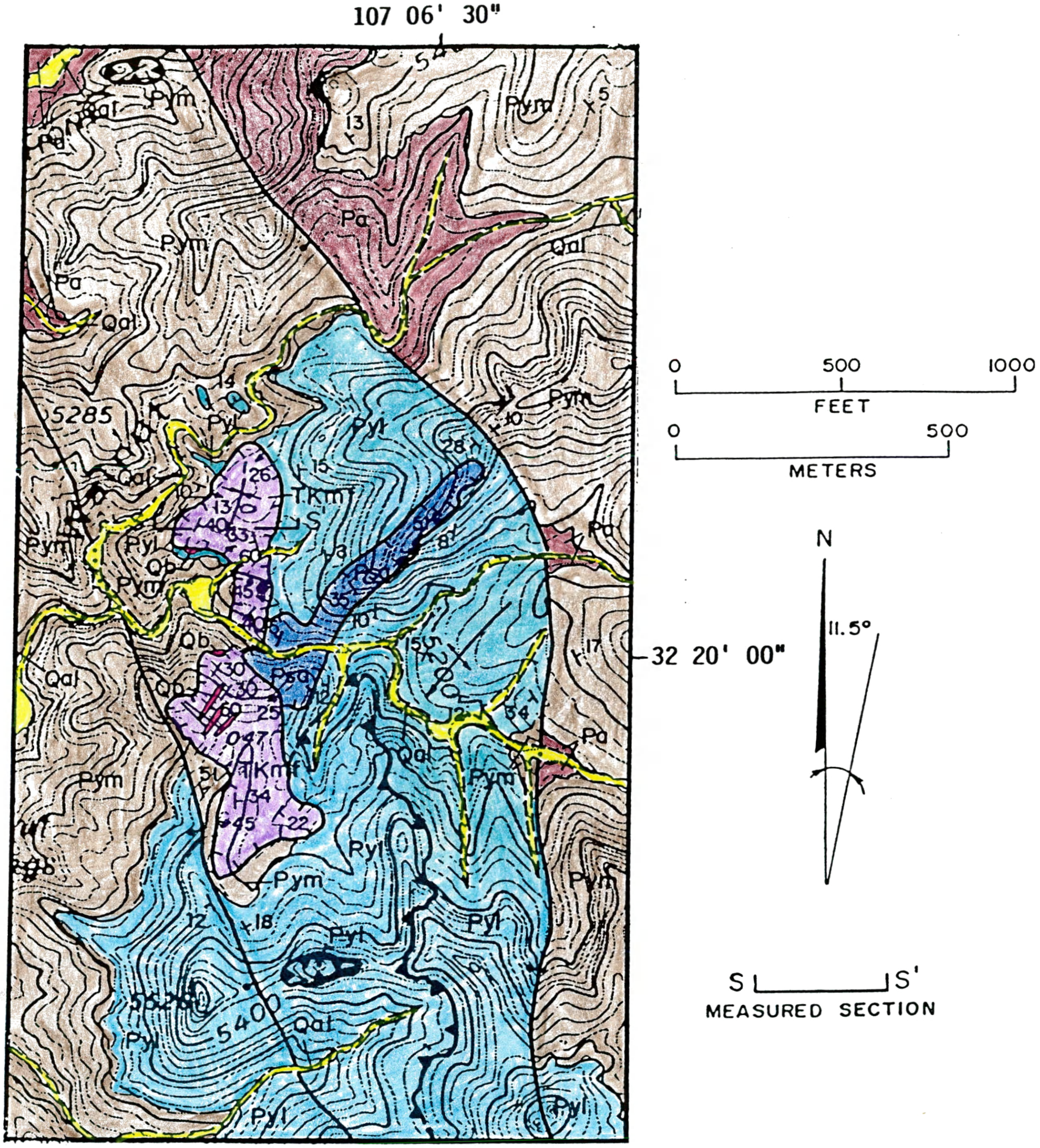
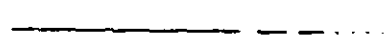


Figure 10: Geologic Map of Walnut Canyon Area. See following page for explanation.

QUATERNARY	Qal	ALLUVIUM Coarse-grained sand, pebbles, cobbles and boulders of siltstone, limestone and sandstone derived from local outcrops; found in channels of intermittent streams and arroyos. 1-10 m
	Qb	BASALT Thin dikes and sills of glassy, locally vesicular brown basalt. Some minor xenoliths of sedimentary origin. 1-3 m
TERTIARY (?)	TKmf	McRAE FORMATION (FRA CRISTOBAL FACIES) Coarse, cross-bedded fluvial sandstones and mudrocks. Beds locally contain granite and basaltic-andesite fragments with some volcanic ash and reworked ash. Logs of petrified wood in one strata. Up to 100 m
PERMIAN	Psa	SAN ANDRES FORMATION Thick to massive bedded, gray to bluish gray micritic limestone. Neomorphic fine to coarse sparry texture over micritic microstructure, sparse local gastropods and cephalopods. Up to 180 m
	Pyl / Pym	YESO FORMATION Complex shoreline deposits of sandstone, siltstone, carbonates and gypsum. Locally divided into Los Vallos (Pyl) and Mesita Blanca (Pym) members. The Los Vallos is a thin to medium bedded carbonate unit, and the Mesita Balnca is a series of silty redbeds. UUp to 400 m
	Pa	ABO FORMATION Distinctive reddish purple shale and mudstone, thin bedded unit which is typically a slope former, locally contains prominent ripple marks, salt casts, raindrop molds and mudcracks. Up to 150 m

	Strike and dip of bedding
	Contact; dashed where approximately located, dotted where covered
	Normal Fault; arrows show dip, ball on downthrown side, dashed where approximately located, dotted where covered
	Thrust Fault; arrows show dip, teeth on upper plate, dashed where approximately located, dotted where covered
	Low-Angle Fault; arrows show dip, ticks on upper plate, dashed where approximately located, dotted where covered
	Anticline; arrow shows plunge
	Syncline; arrow shows plunge

Explanation for Figure 10

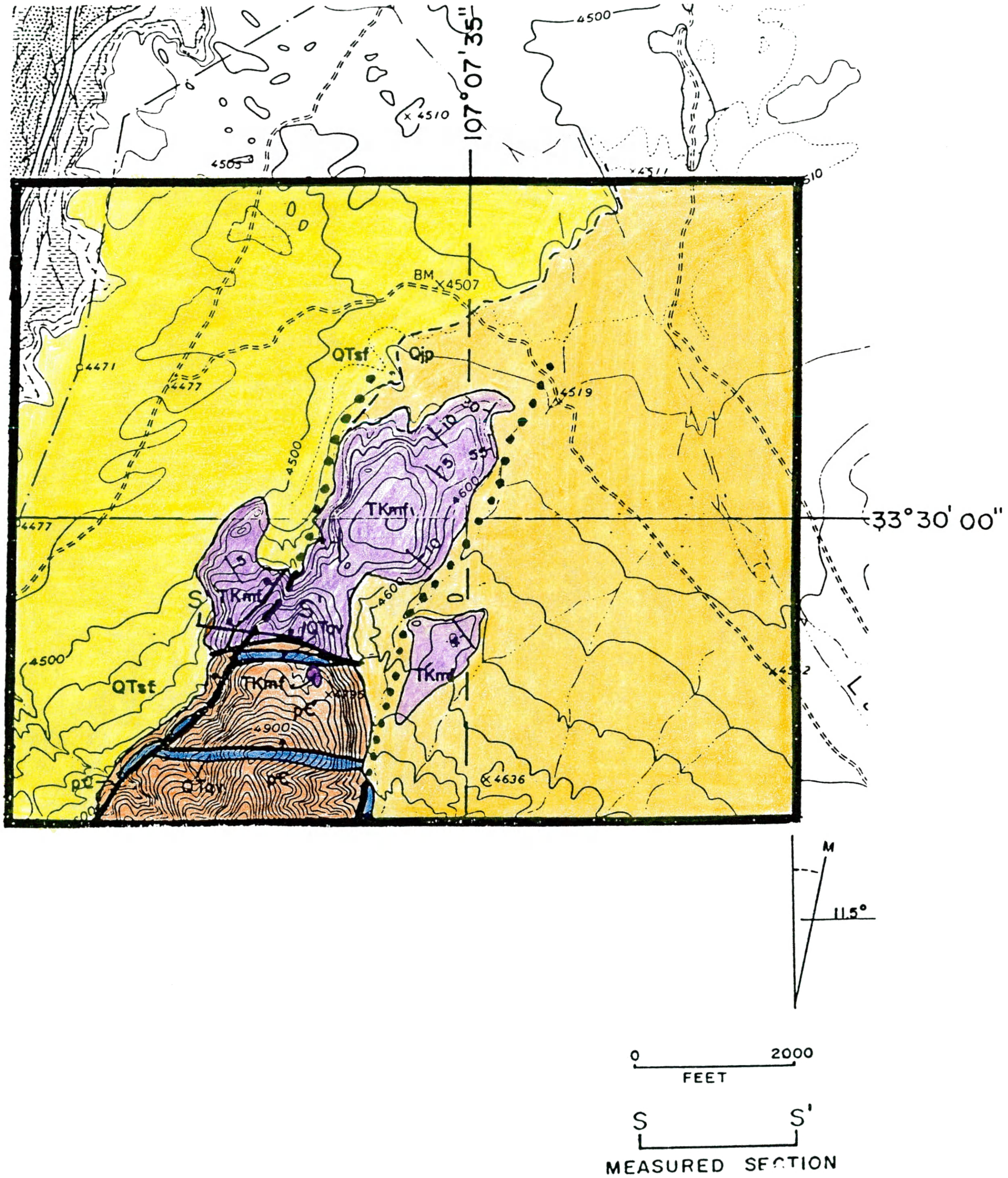


Figure 11: Geologic Map of North Fra Cristobal Range Area

Qjp	JORNADA GRAVELS Desert pediment and basin-playa deposits, eolian and alluvial sands, arroyo deposits, pebble-lag surfaces and coppice dunes. From 3 to 15 m of gypsum and caliche-cemented sand and gravel overlying bedrock (Precambrian through Tertiary) in the Jornada Basin.
QTsf	SANTA FE GROUP Thick alluvial and fluvial deposits in the Neogene Rio Grande rift. Locally a coarse sequence of granite cobbles and boulders interbedded with fluvial sands. Lithologies of clasts in the Santa Fe closely resemble rocks outcropping in the adjacent Fra Cristobal Range.
QTqv	QUARTZ VEINS Locally prominent (up to 15 m thick), resistent, ridge-forming veins of white to pink jasperoid and massive quartz; some veins show multiple episodes of brecciation. Minor local inclusions of barite and fluorite. Found in faults and fissures in the Precambrian granite only, granite clasts locally abundant in some veins.
TKmf	MCRAE FORMATION (FRA CRISTOBAL FACIES) Coarse, arkosic, strongly cross-bedded sandstone and conglomerate with some interbeds of silicified siltstone. Contains large amounts of granite pebbles and cobbles in many beds. Finer grained beds contain local wood and leaf molds, coarser beds may contain cobbles of hard, silicified siltstone.
p€	GRANITE Coarse, pink to greenish gray biotite granite with abundant gray quartz and pink orthoclase, minor biotite and plagioclase. Locally weathered with seracitized feldspars and chloritized biotite.
4 ⊥	Strike and Dip of Bedding
———‐‐‐……	Contact; dashed where approximately located, dotted where covered
—⊥——‐‐•••	Normal Fault; dashed where approximately located, dotted where covered

Explanation for Figure 11

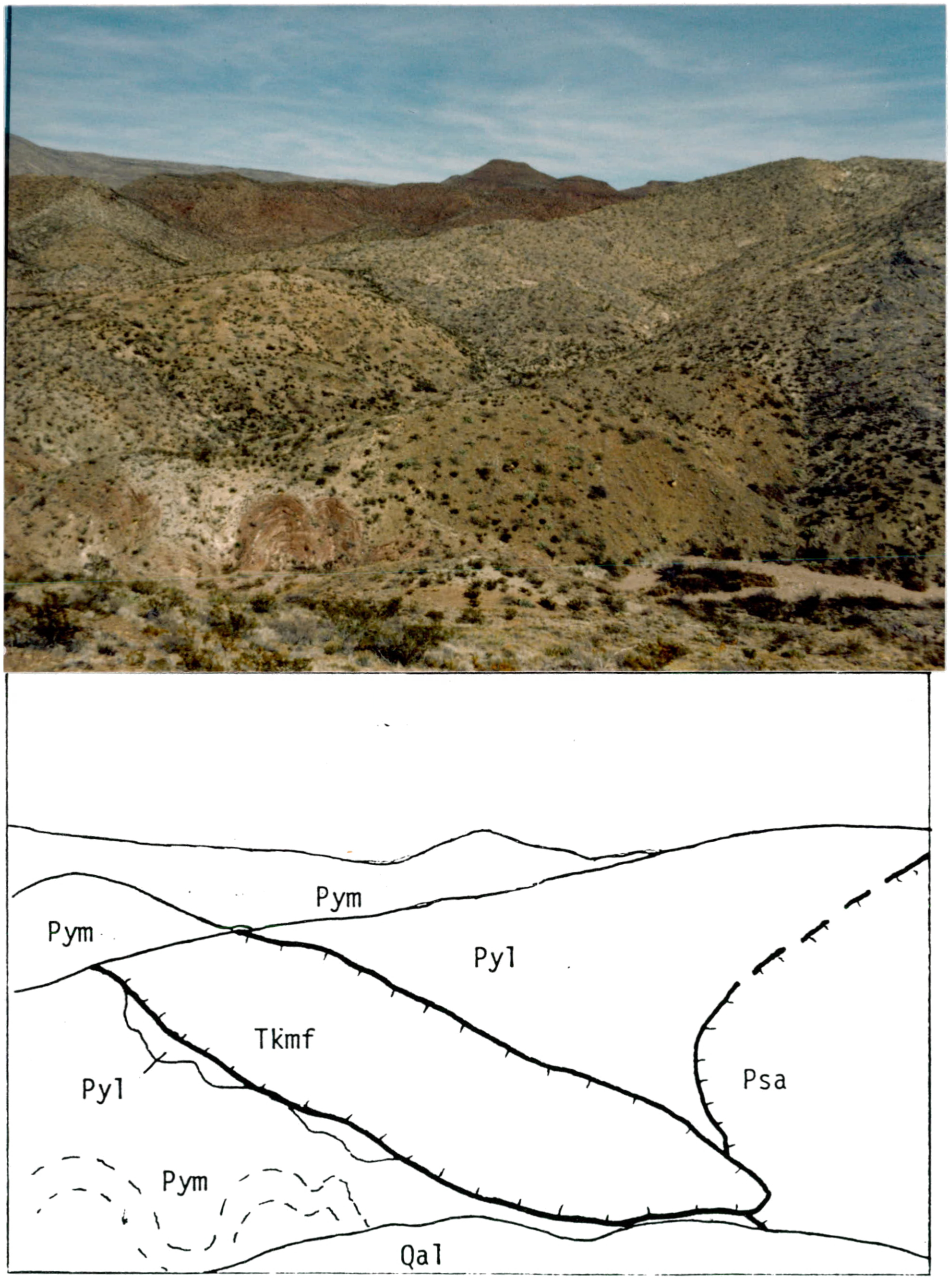


Figure 12: Walnut Canyon outcrops of Fra Cristobal facies of McRae Formation. Note that low-angle fault which separates McRae beds from underlying Yeso and San Andres formation beds is essentially horizontal in lower right center of sketch map. Limestone bed in San Andres is also a detached block.

Figure 13: Conglomerate bed in Walnut Canyon outcrops of McRae Formation. Large cobbles above field book are quartz (left) and granite (right).

Figure 14: Outcrops (above) and close-up (lower) of North Fra Cristobal beds of McRae Formation. Upper photograph shows contact between Precambrian granite and McRae Formation arkose. Note abundant quartz and microcline.

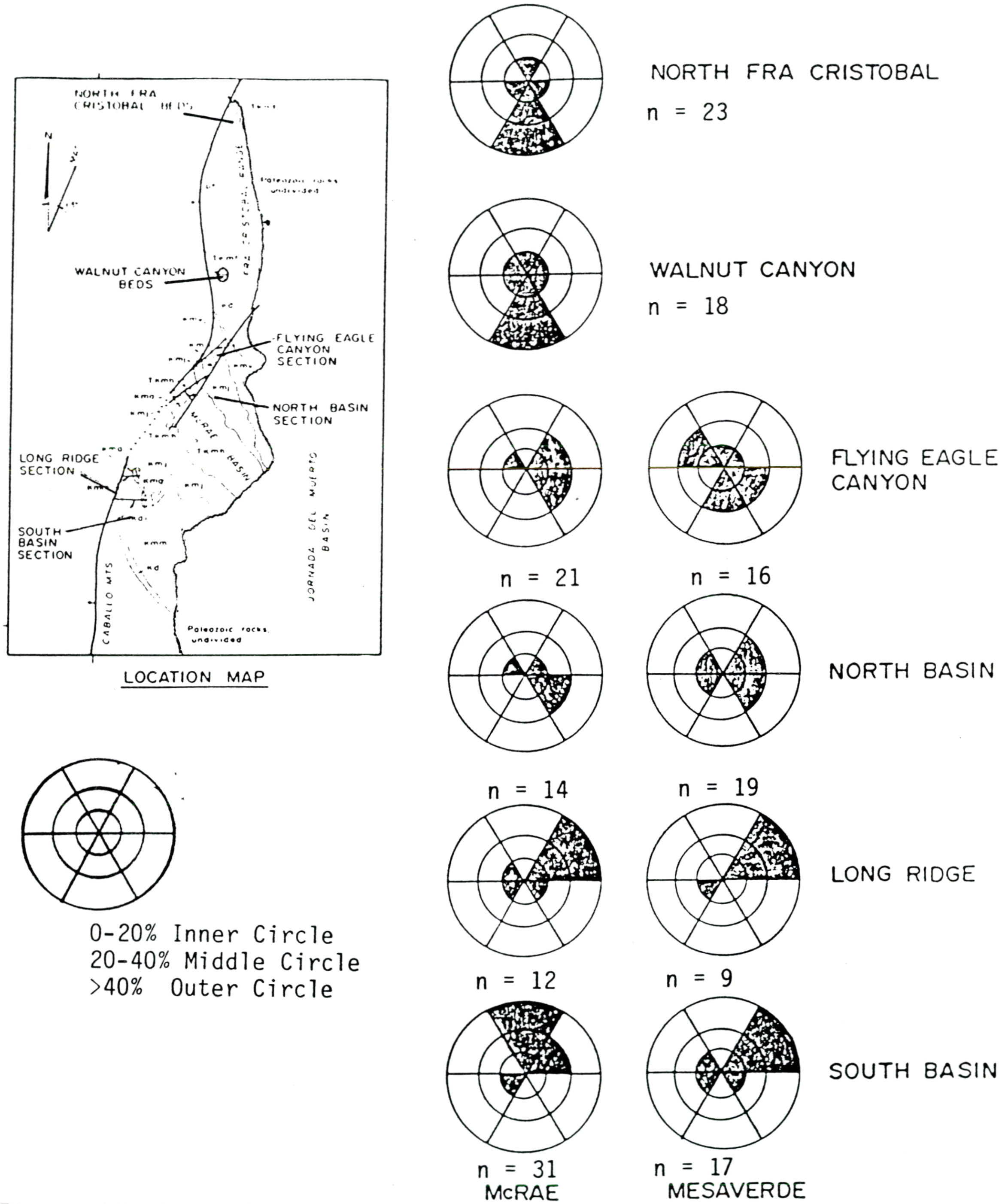


Figure 15: Rose Diagrams Illustrating Paleocurrent Directions. All directions are stereonet corrected. Number of measurements is given as n.

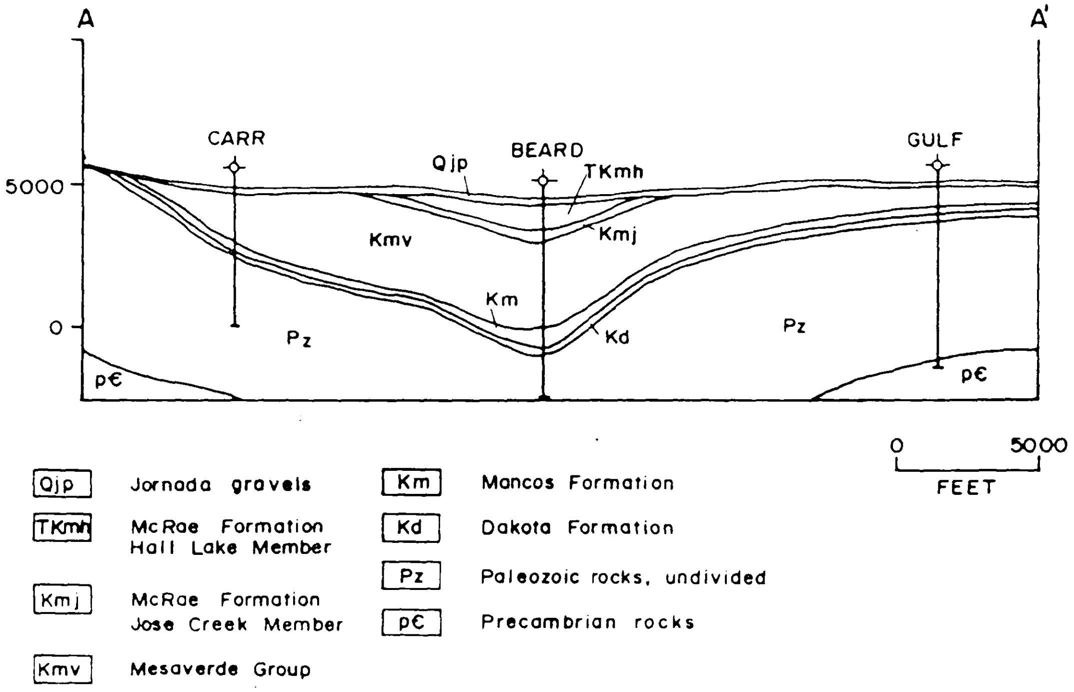


Figure 16: Geologic Cross-Section of Central McRae Basin

Raw point-count data on the detrital petrology is presented in Table 1, and the ratios of detrital constituents are given in Table 2. Table 3 gives the means, variances, and 95% confidence-intervals for major petrologic constituents (by formation and member). Figure 17 presents ternary diagrams illustrating the detrital petrology of the units investigated. Figure 18 is a matrix which shows the parameters which discriminate the various formations and members at 95% confidence.

Samples were collected from seven lithostratigraphic units, among which five distinct petrofacies were identified. Each box in Figure 18 lists the petrologic parameters that distinguish the units whose columns and rows intersect. Note that of the seven lithostratigraphic units, two are not distinct petrofacies. The Damsite intrusion (Kdi) is not discriminated from the Jose Creek Member of the McRae Formation (Kmj) and the Ash Canyon and main members of the Mesaverde Group are also indistinguishable.

TABLE 1: Point Count Data

Fra Cristobal Facies (McRae Formation)

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
043	250	17	2	269	71	48	118	12	43	0	53	95	8	440	543
045	202	13	17	232	3	88	91	121	1	3	125	167	9	448	624
042	155	17	3	175	58	32	90	206	0	20	226	35	20	491	546
046	167	10	18	195	26	23	49	138	2	20	160	131	1	404	536

Hall Lake Member (McRae Formation)

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
024	57	10	4	71	59	24	81	256	24	1	281	48	17	433	498
023	100	4	27	131	26	27	53	208	0	1	209	104	6	393	503
003	91	5	5	101	79	24	103	167	9	11	187	66	56	391	513
002	75	14	21	110	94	1	95	116	0	1	117	140	38	322	500
022	122	31	6	159	32	13	45	18	8	48	74	181	12	278	471

Jose Creek Member (McRae Formation)

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
021	7	0	0	7	162	0	162	295	0	3	298	57	4	467	528
011	0	0	0	0	118	0	118	375	0	0	375	67	6	493	566
010	1	0	0	1	135	0	135	323	0	0	323	63	6	459	528
009	8	0	0	8	112	17	129	183	3	3	189	188	13	326	527
008	8	3	0	11	187	0	187	270	0	1	271	56	7	469	532

TABLE 1 (Continued)

Jose Creek Member (Continued)

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
007	4	0	0	4	143	0	143	282	0	1	283	70	10	430	510
048	12	4	1	17	126	2	128	352	0	5	357	25	38	502	565
028	106	8	34	142	4	16	20	370	1	4	375	24	1	537	562

Damsite Intrusion

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
030	3	1	6	10	82	0	82	147	8	0	155	219	37	247	503
039	2	0	15	17	134	13	147	272	0	4	276	39	23	440	502
040	0	8	4	13	177	0	177	260	1	0	261	33	53	451	537

Ash Canyon Member (Mesaverde Group)

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
006	287	12	46	345	35	2	37	8	1	53	62	57	13	444	514
029	302	16	15	333	14	6	20	16	0	120	136	33	0	489	522
027	244	19	168	431	11	33	44	0	0	3	3	20	2	478	500
041	258	26	267	551	0	0	0	0	0	0	0	8	0	551	559

Main Member (Mesaverde Group)

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
025	266	28	36	330	22	64	86	9	4	30	43	31	11	459	501
035	143	8	14	165	28	9	37	3	0	279	282	33	10	484	527
020	60	8	7	75	33	5	38	0	2	312	314	63	10	427	500

TABLE 1 (Concluded)

Mesaverde Group (Continued)

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
032	118	17	11	146	96	27	123	0	0	90	90	132	9	359	500

Dakota Formation

Sample	Qm	Qp	Qc	Q	P	K	F	Lv	Lm	Ls	L	I	M	QFL	TOT
014	377	20	82	479	0	0	0	0	4	0	4	17	0	483	500
033	388	11	14	413	0	2	2	0	1	14	15	77	2	430	509

EXPLANATION

Sample numbers are arraigned in descending stratigraphic order. The parameters are: monocrystalline quartz (Qm), polycrystalline quartz (Qp), chert (Qc), total quartz (Q), plagioclase (P), potassium feldspars (K), total feldspars (F), volcanigenic lithics (Lv), metamorphic lithics (Lv), sedimentary lithics (Ls), total lithics (L), interstitial material (I) and miscellaneous, mafic and opaque grains (M). Total Q, F, and L grains are given as QFL, and the total number of points counted as TOT.

TABLE 2: Modal Ratios of Detrital Grains

Fra Cristobal Facies (McRae Formation)

Sample	Q’	F	L’	Lv’	Lm	Ls’
043	.61	.27	.12	.24	.60	.16
045	.48	.20	.32	.65	.21	.14
042	.35	.18	.47	.45	.45	.10
046	.44	.12	.44	.39	.40	.21

Hall Lake Member (McRae Formation)

Sample	Q’	F	L’	Lv’	Lm	Ls’
024	.15	.19	.66	.90	.02	.08
023	.26	.13	.60	.88	0	.12
003	.25	.26	.49	.87	.05	.08
002	.27	.30	.43	.84	0	.16
022	.55	.16	.29	.23	.10	.67

Jose Creek Member (McRae Formation)

Sample	Q’	F	L’	Lv’	Lm	Ls’
021	.01	.35	.64	.99	0	.01
011	0	.24	.76	1.0	0	0
010	0	.30	.70	1.0	0	0
009	.02	.40	.58	.97	.02	.01
008	.02	.40	.58	1.0	0	0

TABLE 2 (Continued)

Jose Creek Member (McRae Formation)

Sample	Q'	F	L'	Lv'	Lm	Ls'
007	.01	.33	.66	1.0	0	0
048	.03	.26	.71	.99	0	.01
028	.21	.04	.75	.99	0	.01

Damsite Intrusion

Sample	Q'	F	L'	Lv'	Lm	Ls'
030	.02	.37	.61	.88	.05	.07
039	.01	.36	.63	.99	0	.01
040	.01	.40	.59	1.0	0	0

Ash Canyon Member (Mesaverde Group)

Sample	Q'	F	L'	Lv'	Lm	Ls'
006	.67	.08	.24	.07	.01	.92
029	.65	.04	.31	.11	0	.89
027	.55	.09	.36	0	0	1.0
041	.52	0	.48	0	0	1.0

TABLE 2 (Concluded)

Main Member (Mesaverde Group)

Sample	Q’	F	L’	Lv’	Lm	Ls’
025	.64	.19	.17	.11	.05	.84
035	.32	.07	.61	.05	0	.95
020	.16	.09	.75	0	0	1.0
032	.37	.35	.28	0	0	1.0

Dakota Formation

Sample	Q’	F	L’	Lv’	Lm	Ls’
014	.82	0	.08	0	.05	.95
033	.93	.01	.06	0	.07	.93

EXPLANATION

Sample numbers are arranged in descending stratigraphic order. The parameters are: mono and polycrystalline quartz (Q’), total feldspars (F), volcanic + metamorphic + sedimentary lithics + chert (L’), all expressed as the ratio to Q + F + L; volcanic lithics (Lv’), metamorphic lithics (Lm) and sedimentary lithics (Ls’), all expressed as the ratio to Lv + Lm + Lv + Qc.

TABLE 3: Means, Variances and 95% Confidence Intervals

Fra Cristobal Facies (McRae Formation)

	Q’	F	L’	Lv’	Lm	Ls’
Mean	.50	.19	.31	.43	.42	.15
s	.1115	.0618	.1587	.1698	.1609	.0457
n	4	4	4	4	4	4
95% C.I. (+/-)	.18	.10	.25	.27	.26	.07

Hall Lake Member (McRae Formation)

	Q’	F	L’	Lv’	Lm	Ls’
Mean	.23	.22	.55	.87	.02	.11
s	.0556	.0714	.1041	.0250	.0236	.0385
n	5	5	5	5	5	5
95% C.I. (+/-)	.08	.10	.14	.03	.03	.05

Jose Creek Member (McRae Formation)

	Q’	F	L’	Lv’	Lm	Ls’
Mean	.01	.33	.66	.99	0	.01
s	.0111	.0632	.0674	.0121	.0076	.0079
n	8	8	8	8	8	8
95% C.I. (+/-)	.01	.06	.06	.01	.01	.01

TABLE 3 (Continued)

Damsite Intrusion

	Q’	F	L’	Lv’	Lm	Ls’
Mean	.03	.36	.61	.96	.02	.02
s	.0058	.0300	.0252	.0666	.0289	.0379
n	3	3	3	3	3	3
95% C.I. (+/-)	.01	.07	.06	.17	.07	.09

Ash Canyon Member (Mesaverde Group)

	Q’	F	L’	Lv’	Lm	Ls’
Mean	.60	.05	.35	.05	0	.95
s	.0737	.0411	.1011	.0545	.0050	.0562
n	4	4	4	4	4	4
95% C.I. (+/-)	.12	.07	.16	.09	.01	.09

Main Member (Mesaverde Group)

	Q’	F	L’	Lv’	Lm	Ls’
Mean	.37	.18	.45	.04	.01	.95
s	.1996	.1279	.2702	.0499	.0250	.0733
n	4	4	4	4	4	4
95% C.I. (+/-)	.32	.20	.43	.08	.04	.12

TABLE 3 (Concluded)

Dakota Formation

	Q’	F	L’	Lv’	Lm	Ls’
Mean	.87	.01	.12	0	.04	.96
s	.0778	.0071	.0800	0	.0141	.0141
n	2	2	2	2	2	2
95% C.I. (+/-)	.70	.06	.76	0	.13	.13

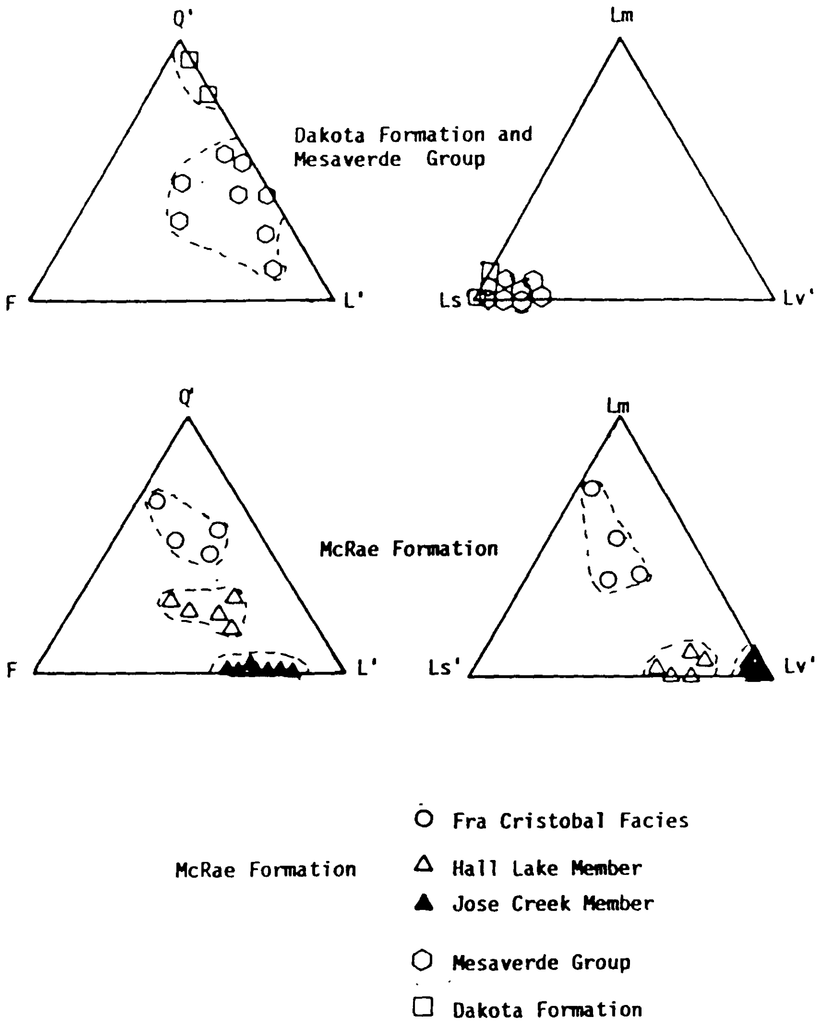


Figure 17: Ternary diagrams illustrating Q'F L' and Lv'Lm Ls' ratios of Dakota, Mesaverde and McRae formation specimens

	Tkmf	TKmh	Kmj	Kdi	Kma	Kmv	Kd
TKmf	O						
TKmh	Q' Lv' Lm'	O					
Kmj	Q' L' Lm' Ls'	Q' Lv' Ls'	O				
Kdi	Q' Lv' Lm'	Q' F	O	O			
Kma	Lv' Lm' Ls'	Q' Lv' Ls'	Q'F L' Lv' Ls'	Q'F L' Lv' Ls'	O		
Kmv	Lv' Lm' Ls'	Lv' Ls'	Q' Lv' Ls'	Q' Lv' Ls'	O	O	
Kd	F Lv' Ls'	F Lv' Ls'	Q' F, Lv', Ls	Q' F Lv'	Lv'	Lv'	O

Figure 18: Petrofacies Discrimination Matrix. Units are Fra Cristobal beds of McRae Formation (TKmf), Hall Lake (Tkmh) and Jose Creek members (Kmj) of McRae Formation, Damsite intrusion (Kdi), Ash Canyon (Kma) and main members of the Mesaverde Group (Kmv) and the Dakota Formation (Kd).

DETRITAL PETROLOGY OF BASIN STRATA

Point-count data reflecting modal constituents were taken from samples of the Dakota Formation, main and Ash Canyon Members of the Mesaverde Group, Jose Creek and Hall Lake members of the McRae Formation, Walnut Canyon and North Fra Cristobal beds of the McRae Formation, and the Damsite intrusion. The student's t-test was used to define 95% confidence intervals for the modal ratios of the detrital parameters Q', F, L', Lv', Lm and Ls'. Figure 18 shows which parameters discriminate the various units with respect to all others.

Statistical analysis of the detrital-mode ratios of Q', F, L', Lv', Lm and Ls' show, at 95% confidence, that there are five distinct petrofacies represented in the eight units examined (see Table 3, Figure 18). The petrofacies so defined are the Dakota Formation, the Mesaverde Group inclusive of its Ash Canyon Member, the Jose Creek Member of the McRae Formation, the Hall Lake Member of the McRae and a new unit, here named the Fra Cristobal beds of the McRae Formation. The Fra Cristobal beds includes the Walnut Canyon and North Fra Cristobal beds of the McRae Formation, that are identical at 95% confidence. Also identical at 95% confidence are the main Mesaverde Group and its Ash Canyon Member. The Jose Creek Member of the McRae Formation and the Damsite intrusion are also indistinguishable based on these petrologic parameters.

The nature of these petrofacies, the inferred locations of their source terranes and times of emergence are discussed in the following sections. Petrologic changes through time are graphically illustrated in Plate 8, which shows evolutionary trends in the petrology of the central McRae basin.

Marine, Deltaic and Fluvial Deposits: Dakota and Mancos Formations and Mesaverde Group

The earliest post-Paleozoic deposit preserved in the basin is the Dakota Formation, which was deposited by a regional transgression during the Cenomanian. The Dakota Formation is typically an extensive blanket 10 to 30 m of quartz-rich, chemically and texturally mature sandstone. In addition to quartz (average 87% Q'), the Dakota Formation contains locally abundant clasts of chert-replaced limestone (see Tables 1 and 2, pp. 42-44) . The chert is probably formed by silicification of fragments of the underlying San Andres Limestone. The non-chert fraction of the Dakota is almost entirely fine, well-sorted grains of monocrystalline quartz with clear silica cement. This high degree of chemical and textural maturity is indicative of considerable transport and mechanical abrasion, indicating multiple cycles of reworking and/or a distant source area. There is insufficient evidence to allow identification of specific source areas for the quartz.

Following the Dakota-age transgression, initial subsidence of the McRae basin began. The Mancos depositional period was dominated by pelagic sedimentation of dark, organic-rich clays (Cook and Bally, 1975). The absence of beds of sand-sized material in the Mancos Formation prevented petrologic analysis of this unit.

The base of the Mesaverde Group, which overlies the Mancos Formation, is marked by a prominent, ridge-forming bed of regressive sandstone that is scoured into the Mancos. The Mesaverde GRoup began as a marine-regressive deposit, but the upper 60% of this unit was deposited under terrestrial conditions in the McRae basin. This is seen in the South Basin section (Plate 6) where indicators of marine deposition (e.g., burrows and bioturbation) are absent above the sandstone beds at 302-338 m.

Petrologically, the sandstones of the Mesaverde Group grade upsection from basal marine beds rich in sedimentary lithic fragments and feldspar to more quartzose and chemically mature terrestrial deposits with a minor component of volcanic lithic fragments (see Tables 2 and 3, Figure 17). A distinct increase in quartz is associated with the first appearance of andesitic lithic fragments in the lower-middle parts of the unit.

Petrologic and stratigraphic evidence (paleocurrents indicative of sediment sources to the west and south, presence of volcanic lithic fragments) shows that much of the detrital material in the Mesaverde was derived from sources to the west and south. These source terranes were probably associated with a large arc-trench system which dominated western North America during most of the Mesozoic (Dickinson and Snyder, 1978).

The most stratigraphically distinctive part of the Mesaverde Group is the Ash Canyon Member (Bushnell, 1953). This unit is typically a coarse, pebble conglomerate of quartz and chert (see Figure 5, p. 6). The very high percentage of silica (average 60% Q') should make this unit statistically distinct from the rest of the Mesaverde Group (37% Q'), but the large variance in Q' (and all other parameters) observed in the main Mesaverde causes the confidence interval for these all of these parameters to overlap the ranges of the Ash Canyon Member (see Tables 2 and 3).

Large (up to 1 m) sets of trough and foreset cross-beds, sharply scoured lower contacts, and the lenticular geometry of the coarser beds indicate that the Ash Canyon Member was deposited in fluvial channels which are cut into the underlying main member of the Mesaverde Group (see Long Ridge section, Plate 6).

On a larger scale the Ash Canyon Member is arealy discontinuous, and is only found as elongated sandstone and conglomerate lenses. These isolated outcrops are typically less than one square kilometer in area, and are most common in the southwestern McRae basin. The abundant chert pebbles in this deposit are the result of quartz replacement of carbonate-rock clasts. This is supported by the presence of Paleozoic coral fossils in some of the larger chert pebbles (see Figure 5).

The Ash Canyon Member contains a small percentage of volcanic lithic fragments (Lv'= 5%); this is statistically identical to the Mesaverde average (Lv'= 4%). These are no larger than fine sand, as opposed to the large gravel to small cobble sizes of the chert. This indicates a more local source for the chert, and a distal source for the volcanics. On the basis of this textural evidence, it is unlikely that the uplift which supplied the chert was accompanied by any local volcanic activity.

Paleocurrent data from the Ash Canyon Member indicate southerly to easterly sources for the sediments. The grain sizes, petrology, paleocurrents and the fluvial nature of sedimentary structures of the Ash Canyon all indicate the presence of an eroding highland with an exposed Paleozoic section, located near the to the southeastern structural margin of the basin. This highland was the ancestral Caballo uplift, which was cored by carbonate-mantled basement. The Caballo uplift emerged as the first amagmatic, basement-cored source terrane in or adjacent to the McRae basin. All earlier sediments were predominantly derived from more distal sources.

Both the locally-preserved Ash Canyon Member and the underlying Mesaverde Group are truncated by the same unconformity, which probably formed during the final, Turonian-Campanian withdrawal of the Cretaceous seas from central New Mexico. This places a Campanian upper-age limit on the Ash Canyon and its source terrane.

Volcaniclastic Deposits: Jose Creek and Hall Lake Members of McRae Formation

Bushnell's (1953) work identified two members of the McRae Formation: the lower Jose Creek Member of Campanian-Maastrichtian age and the Hall Lake Member of Maastrichtian-Danian (?) age. These members were identified and mapped on the basis of the disconformity that separates them and the distinct stratigraphic and lithologic characteristics of the units. Petrographic study has shown that these lithostratigraphic units are also distinguishable as petrofacies, and are derived, at least in part, from different source terranes.

Jose Creek Member of McRae Formation

Overlying the unconformity that truncates the Mesaverde Group lies the Jose Creek Member of the McRae Formation. This member is composed almost exclusively of lithic fragments (66% L') and plagioclase feldspar (33% F). Of the 66% L', 99% is Lv' (see Table 3, p. 45). With the exception of a single specimen from the most basal bed (028, Table 2) with 21% Q', no other Jose Creek specimen has over 3% Q' and the average value is 1%.

The Jose Creek Member grades texturally and stratigraphically from extremely coarse alluvial-fan and mudflow deposits in the Elephant Butte area into much finer-grained fluvial sandstones and siltstones in the central McRae basin. This profound textural change is not accompanied by any discernable changes in detrital petrology. As seen in the ternary diagrams (Figure 17), the Jose Creek Member's composition occupies a very small area of both Q'F L' and Lv'Lm Lv' space. This indicates that the unit is petrologically homogeneous across the basin. Plate 8 shows that the Jose Creek Member's petrology is also very consistent throughout its deposition.

Easterly paleodrainage (Figure 15) carried detritus from the Damsite intrusion into the basin and along its axis. Maturation during transport and deposition was primarily textural (reduction in grain size and disaggregation of composite grains), while chemical maturation comprised alteration of feldspars to clays and zeolites and devitrification of glassy igneous matrix material to clays. The products of chemical maturation (and subsequent diagenesis) have typically cemented the Jose Creek sandstones into extremely well-lithified rocks which strongly resemble their volcanic parents.

The period of Jose Creek deposition was dominated by the introduction of large volumes of volcaniclastic sediments from the southern side of the basin. Jose Creek-like deposits are not observed in areas outside the main McRae basin. At the northwestern end of the basin, near Elephant Butte Lake, the Jose Creek is approximately 100 m thick. The overlying Hall Lake Member and younger Tertiary and Quaternary deposits have obscured the thickness and nature of the Jose Creek in the central parts of the basin.

Hall Lake Member Of McRae Formation

The Hall Lake Member of the McRae Formation disconformably overlies the Jose Creek, and is best recognized in the field by its vivid purple mudstones and shales. These are locally interbedded with deposits of fluvial sandstones, siltstones and conglomerates. The Hall Lake Member appears to be a low-energy, fluvial and overbank deposit which accumulated in a basin of much lower topographic relief than was the case during Jose Creek deposition.

The base of the Hall Lake Member is locally marked by a prominent, 5-10 m bed of conglomeratic sandstone, the purple color of which strongly contrasts with the dusky brown of the underlying Jose Creek Member. Figure 17 and Plate 8 show the abrupt change in petrologic composition between these members.

The basal Hall Lake Member contains the first appearance of plutonic and metamorphic rock fragments, and granitic pebbles are locally observed in hand specimen. Compared to the Jose Creek Member, the following changes in petrology are observed. Quartz (Q') increases from 1% to 23% and feldspar decreases from 33% to 22%. Rock fragments are reduced from 66% to 55% Volcanic rock fragments remain the major lithic constituent (87% of total lithics) but metamorphic (2%) and sedimentary (11%) lithics become significant (see Tables 2 and 3).

Although the volcanic rock fragments in the Hall Lake Member are very similar to those in the Jose Creek Member, the stratigraphy of the Hall Lake is very different. The Hall Lake is predominantly a deposit of purple mudstones with some discontinuous "shoestring" bodies of arkosic sandstone. The fluvial sandstones locally truncate the older Jose Creek, but do not appear to be derived substantially from reworking of the Jose Creek. The much finer texture of the Hall Lake may be due to a more distal source of the volcanigenic material. Unlike the Jose Creek, the Hall Lake beds cannot be traced laterally into a specific source area.

Paleocurrents (Figure 15) indicate that much of the sediments in the Hall Lake Member came from a source area to the south, west and north of the McRae basin. The basal conglomerate at the base of the Hall Lake Member is observed to be thicker and more extensive in the northern part of the basin, and granite pebbles are must abundant in northern outcrops of this bed (see Flying Eagle Canyon section, Plate 6). This may indicate a westerly source for the volcanic material and a northern source for the granitic detritus.

Basin-Margin Deposits: Fra Cristobal Beds

Field work for this study confirmed that a deposit at the northern extremity of the Fra Cristobal Range is part of the McRae Formation as mapped by Bushnell (1953). Another tectonic fragment of McRae was discovered by this study, in the Walnut Canyon area of the Central Fra Cristobal Range (Plate 5, Figures 10, 11). These outcrops comprise tectonic and erosional remnants of the fluvial systems which once transported sediment south into the basin from sources to the north and west:

1) In Walnut Canyon, approximately 15 km north of the central basin, there is a tectonic fragment of a fluvial deposit, which is petrologically very similar to the fluvial facies of the Hall Lake; paleocurrents indicate southerly flow and both granitic rock fragments and petrified wood are present,

2) At the extreme northern tip of the Fra Cristobal Range and in sedimentary contact with the granitic basement is a cross-bedded deposit of arkosic conglomerate and sandstone containing locally abundant plant fossils; paleocurrents are southerly, and granite and feldspar fragments are very common

Petrographic study has shown that the Walnut Canyon and North Fra Cristobal beds are statistically identical with respect to all six parameters examined. Quartz (Q') averages 50%, feldspars 19% and lithic fragments 31%. The lithic fragments subdivide into 43% Lv', 42% Lm and 15% Ls. The Fra Cristobal facies are the only unit examined that contained more than 4% Lm. This is attributed to the influence of nearby exposed basement.

Walnut Canyon beds

The Walnut Canyon beds are exposed in a narrow, north-trending fault block which overlies an intensely folded terrane of Permian siltstones and shales (see Figures 10, 12). The fault bounding this block is a low-angle detachment which do not show evidence of large amounts of vertical motion. On all sides of the block the fault dips 20 to 45 degrees toward the center of the block. Outcrops on the north side of Walnut Canyon show that the fault is essentially horizontal under the block of McRae Formation. The fault block is therefore a lenticular, flat-bottomed detachment sheet as opposed to a graben block.

This type of fault geometry does not easily allow large amounts of vertical motion. Also, the McRae fault block tectonically overlies in imbricate fashion a similarly-faulted block of San Andres Formation. The San Andres block is downfaulted against the middle Yeso Formation, indicating a stratigraphic displacement of approximately 100 m or less. No field evidence is seen in Walnut Canyon for any fault with a vertical displacement large enough to juxtapose the McRae and the Yeso formations (approximately 2000 m of stratigraphic separation).

An alternative hypothesis is that the McRae and Yeso formations were not separated by 2000 m of intervening deposits. The Walnut Canyon beds may have been deposited in a fluvial system that was downcutting on the flanks of the rising Fra Cristobal uplift while the McRae basin subsided to the south.. This channel system appears to have cut down-section to a level near the relatively resistant San Andres Limestone. Later, during Tertiary rifting and associated uplift of the present-day Fra Cristobals, low-angle detachment faulting brought tectonic fragments of these McRae Formation (and closely underlying San Andres Formation) beds into tectonic contact with the Permian Yeso Formation.

North Fra Cristobal Beds

At the extreme northern end of the present-day Fra Cristobal Range lies a small outcrop of coarse, arkosic sandstone and conglomerate which is in stratigraphic contact with the underlying Precambrian basement (Figures 10 and 18). The presence of leaf and wood impressions in finer-grained facies of this unit (Plate 6) indicates that the beds are much younger than the only other sedimentary unit which contacts the basement, the Cambrian Bliss Formation (see Plate 5). The sandstone and conglomerate are composed predominantly of quartz (average = 58%), potassium feldspar (average = 24%) and plutonic and metamorphic rock fragments (average = 18%). In outcrop, these beds closely resemble the granitic basement in color and texture.

The unit is cross-bedded, and numerous good-quality paleocurrent indicators were measured (average direction = 198^0). This outcrop appears to be an area of epiclastic erosion and deposition on basement exposed during the ancestral uplift of the Fra Cristobal Range. Sediment was transported to the south along the same drainage system which flowed through Walnut Canyon.

CONCLUSIONS

PETROSTRATIGRAPHIC EVOLUTION

Examination of the stratigraphy of the McRae basin, the petrology of its sedimentary fill and the directions of paleocurrents allows the reconstruction of the structural and stratigraphic evolution during the Laramide orogeny. Five statistically distinct petrofacies have been identified by petrographic analysis of detrital modes and tentatively correlated with source terranes whose locations are indicated by paleocurrent trends. The relative timing of the emergence of these source terranes is also apparent from the stratigraphic relationships of the respective petrofacies.

The oldest petrofacies is the Dakota Formation. This mature orthoquartzite is composed of quartz that is either from a distant source or the product of considerable reworking, and a minor component of chert, possibly formed by silicification of limestone fragments from the underlying San Andres Formation.

The Mesaverde Group is the second petrofacies defined. Quartzose and lithic sediments from cratonic and volcanic highlands to the west provided most of the basin fill during Mesaverde time.

Following the withdrawal of the last Campanian sea the ancestral Caballo uplift (to the south of the basin) became the first proximal source terrane. Clastic detritus shed from this uplift is preserved in the Ash Canyon Member of the Mesaverde Group. Although the entire Mesaverde Group forms a single petrofacies, stratigraphic evidence clearly points to the Caballo uplift area as a source for the Ash Canyon Member.

Following the uplift of the ancestral Caballos and the deposition of the Ash Canyon Member, the McRae basin area was eroded as evidenced by the unconformity that truncates the Mesaverde Group.

Deposits above this unconformity mark the beginning of the volcaniclastic phase of basin evolution, the emplacement of the Damsite intrusion and the deposition of the Jose Creek Member of the McRae Formation as detritus eroded from that intrusion (third petrofacies). This intrusion and basin filling was accompanied by major subsidence of the basin. The Jose Creek Member is the most uniform petrofacies examined, and consists almost entirely of volcaniclastic detritus.

After cessation of volcanic activity at the Damsite intrusion, the locus of volcanic activity appears to have shifted to the west, as evidenced by paleocurrents and by changes in the texture and composition of the sediments in the Hall Lake Member. Detritus from this hypothetical western source is statistically distinct from the Jose Creek material, and constitutes the fourth petrofacies identified. This second volcanic episode was closely accompanied in time by the uplift of the ancestral Fra Cristobal Range to the north of the basin. This uplift introduced a quartz and potassium-feldspar-rich component into the Hall Lake Member. This material was derived from erosion of exposed granitic basement in the core of the uplift.

Deposits from a major drainage system that evolved parallel to the strike of the emerging Fra Cristobal uplift form the fifth petrofacies. This drainage transported sediments eroded from Paleozoic and Precambrian rocks exposed on the flanks of the emerging Fra Cristobal Range southward into the basin. Remnants of this drainage system contain rocks that are intermediate in composition between the basement source-rocks and the Hall Lake rocks in the central basin.

STRUCTURAL EVOLUTION

Structural evolution of the McRae basin is first seen as subsidence during Mancos deposition. Subsequent events included a general trend of uplift and/or regression during deposition of the Mesaverde Group, the emergence of the Caballo uplift to the south, erosional truncation of all Mesaverde deposits, the emplacement of the Damsite intrusion, major subsidence of the basin, a shift in the location of volcanic centers to the west, and the emergence of the Fra Cristobal uplift to the North.

From Cretaceous through early Tertiary (?) time, the centers of volcanic and tectonic activity shifted in space. The earliest orogenic activity was the emergence of the Caballos south of the basin, well before the beginning of any volcanic activity. The exclusively volcaniclastic composition of the Jose Creek Member of the McRae Formation shows, however, that uplift in the Caballo area had essentially ceased by the time of the Damsite intrusion.

The unconformity that separates the Jose Creek and Hall Lake members of the McRae Formation is evidence for a hiatus in local volcanic activity. Following this period of non-deposition and erosion the site of volcanic activity shifted to the west, and appears to have changed in texture to a much finer-grained and ashy material. During these two periods of volcaniclastic deposition, the basin subsided over

800 meters as it filled with sediment.

As the locus of volcanic activity shifted to the west, a second center of orogenic uplift (the Fra Cristobal Uplift) was established to the north of the basin. Tectonism in this uplift was quite complex as seen in the intensely folded and faulted strata now exposed in that area.

The geology of the McRae basin area, including the Caballo Mountains and the Fra Cristobal Range, has revealed a complex sequence of structural and depositional events during the Late Cretaceous and early Tertiary. Many areas remain open for future research, especially the wide variety of tectonic styles seen in this area.

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