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Characteristics, Evolution, and Lateral Variation of Lower Cretaceous Supradetachment Basins in the Daqing Shan, Inner Mongolia, China

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CHARACTERISTICS, EVOLUTION, AND LATERAL VARIATION OF LOWER CRETACEOUS SUPRADETACHMENT BASINS IN THE DAQING SHAN, INNER MONGOLIA, CHINA

by

Adrian K. Berry

A thesis submitted in partial fulfillment of the requirements of the degree of MASTER OF SCIENCE in Geology

Approved:

UTAH STATE UNIVERSITY
Logan, Utah
2003
ABSTRACT

Characteristics, Evolution, and Lateral Variation of Lower Cretaceous Supradetachment Basins in the Daqing Shan, Inner Mongolia, China

by

Adrian K. Berry, Master of Science

Utah State University, 2003

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Department: Geology

Lower Cretaceous basins associated with the Hohhot detachment in the Daqing Shan of Inner Mongolia, China, allow us to better understand the tectonic evolution of extensional basins formed in association with detachment faulting and metamorphic core complex formation. The six basins, informally named N1, N2, S1, S2, S3, and S4, are located in different structural settings, or depozones, throughout the detachment-metamorphic core complex setting, and although all basins are consistent with previously proposed models for supradetachment basin sedimentation, second-order variability in sedimentary style is exerted by these distinct structural settings. The basins are composed of coarse, predominantly footwall derived, conglomerate deposited by mass-wasting and alluvial fan processes. Paleocurrent direction is generally southerly, indicating transverse transport away from the bounding detachment fault.
Two of the basins, N2 and S3, provide us with an understanding of the temporal evolution of supradetachment basins in the upper plate of a metamorphic core complex. These basins were joined in their early stages, but were later separated as extensional unroofing exhumed the lower plate of the core complex and folded the master detachment fault, causing it to propagate a new splay to the surface. Continued extension was accommodated on this new splay, allowing for continued deposition of Lower Cretaceous strata above the detachment fault on the southern flank of the Daqing Shan antiform. Another basin, S2, displays the same stratigraphy and records a similar evolution, but we speculate that it formed separately in a primary corrugation of the master detachment fault. The only unit exposed in basin S4, located near the eastern end of the detachment, is the uppermost unit. Paleocurrent and provenance data are similar to other basins. Thus, it strongly resembles the other basins in spite of the magnitude of extension. Basin S1 is located in an intra-hanging wall setting and resembles the other basins with the exception of a centrally located fine-grained interval. Basin N1 was filled by similar depositional processes, but the proportions of fill that these processes are responsible for is variable in comparison to the other Lower Cretaceous basins in the Daqing Shan. This study establishes that the basins described are all of similar geometry and depositional style, and that supradetachment basins of this style may occur in various positions within a detachment-metamorphic core complex setting, regardless of proximity to the exhumed metamorphic core and magnitude of extension.
ACKNOWLEDGMENTS

Acknowledgment is made to the Donors of the American Chemical Society Petroleum Research Fund (PRF # 35596-GB8 and PRF # 38900-B8 to Ritts), AAPG Grants-in-Aid program, Anadarko Petroleum Company, and Utah State University for providing financial support of this research. I would also like to thank Wang Jianmin of the Nei Mongol Bureau of Geology for logistical support. We thank Brian Darby, Cari Johnson, Greg Davis, Zheng Yadong, and Yaming Davis for their assistance and advice in the field. I would like to give special thanks to Lynde Nanson for her assistance in the field and for being a good cohort through a long field season. I would like to thank faculty and fellow graduate students at Utah State University, as well as my family and friends for supporting me as I worked on this project. Lastly, I would like to thank Carey Wicks for putting up with me on a daily basis and supporting me through this effort.

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CHAPTER I
INTRODUCTION

Supradetachment basins are an important type of extensional sedimentary basin related to movement on low-angle normal faults (detachment faults) and, sometimes, uplift of mid-crustal domes in metamorphic core complexes (Friedmann and Burbank, 1995; Lister and Davis, 1989). Because this type of basin has only recently been recognized, its classification, genetic stratigraphy, and tectonic significance remain incompletely understood. Many examples of supradetachment basins have been described, especially from the western United States; however, incomplete exposure and structural dismemberment hinder a holistic understanding of the geology and evolution of these systems (Beratan, 1991; Beratan and Nielson, 1996; Dickinson, 1991; Dorsey and Becker, 1995; Dorsey and Roberts, 1996; Fedo and Miller, 1992; Fillmore and Walker, 1996; Fillmore et al., 1994; Forshee and Yin, 1995; Friedmann and Burbank, 1995; Friedmann et al., 1996; Janecke et al., 1999, in press; Miller and John, 1988, 1999; Nielson and Beratan, 1995; Yarnold, 1994).

A series of newly documented syn-extensional supradetachment basins associated with the recently discovered Early Cretaceous Hohhot metamorphic core complex presents the opportunity to better understand the coupled structural and stratigraphic evolution of such systems (Davis et al., 2002). The well-documented structural geology and evolution of the Hohhot metamorphic core complex and associated detachment fault (Davis et al., 2002), make the Hohhot extensional system an unparalleled natural laboratory for studying the sedimentary geology of such systems. Depositional facies, detrital provenance and paleodrainage patterns in this evolving basin
system record initial movement on the detachment, breakup of the upper plate, and ultimately uplift of a metamorphic dome. Description of this sedimentary geology and basin evolution can provide new insights into general models of the formation of supradetachment basins.

Previous research concerning supradetachment basins provides conceptual models for supradetachment basins (Fillmore and Walker, 1994; Friedmann and Burbank, 1995). However, the general applicability of these models has been disputed (Janecke et al, 1999), largely due to variability of sedimentary styles in various structural settings. This research was undertaken to document a newly discovered series of basins above low-angle normal faults, as well as to provide a case study for comparison with previously studied supradetachment basins and related conceptual models. The preservation of the Daqing Shan basins in a variety of structural settings allow us to examine changes in basin geometry in response to variability of the controlling structures
CHAPTER II

CHARACTERISTICS AND EVOLUTION OF SUPRADETACHMENT BASINS ADJACENT TO THE HOHHOT METAMORPHIC CORE COMPLEX, INNER MONGOLIA, CHINA

Abstract

Lower Cretaceous basins associated with the Hohhot metamorphic core complex in the Daqing Shan of Inner Mongolia, China, allow us to understand the tectonic evolution of extensional basins formed coincident with detachment faulting and metamorphic core complex formation. The three-part stratigraphy in the basins records debris flow, mass-wasting, and waterlain deposition in an alluvial fan setting. These sedimentary rocks provide evidence of extensional break-up and reworking of these units early in the basin history, followed by sedimentation of coarse, transversely transported subaqueous channelized and sheetflood deposits of an alluvial fan system. The basins adjacent to the exhumed metamorphic core also record the structural evolution of the Hohhot metamorphic core complex. Extensional unroofing exhumed the metamorphic core and folded the master detachment fault, causing it to propagate a new splay to the surface and separate the previously contiguous basins. This new splay accommodated continued extension and allowed continued deposition of Lower Cretaceous strata above the detachment fault on the southern flank of the Daqing Shan antiform. The strata in these basins strongly resemble the proposed end-member model for supradetachment.
basins (Friedmann and Burbank, 1995), and support the relevancy of models for supradetachment basin systems in research concerning highly extended regions.

**Introduction**

Supradetachment basins are an important type of extensional sedimentary basin related to movement on low-angle normal faults (detachment faults) and, sometimes, uplift of mid-crustal domes in metamorphic core complexes (Friedmann and Burbank, 1995; Lister and Davis, 1989). Because this type of basin has only recently been recognized, its classification, genetic stratigraphy, and tectonic significance remain incompletely understood. Many examples of supradetachment basins have been described, especially from the western United States; however, incomplete exposure and structural dismemberment hinder a holistic understanding of the geology and evolution of these systems (Beratan, 1991; Beratan and Nielson, 1996; Dickinson, 1991; Dorsey and Becker, 1995; Dorsey and Roberts, 1996; Fedo and Miller, 1992; Fillmore and Walker, 1996; Fillmore et al., 1994; Forshee and Yin, 1995; Friedmann and Burbank, 1995; Friedmann et al., 1996; Janecke et al., 1999, in press; Miller and John, 1988, 1999; Nielson and Beratan, 1995; Yarnold, 1994).

A series of newly documented syn-extensional supradetachment basins associated with the recently discovered Early Cretaceous Hohhot metamorphic core complex presents the opportunity to better understand the coupled structural and stratigraphic evolution of such systems (Davis et al., 2002). The well-documented structural geology and evolution of the Hohhot metamorphic core complex and associated detachment fault
(Davis et al., 2002), make the Hohhot extensional system an unparalleled natural laboratory for studying the sedimentary geology of such systems. Depositional facies, detrital provenance and paleodrainage patterns in this evolving basin system record initial movement on the detachment, breakup of the upper plate, and ultimately uplift of a metamorphic dome. Description of this sedimentary geology and basin evolution can provide new insights into general models of the formation of supradetachment basins.

Geologic Setting

The Hohhot metamorphic core complex is one of the most important structural features in the eastern Daqing Shan (Davis et al., 2002). It is located near the northern margin of the North China Block (Fig. 1), where it is superposed on a Late Jurassic through Early Cretaceous fold-thrust belt (Davis et al., 1998, 2001, 2002; Darby et al., 2001, 2002). The core complex, which was exhumed by a minimum of 40 km of extension on the Hohhot detachment fault, formed in response to rapid crustal extension that most likely occurred due to gravitational collapse following over-thickening of the crust in the Late Jurassic and earliest Cretaceous (Davis et al., 1998, 2002).

The Hohhot metamorphic core complex (as described by Davis et al., 2002), consists of the Daqing Shan antiform, a roughly east-west trending culmination of metamorphic and plutonic rocks, the Hohhot extensional detachment, and an upper plate of pre-Cretaceous crystalline and sedimentary units and Lower Cretaceous syn-extensional strata. South of the Daqing Shan antiform, the Hohhot detachment fault is a south-dipping low-angle (15-30°) normal fault system that is exposed along strike for
Fig. 1: Simplified tectonic map showing location of Hohhot metamorphic core complex and cross-section (modified from Davis et al., 2002).

Jurassic sedimentary and Late Paleozoic (includes some Permian plutons in lower plate)

Middle plate—mainly Proterozoic plutons lacking mylonitic fabric

Lower plate—undifferentiated Archean and Proterozoic generally contains mylonitic fabric in western half of map

Lowermost detachment (dashed where uncertain)

Second detachment

Large normal fault (ball on HW)

Antiform

Synform

Mylonitic front

Thrust fault

Area of Figs. 16 and 17

N 4°10' 0" W

N 4°10' 0"

N 4°20' 0"

E 112'30"

E 111'30"

E 112'30"

E 111'30"

E 112'30"
>120 km (Fig. 1 and 2). This fault is the master detachment and is corrugated (Davis et al., 2002), with synforms in the detachment preserve numerous Lower Cretaceous nonmarine clastic basins. On the northern flank of the antiform, two detachment faults are stacked and synformally folded, with top-to-the south slip on both splays (Fig. 2) (Davis et al., 2002). The lower detachment separates mylonitic rocks from overlying non-mylonitic rocks, primarily Proterozoic crystalline rocks and Permian granitic gneisses. The upper detachment carries a succession of Cretaceous volcanic and sedimentary rocks in its upper plate (Fig. 2), that are highly deformed by normal faulting related to extension. The lower, oldest, detachment was the original detachment, but with extension, the footwall was progressively unloaded triggering isostatic uplift and bringing lower plate rocks to the surface. The resultant antiformly folded detachment was deactivated and a new splay propagated to the surface to accommodate further extension (Davis et al., 2002). The new splay, in turn, was also antiformly folded due to continued uplift with further unloading. The Hohhot detachment, on the southern flank of the Daqing Shan antiform, is the youngest fault splay and accommodated the remaining extension (Davis et al., 2002).

Characteristics of Lower Cretaceous Basins

Lower Cretaceous sedimentary basins are found discontinuously along the 120 km length of the Hohhot detachment. This study focuses on two of the Lower Cretaceous basins in the central part of the metamorphic core complex, one on the southern flank of the Daqing Shan antiform, the other on the northern flank, in a synformal keel (Fig. 1).
Modified from Darby et al. (2001)

Fig. 2: Cross-section through Hohhot metamorphic core complex and Lower Cretaceous basins (modified from Davis et al, 2002). Cz - cenozoic, K2 - Late Cretaceous, K1 - Lower Cretaceous, u/c - unconformity.
These Lower Cretaceous sedimentary basins above the Hohhot detachment are interpreted to be syn-extensional for several reasons. First, Lower Cretaceous rocks are separated from older rocks by the Hohhot detachment, related normal faults, or unconformities, and occur only in the upper plate of the detachment. Second, these rocks are cut by low- and high-angle normal faults as a result of northwest southeast extension, consistent with movement on the detachment. Third, volcanic rocks in the base of the Lower Cretaceous succession have been dated at $125.2 \pm 0.7$ Ma, $125.7 \pm 0.6$ Ma, and $125.8 \pm 0.6$ Ma (sanidine single-crystal, weighted means $^{40}\text{Ar}/^{39}\text{Ar}$ age), coincident with the age of faulting determined by cooling ages and cross-cutting relationships in the footwall of the detachment (Davis et al., 2002). Fourth, these rocks consist predominantly of coarse conglomerate derived from sources that include footwall mylonite and other metamorphic rocks common in the lower plate of the detachment. Fifth, intraformational unconformities are present indicating rotation of strata due to continued upper plate faulting during deposition.

**Stratigraphy and Sedimentology**

The Hohhot basins comprise a dominantly clastic sedimentary section that is more than 1200 m thick (Fig. 3). We informally divide the basins into three lithostratigraphic members, K1a, K1b, and K1c, from bottom to top. These members are recognized in each basin, although their thickness and internal stratigraphy varies considerably throughout the study area.

The basal unit, K1a, is composed dominantly of unorganized, red, matrix-supported, pebble to cobble, conglomerate with interbedded bimodal volcanic rocks (Fig.
Fig. 3: Composite sections for the Hohhot basins tracking paleocurrent and provenance data.
FACIES CODES

- Gmm: matrix-supported massive conglomerate
- Gcm: clast-supported massive conglomerate
- Gcmi: clast-supported imbricated conglomerate
- Gch: horizontally-stratified conglomerate
- Gel: low angle cross-stratified conglomerate
- Sm: massive (structureless) sandstone
- Sh: plane laminated sandstone
- Sp: planar cross-stratified sandstone
- St: trough cross-stratified sandstone
- Sl: low angle cross-stratified sandstone
- Sr: rippled sandstone
- Fm: massive mudstone
4). The base of the section, depending on the location, is either a fault or an erosional unconformity over older rocks (Fig. 5). Member Klb, which overlies Kla, has similar red, matrix-supported conglomerate beds (Fig. 6) and lesser clast-supported, lenticular, pebble to cobble conglomerate. Klb lacks volcanic flows, but volcaniclastic grains are common in the matrix and minor sandstone beds. In addition, monolithologic blocks and megabreccia units are common in Klb (Fig. 7), and are most commonly composed of Proterozoic marble. The marble can be fairly intact, but is usually intensely fractured and brecciated and may be injected with the silty, red matrix that is common in Klb (Fig. 6).

Kla and Klb are interpreted as dominantly debris flow deposits based on the matrix-supported, disorganized nature of the conglomerate beds. Lesser streamflow and sheetflood deposits are marked by the better organized, clast-supported, lenticular to tabular conglomerates. This combination of minor waterlain deposits and debris flow deposits is interpreted to represent a proximal alluvial fan environment (Blair and McPherson, 1994). Large blocks and megabreccia units are interpreted as slide blocks and rock avalanche deposits, because they are completely contained within Lower Cretaceous conglomerate and exhibit characteristics of being emplaced as coherent to semi-coherent units (Friedmann, 1997).

The thickest unit, Kl c, dominantly consists of well-organized, clast-supported, pebble to cobble conglomerate (Fig. 8). Beds are lenticular with erosive bases, and are interbedded with coarse sandstone and rare mudstone. Individual beds are organized into relatively tabular units on the order of a few meters to 10 m thick and extend for at least hundreds of meters laterally. Imbrication is abundant, as is trough cross-stratification and
Fig. 4: Photograph of K1a. K1a is a red, unorganized, matrix-supported, pebble to cobble conglomerate.

Fig. 5: Photograph of unconformity separating Lower Cretaceous sedimentary rocks from older rhyolitic volcanic rocks. Red line denotes unconformity.
Fig. 6: Photographs of K1b. K1b is an unorganized, matrix-supported, pebble to cobble conglomerate (upper photo), with lesser organized, clast-supported, pebble to cobble, lenticular conglomerate beds (lower image).
Fig. 7: Photographs of gravity-driven slide blocks within K1b. Slide blocks are white, Proterozoic marble, encased in red, K1b conglomerate. Arrow in lower photo points to a person for scale.
Fig. 8: Photographs of K1c. K1c is an organized, clast-supported, pebble to cobble conglomerate with abundant imbrication.
plane lamination in the sandstone. These conglomerates are interpreted as subaqueous channelized and sheetflood deposits based on their clast-supported, well-organized character. Large monolithologic, brecciated, gravity-driven slide blocks also occur in \( K_{1c} \). These blocks reach >2 km (long-axis) in size, and are typically composed of Proterozoic marble (Fig. 9). These deposits are interpreted to have formed in an alluvial fan system, based on the uniformly coarse conglomeratic nature of \( K_{1c} \), dominance of streamflow and sheetflood processes, and association with gravity-driven slide blocks and rock avalanche deposits (Blair and McPherson, 1994; Friedmann, 1997).

The basin on the northern flank of the Daqing Shan antiform contains \( K_{1a} \), \( K_{1b} \), and \( K_{1c} \), although the \( K_{1c} \) unit is relatively thin. \( K_{1a} \) and \( K_{1b} \) are difficult to separate in this basin and are generally considered one unit that is easily distinguished from \( K_{1c} \), based on its greater content of red fine-grained sediment, volcaniclastic detritus, and debris flow deposits. Intense faulting in this basin inhibits measurement of a complete section (Fig. 10); a maximum of only about 200 m of continuous section can be measured without crossing significant normal faults. However, a composite section was constructed by correlating like-parts of repetitive lithostratigraphic sequences, which suggests a minimum basin thickness of nearly 400 m with at least 200 m of \( K_{1c} \) sediment (Fig. 3). Angular unconformities are present in the basin (Fig. 11) and indicate syn-depositional rotation of Lower Cretaceous strata. Large slide blocks and rock-avalanche breccias are common within this northern basin (Fig. 7).

The basin on the southern flank of the Daqing Shan antiform also contains \( K_{1a} \), \( K_{1b} \), and \( K_{1c} \), with a much thicker \( K_{1c} \) member. \( K_{1a} \) and \( K_{1b} \) are distinguished from
Fig. 9: Photograph of slide block within K1c. Slide block is white, Proterozoic marble encased in darker K1c conglomerate.
Fig. 10: Profile showing transect in northern basin with stratigraphic columns, paleocurrent data, and clast compositions.
Fig. 11: Photograph of angular unconformity in Lower Cretaceous strata. Red line marks change from upper gently dipping beds to lower more steeply dipping beds.
each other in this basin based on the presence of volcanic flows. K1a and K1b are clearly distinguished from K1c based on their greater content of red fine-grained sediment, volcanic detritus, and debris flow deposits. The measured thickness of the southern basin is a minimum of 1120 m, including 900 m of K1c strata (Fig. 3). Pebble-to-cobble conglomerate is dominant in the section, but sandstone content increases upsection (Fig. 3). The sand-rich upper portion of the section still contains interbedded conglomerate beds and areally, coarse conglomerate is present at every location in this basin.

Packages of beds are generally continuous and can often be traced laterally around the southern basin (Fig. 12). Large, easily defined normal faults commonly cut the strata, but do not inhibit section measurement. The K1a and K1b part of the section in the southern basin is more pervasively faulted than the K1c section. Offset on these normal faults range from cm-scale to several meters and dips span from horizontal to moderately dipping (Fig. 13). The slip direction determined from fault planes is consistent with south-southeast extension.

Paleocurrent and Provenance Data

Paleocurrent data were collected about both basins (Fig. 14). The average paleocurrent directions for combined K1a and K1b are 155° in the northern basin and 214° in the southern basin. The paucity of imbricated clasts within K1a and K1b makes paleocurrent measurement within these units difficult. Well-imbricated conglomerate is abundant in K1c in both basins, and yields south-directed paleocurrent directions averaging 187°. K1c paleocurrents show little variability, except in the upper 200 m of
Fig. 12: Photograph showing laterally continuous strata. K1c conglomerate beds can be traced laterally around the basin.
Fig. 13: Photographs of intra-K1b normal faults. Red lines on top photo mark fault planes. Lower photo shows intra-member half-graben.
Fig. 14: Aerial distribution of paleocurrent data.
Southern basin paleocurrent data

Northern basin paleocurrent data

km
the section in the southern basin, coincident with the increase in sandstone:conglomerate ratio (Fig. 3).

Areally distributed clast-count data clearly demonstrate the dominance of clasts derived from the footwall of the detachment throughout both basins (Fig. 15). Granitoid plutonic clasts are dominant, with foliated plutonic, conglomerate, and sandstone clasts spatially distributed fairly uniformly. Marble and volcanic clasts are locally important in parts of each basin, with volcanic clasts concentrated along the western margin of each basin (where volcanic rocks of K1a or older are still preserved).

There is little vertical stratigraphic variability in clast composition, with plutonic clasts dominating throughout the section. However, minor clast types show some important vertical trends (Fig. 3). Gneiss clasts are common in K1c, but are not present in K1a or K1b (Fig. 3, 10, and 15); similarly, mylonitic clasts are not observed in K1a or K1b and are not commonly seen in the lower part of K1c. These mylonitic clasts appear in the upper 200 m of the section in the southern basin, but are not found in the northern basin (Fig. 3 and 15). Sandstone clasts, some of which may be recycled Lower Cretaceous clasts, decrease in abundance up section (Fig. 3).

Discussion

Geologic Evolution of the Hohhot Basins

The evolution of the basins can be broadly subdivided into two phases, based on the contrasting depositional and deformational styles in K1a-K1b and K1c (Fig. 16). The
Fig. 15: Areal distribution of clast composition data.
Fig. 16: Model for tectonic evolution of northern and southern basins. A) Initial faulting and syn-extensional basin filling. B) Continued extension and beginning of upperplate break-up with deposition in isolated half-graben. C) Continued extension and deposition with uplift of the upper plate causing folding and propagation of new detachment splay. D) Continued extension and deposition with uplift causing folding and propagation of a third detachment splay. E) Exhumation of Daqing Shan antiform. Northern basin is inactive with continued extension and deposition of Lower Cretaceous sediment on the southern flank of the Daqing Shan antiform.
bulk of the basin fill consists of Klc, suggesting longer-lived basins later in the evolution of the system.

Kla and Klb are dominated by proximal alluvial fan facies and include abundant debris flow, rock avalanche, and slide block deposits. These units were deposited with the onset of extension and the concomitant creation of topographic relief and isolated basins. Early stage sedimentation was concurrent with volcanism, which ceased by the Kla-Klb boundary.

The Hohhot basins were deformed and dissected by normal faults synchronous with deposition of Kla-Klb, as evidenced by the much greater density and multiple generations of normal faults in Kla and Klb versus Klc. Further evidence for dissection are angular unconformities between volcanic rocks and Lower Cretaceous strata in the northern basin (Fig. 11), and the abundance of reworked volcaniclastic detritus in sandstone and conglomerate of Klb (Fig. 17). Intrabasinal breakup of the Hohhot basins during Kla and Klb sedimentation, as well as the creation of intrabasinal graben (Fig. 13) resulted in variable paleocurrent directions and local changes in clast sources (Fig. 14 and 15).

Klc is a much more consistent unit laterally and stratigraphically, dominated by sheetflood and streamflow processes in an alluvial fan setting with additional deposition by rock-avalanche and large gravity-driven slide blocks. Paleocurrent indicators are uniformly south-directed in both basins, and demonstrate a well-developed transverse paleodrainage system flowing away from the detachment fault in the direction of extension. However, local variation in clast composition (but not depositional style or
Fig. 17: Photomicrograph of K1b. Arrows mark volcanic lithic grains with plagioclase laths.
paleocurrent) suggest that these fans were not being deposited in a homogenized drainage basin, but rather were deriving sediment from small catchments or source regions of spatially variable rock types (Ingersoll, 1990). Paleocurrent trends around the basins do not reflect primary corrugation of the detachment fault. This observation does not address the presence or absence of the corrugations as primary features, given that energetic depositional systems flowing down the axis of the corrugation are expected to obscure any more minor flow components off the sides of the corrugations.

These data suggest that the basins on both flanks of the Daqing Shan antiform were originally contiguous during deposition of K1a, K1b and the lower portion of K1c (Fig. 16). Both basins exhibit K1a-K1b strata of similar thickness that were deposited by debris flow and rock-avalanche processes. Units K1a and K1b are overlain by K1c sediment that was deposited by similar processes in both basins. Transport direction for K1c in the northern basin is 187°, suggesting that the exhumed lower plate, currently a topographic high, was not exposed and bisecting the basins during deposition of the lower portion of the section. Clast types in K1a, K1b, and the lower part of K1c are also similar. Granitoid plutonic clasts dominate and clasts of reworked Lower Cretaceous conglomerate and sandstone clasts are present. Also, gneiss clasts do not appear in either basin until K1c is deposited. Age relationships from intrabasinal volcanic rocks and footwall cooling ages suggest concurrent sedimentation was occurring in both basins.

The appearance of higher metamorphic grade, including mylonitic, clasts high in the section in the southern basin suggests progressive unroofing of deeper crustal material as extension and uplift of the lower plate continued. Likewise, the absence of such clasts
in the northern basin suggests that the northern basin had stopped receiving sediment by the time those clast types were exposed in the source terrane. This apparent shorter-lived deposition on the northern flank of the core complex, also supported by the much thinner K1c section, is interpreted to record the uplift of the Daqing Shan antiformal dome during unroofing of the metamorphic core complex. Specifically, midway through deposition of K1c in the southern basin, exhumation of the lower plate and uplift of a mid-crustal dome separated the previously contiguous northern and southern basins (Fig. 16). Much as uplift of the metamorphic core complex resulted in deactivation of the folded northern splays of the Hohhot detachment (Davis et al., 2002), uplift of the core complex resulted in deactivation of the northern basin. Following uplift of the core of the metamorphic core complex, continued extension on the southern splay of the Hohhot detachment (Davis et al., 2002) continued to create accommodation space in the southern basin, where K1c continued to accumulate (Fig. 16).

**Supradetachment Basin Evolution and Style**

Previous work concerning supradetachment basins has presented conceptual models suggesting that supradetachment basins exhibit predictable characteristics that are a result of the structural controls exerted by the unique setting in which they form (Fillmore et al., 1994; Friedmann and Burbank, 1995). The general applicability of these models has been disputed, largely due to the variability of sedimentary styles in documented supradetachment basins, as well as the imprecision with which supradetachment basin nomenclature is applied (e.g. Janecke et al., 1999).
The most widely cited and applied model for sedimentation is supradetachment basins is that of Friedmann and Burbank (1995), who classify supradetachment basins as an end-member basin style in extensional continental settings opposite the better-known half-graben rift basin of Leeder and Gawthorpe (1987) (Table 1). Friedmann and Burbank (1995) describe supradetachment basins as those that form “above a low-angle normal fault system.” More specifically, “the term also represents the end-member model presented [in Friedmann and Burbank, 1995].” These basins are thin, short-lived and are dominated by coarse, predominantly footwall-derived sediments delivered to the basin by transverse drainages and often deposited by mass-wasting processes (Table 1). Supradetachment basins generally are expected to lack either significant fine-grained, lacustrine deposits or axial drainage systems, which are commonly found in half-graben (Leeder and Gawthorpe, 1987). This type of extensional basin tends to occur in back-arc regions where the crust has recently experienced dramatic thickening, and rock may be warmer due to magmatism and high radiogenic heat flow (Friedmann and Burbank, 1995). In contrast, most rifts occur in areas with cold normal crust lacking recent contractile tectonism (Friedmann and Burbank, 1995).

The geological characteristics documented for both our northern and southern study basins, conform well to the Friedmann and Burbank (1995) end-member supradetachment basin model. The Hohhot basins are thin (<1200 m), contain angular unconformities, and are dominated by coarse conglomerate derived from the footwall of the detachment fault and transported to the basin in transverse drainage systems with paleocurrents parallel to the extension direction. Rapid rates of footwall uplift relative to
Table 1: CHARACTERISTICS OF EXTENSIONAL BASINS. (Modified from Friedmann and Burbank, 1995. Additional data sourced from: a) Davis et al., 2002 b) Stewart and Diamond, 1990; Diamond and Ingersoll, 2002)

<table>
<thead>
<tr>
<th>Basin Characteristics</th>
<th>Lake Baikal</th>
<th>Mid-continent Rift</th>
<th>Shadow Valley</th>
<th>Chemehuevi</th>
<th>Hohhot&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Esmarelda&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bounding fault geometry</td>
<td>Steep (50-70°), listric, planar</td>
<td>Steep (60-65°), multiple planar</td>
<td>~31°, curviplanar, corrugated</td>
<td>12-26°, curviplanar, corrugated</td>
<td>15-30°, curviplanar, corrugated</td>
<td>25-30°, corrugated, curviplanar</td>
</tr>
<tr>
<td>Total Extension (km)</td>
<td>10-25</td>
<td>??</td>
<td>11-26</td>
<td>40-75</td>
<td>&gt;40</td>
<td>~11</td>
</tr>
<tr>
<td>Extension rate (km/Myr)</td>
<td>0.3-0.84</td>
<td>??</td>
<td>12-1</td>
<td>10.1-4.5</td>
<td>??</td>
<td>1.2-1.8?</td>
</tr>
<tr>
<td>Duration of sedimentary record (Myr)</td>
<td>35-30, in progress</td>
<td>15-30</td>
<td>&lt;7</td>
<td>7-9</td>
<td>3-7</td>
<td>6-9</td>
</tr>
<tr>
<td>Fill thickness (km)</td>
<td>4-6</td>
<td>3.3-7.3</td>
<td>3</td>
<td>2-3</td>
<td>0.3-1</td>
<td>4.4-5.4</td>
</tr>
<tr>
<td>Dominant provenance</td>
<td>Hanging wall</td>
<td>??</td>
<td>Footwall</td>
<td>Hanging wall and footwall</td>
<td>Footwall</td>
<td>Hanging wall and footwall</td>
</tr>
<tr>
<td>Dominant transport pathways</td>
<td>Hanging wall</td>
<td>??</td>
<td>Transverse, ext. parallel</td>
<td>Transverse, ext. parallel</td>
<td>Transverse, ext. parallel</td>
<td>Transverse, ext. parallel</td>
</tr>
<tr>
<td>Sedimentary style</td>
<td>Fluvial (meandering), delta</td>
<td>Fans, fluvial (braided, meandering)</td>
<td>Mass wasting, fans</td>
<td>Mass wasting, fans</td>
<td>Mass wasting, fans</td>
<td>Mass wasting, fans, braided fluvial, major lake (playa, perennial)</td>
</tr>
<tr>
<td></td>
<td>Deep lake (muds, turbiditic)</td>
<td>Shallow lake, mudflat</td>
<td>Major lake (playa, perennial)</td>
<td>Major lake (playa, perennial)</td>
<td>Fluvial (?) sandstone</td>
<td></td>
</tr>
<tr>
<td>Associated magmatism</td>
<td>Alkalic, tholeitic</td>
<td>Alkalic, tholeitic</td>
<td>Calc-alkaline</td>
<td>Calc-alkaline</td>
<td>Rhyolitic, minor basalt</td>
<td>Calc-alkaline</td>
</tr>
</tbody>
</table>
basin subsidence minimized proximal accommodation space and prevented proximal trapping of sediment adjacent to the fault (as occurs in half-graben), thus promoting distal deposition of coarse material derived from the lower plate. The Hohhot basins show no evidence of axial drainage and do not contain fine-grained lacustrine intervals as with Friedmann and Burbank (1995) type supradetachment basins. Instead, coarse conglomerate is present from the detachment fault to the most distal strata exposed. Finer grained rocks may exist further into the basin, as is preserved in some supradetachment basins (Diamond and Ingersoll, 2002; Stewart and Diamond, 1990), but Neogene cover prevents observation beyond the mountain front and coarse sediment is present everywhere we see Lower Cretaceous strata. The only prominent distinction between the two Hohhot supradetachment basins described in this study is that the northern basin is thinner and has experienced more deformation as a result of the uplift of the metamorphic core of the Hohhot core complex.

In contrast to these characteristics, other workers have documented syn-extensional basins that form above detachment faults but do not conform to the Friedmann and Burbank (1995) end-member. For example, Fedo and Miller (1992) studied the Crestview Wash basin, located above the Sacramento Mountain detachment fault in the Colorado River extensional corridor, wherein they describe a basin that resembled a half-graben above a low-angle normal fault. The Crestview Wash basin has three facies associations indicating (1) small, high-gradient, mass movement dominated alluvial fans; (2) lake and lake margin; and (3) large, low-gradient, streamflow dominated alluvial fans (Fedo and Miller, 1992). This basin is dissected by a series of normal faults
that are consistent with detachment movement, but no angular unconformities or growth strata were observed. Structural reconstruction accomplished with the aid of younger sedimentary deposits and dated volcanic rocks, and the lack of growth strata lead Fedo and Miller (1992) to interpret the Crestview Wash basin fill as deposited during a period of tectonic quiescence after an initial extensional event.

Although the basin is located above a regional detachment, is thin, and contains coarse sediment from mass-wasting and alluvial fan processes. It has relatively little distally located, coarse sediment, contains a significant lacustrine component, and is lacking in angular unconformities. The structural setting, with respect to the domed lower plate, of the Crestview Wash basin is similar to the northern basin in the Daqing Shan, but these basins clearly do not share similar tectonic histories. The Crestview Wash basin may have formed with the onset of extension at the detachment breakaway, but was not involved in the uplift and exhumation of the Chemehuevi-southern Sacramento metamorphic core complex. The basin was also not continuous with the basins that formed on the eastern flank of the Chemehuevi-Sacramento ranges.

The Chemehuevi-Sacramento detachment basin was cited by Miller and John (1999) as a good example of a Friedmann and Burbank-style supradetachment basins. The Chemehuevi-Sacramento detachment basin is dominated by coarse deposits formed by sediment-gravity and streamflow processes on alluvial fans, with minor fine-grained playa and shallow-lake deposits (Miller and John, 1999). The basin is also thin (2-3 km), located above a gently dipping normal fault, and has had a tectonic history similar to the Hohhot basins. These basins thus fit the Friedmann and Burbank model well.
Janecke et al. (1999) describe the Muddy Creek basin of south-west Montana as a basin formed above a low-angle normal fault that contrasts with the end-member supradetachment basin model. This basin is bounded by three en echelon, left-stepping normal faults with dips ranging from 8°-60° that flatten at depth. The basin contains centrally deposited lacustrine shale, mudstone, and sandstone and is bordered by a fringe (<1.5 km) of coarse alluvial fan and fan delta conglomerate and sandstone, proximal to the basin bounding faults (Janecke et al., 1999). Angular unconformities are only observed in the syn-tectonic fill and rock-avalanche material is present but rare. Extension magnitude is low (1.8-2.9 km) as is rate of extension (0.2-0.35 km Myr⁻¹) (Janecke et al., 1999).

The Muddy Creek basin does not conform to the end-member supradetachment basin for several reasons. The basin formed above a series of normal faults that have inconsistent dips ranging from 8°-60° and are not corrugated on the scale of other detachment faults. Also, extension rate and magnitude on these faults is extremely low in comparison to other regions where supradetachment basins form. Basin sediments include a significant fine-grained interval and lack significant amounts of distally deposited coarse conglomerate, rock-avalanche deposits, or angular unconformities. Sediment accumulation was relatively long-lived (47.1 to < 35 Ma) in comparison to other supradetachment basins. Collectively, the data indicate that the Muddy Creek basin is not a supradetachment basin (as described by Friedmann and Burbank, 1995), but more closely resembles a typical half graben that, in places, is bounded by low-angle normal faults.
An earlier model for supradetachment basin sedimentation based on the Pickhandle basin of the western United States (Fillmore et al., 1994) contrasts with the more Friedmann and Burbank-like model K1c interval of the Hohhot basins. Fillmore et al. (1994) described the Pickhandle basin as forming early in the evolution of a regional detachment, prior to uplift of the central Mojave metamorphic core complex. The Pickhandle basin is characterized by deposition of epiclastic volcanic rocks, pyroclastic rocks, and coarse sediment by alluvial fan and rock-avalanche processes. Paleocurrent indicators in the Pickhandle imply a complex drainage pattern providing evidence for transverse sediment transport, a hanging wall-derived sediment source, and an axial drainage system. Comparison with the Hohhot basins reveals that the Pickhandle basin shares characteristics with the K1a and K1b units in the lower part of the section. Both basins are dominated by coarse clastic sediments that were deposited with variable drainage patterns by alluvial fan and rock-avalanche processes into asymmetrical half-graben. These similarities follow from the structural setting shared by the K1a, K1b, and Pickhandle basins, all of which formed early in movement of the detachment and record local break-up of the upper plate. Thus the Fillmore et al. (1994) supradetachment basins and the Friedmann and Burbank (1995) supradetachment basins may be more appropriately considered evolutionary steps in the same model. Specifically, Fillmore et al. (1994) style basins may form with early extension on a detachment, as is observed with K1a and K1b strata in the Hohhot basins. However, with the large-magnitude extension (generally expected on detachment faults), supradetachment basins evolve
quickly into larger Friedmann and Burbank (1995) style basins, as is observed in K1c strata of the Hohhot basins.

The Hohhot basins as well as many basins in the western United States all display Friedmann and Burbank (1995) supradetachment basin type characteristics (Diamond and Ingersoll, 2002; Miller and John, 1999), further justifying the applicability of such an end-member model to continental extensional basin study. Other examples of basins that do not seem to work with the established model can be explained by structural variability that contributes to lower rates of extension and higher angle fault geometry. Assignment of strict models for basins associated with detachment faulting is difficult due to structural variation in different settings, yet a type basin model is useful as a guide. Further examination of these types of basins in different settings will help understanding of specific controls on supradetachment basin geometry, and the probable range of variation in sedimentary style that accompanies structural variability.

Conclusions

- The supradetachment basins near Hohhot are thin basins formed above multiple splays of the low-angle Hohhot detachment fault. Sedimentation in these basins was dominated by mass-movement and alluvial fan processes that transported coarse, predominantly footwall-derived conglomerate transversely away from the detachment. No fine-grained lacustrine sediments are preserved in these basins.
• The basin on the northern flank of the Daqing Shan antiform is thinner, was shorter-lived, and is more highly faulted than the basin on the southern flank of the Hohhot metamorphic core complex.

• These basins are syn-extensional sedimentary deposits associated with the formation of the Hohhot metamorphic core complex. The northern and southern basins were originally contiguous with the onset of extension, but were bisected as extension unroofed the lower plate and triggered isostatic uplift and exhumation of the metamorphic core of the core complex. Folding of the Hohhot detachment fault caused the Daqing Shan antiform and resulted in propagation of new detachment splays on the southern flank of the metamorphic core complex that allowed further extension and created accommodation space for Lower Cretaceous basins there.

• The basins associated with the Hohhot metamorphic core complex strongly reflect the supradetachment basin model presented by Friedmann and Burbank (1995) in the K1c interval, which is the bulk of the basin volumetrically. However, the earlier basin history, recorded by K1a and K1b is similar to the early-breakup supradetachment basin model proposed by Fillmore et al. (1994). These results suggest that the Friedmann and Burbank (1995) model is applicable for systems, or for stages during the evolution of a system, where low-angle normal faults rapidly accommodate large amounts of extension.
CHAPTER III
LATERAL VARIATION IN SUPRADERACHMENT BASIN STYLE,
DAQING SHAN, INNER MONGOLIA, CHINA

Introduction

Supradetachment basins have been the focus of many recent studies concerning continental extensional basins (Beratan, 1991; Beratan and Nielson, 1996; Dickinson, 1991; Dorsey and Becker, 1995; Dorsey and Roberts, 1996; Fedo and Miller, 1992; Fillmore and Walker, 1996; Fillmore et al., 1994; Forshee and Yin, 1995; Friedmann and Burbank, 1995; Friedmann et al., 1996; Janecke et al., 1999, in press; Miller and John, 1988, 1999; Nielson and Beratan, 1995; Yarnold, 1994). The goals of these studies have been many, including constraining timing relationships between basins and basin-bounding structures, determining the structural setting from characteristics of basin sediments, and simply establishing a definition for a supradetachment basin. Though examples of supradetachment basins have been described an inadequate understanding of specific controls on basin geometry remains (Janecke et al., 1999).

A series of newly documented Lower Cretaceous extensional basins associated with the Early Cretaceous Hohhot detachment and its splays in the Daqing Shan of Inner Mongolia, China, presents an opportunity to identify geometric differences of sedimentary basins located in variable positions within detachment settings. The well-documented structural geology and evolution of the Hohhot detachment and Hohhot metamorphic core complex (Davis et al., 2002), as well as preservation of well-exposed
basins in several distinct structural settings for more than 120 km along strike, and on both flanks of the metamorphic core complex make the Hohhot extensional system an excellent natural laboratory for studying the sedimentary geology of such systems. Comparing and contrasting the depositional facies, detrital provenance and paleodrainage patterns in these basins will help to gain a greater understanding of specific controls on basin formation associated with detachment-style faulting.

Previous research concerning supradetachment basins provides conceptual models for supradetachment basins (Fillmore and Walker, 1994; Friedmann and Burbank, 1995). However, the general applicability of these models has been disputed (Janecke et al., 1999), largely due to variability of sedimentary styles in various structural settings. This research was undertaken to document a newly discovered series of basins above low-angle normal faults, as well as to provide a case study for comparison with previously studied supradetachment basins and related conceptual models. The preservation of the Daqing Shan basins in a variety of structural settings allow us to examine changes in basin geometry in response to variability of the controlling structures.

Geologic Setting

Daqing Shan Geologic History

The geology of the Daqing Shan has recently been the subject of extensive study (Darby et al., 2001; Ritts et al., 2001; Davis et al., 2002). The Daqing Shan, which borders the northern edge of the Ordos basin, compose a segment of the east-west trending Yinshan belt, an intracontinental mountain belt that spans from northeast of
Paleozoic as a result of the complex amalgamation of northern China. The current understanding of the history of the Daqing Shan is divided into 6 stages (Darby et al., 2001; Ritts et al., 2001): 1) A poorly understood period of broad-wavelength folding in the Middle Paleozoic; 2) Post-Permian through pre-Early Jurassic contractile deformation characterized by north-vergent basement-involved thrusts; 3) Early Jurassic extensional normal faulting and half-graben basin development; 4) Late Jurassic contractile faulting with north-vergent basement involved thrusts, folding, and inversion of Lower Jurassic half-graben; 5) Early Cretaceous detachment faulting and metamorphic core complex formation; 6) Neogene normal faulting. The high strain extension following Late Jurassic contraction is seen throughout northern China and Mongolia (Davis et al., 2001; Webb et al., 1999), and is responsible for the detachment faulting and the formation of the metamorphic core complex and associated supradetachment basins of interest to this study.

**The Hohhot Detachment and Hohhot Metamorphic Core Complex**

The Hohhot detachment fault is a south-dipping, low-angle (15-30°) normal fault that is exposed along strike for > 120 km (Fig. 1 and 18). A minimum of 40 km of extension occurred along the Hohhot detachment, accommodating rapid crustal extension that followed Late Jurassic through Earliest Cretaceous contraction (Davis et al., 2002). Siliceous volcanic rocks exposed to the west-northwest of Hohhot, located in the upper
Fig. 18: Photographs of Hohhot detachment fault.
plate have yielded Early Cretaceous $^{40}$Ar/$^{39}$Ar ages (127.2 ± 1.0 Ma, whole rock isochron; 125.5 ± 0.7 Ma, single-crystal sanidine weighted mean) (Davis et al., 2002).

Also, syn-sedimentary volcanic rocks above the Hohhot master detachment fault yield Early Cretaceous $^{40}$Ar/$^{39}$Ar ages (125.2 ± 0.7 Ma, 125.7 ± 0.6 Ma, and 125.8 ± 0.6 Ma (sanidine single-crystal weighted means) (Davis et al., 2002). Footwall biotite and hornblende cooling ages determined using $^{40}$Ar/$^{39}$Ar methods show coincident Early Cretaceous ages (121.4 ± 0.9 Ma and 121.5 ± 1.3 Ma, respectively) (Davis et al., 2002).

The age relationships reported here show that deposition of Lower Cretaceous syn-extensional strata began ca. 125 Ma and that extension on the Hohhot detachment fault began prior to rapid cooling of the footwall at ca. 121 Ma (Davis et al., 2002).

Large magnitude extension on the Hohhot detachment fault most likely occurred due to gravitational collapse of over-thickened crust (Darby et al., 2001; Davis et al., 1998, 2001, 2002). Dramatic extension resulted in an isostatic response in the footwall of the detachment that exhumed the Daqing Shan antiform, an east-west trending culmination of metamorphic and other crystalline rocks (Fig. 1 and 2). The master Hohhot detachment fault is located on the southern flank of this antiform. Along this flank, the detachment is corrugated with synforms that preserve numerous syn-extensional non-marine clastic basins. North of the antiform, two detachment faults are stacked and synformally folded, with top-to-the-south slip on both fault splays (Fig. 1 and 2). These faults were active early in the evolution of the detachment. The lower detachment separates mylonitic rocks from non-mylonitic, primarily Proterozoic crystalline rocks and Permian granitic gneisses (Davis et al., 2002). The upper
detachment carries a highly deformed succession of Cretaceous volcanic and sedimentary rocks. The lower, oldest detachment was the original detachment, but with extension, the footwall was progressively unloaded triggering an isostatic up-warp in the lower plate. The resultant antiformally folded detachment was deactivated and a new detachment splay propagated to the surface to accommodate further extension. The new splay, in turn, was also antiformally folded due to continued uplift with further unloading. The Hohhot detachment, on the southern flank of the Daqing Shan antiform, is the youngest fault splay and accommodated the remaining extension (Davis et al., 2002).

These processes of extensional exhumation resulted in the formation of the Hohhot metamorphic core complex, one of the most important structural features of the eastern Daqing Shan (Davis et al., 2002). The Hohhot metamorphic core complex is located north and northeast of Hohhot and consists of the Daqing Shan antiform, the Hohhot detachment, and an upper plate of pre-Cretaceous crystalline and sedimentary rocks and Lower Cretaceous syn-extensional strata (Fig. 1 and 2). The footwall of the detachment contains a mylonitic fabric within the limits of the metamorphic core complex. The mylonitic front exposed in the Daqing Shan (Fig. 1) represents a thermally controlled strain boundary below which quartz has undergone penetrative crystal-plastic deformation (Davis and Lister, 1988; Davis et al., 2002).

The Hohhot detachment extends to the east and west of the Hohhot metamorphic core complex, where the magnitude of extension is lower. East of the Hohhot metamorphic core complex, the detachment separates Lower Cretaceous clastic sedimentary rocks and upper plate crystalline rocks from non-mylonitic footwall rocks.
West of the Hohhot metamorphic core complex, the crystalline hanging wall is preserved, though it is cut by several normal faults responsible for doming of the detachment fault to a lesser degree than what is documented within the metamorphic core complex.

Hohhot Supradetachment Basins

Lower Cretaceous sedimentary basins are found discontinuously along the length of the Hohhot detachment for its 120 km length along strike. These basins occur on both the southern and northern sides of the Daqing Shan, and in the central part of the detachment, north of Hohhot (Fig. 1). This study describes all of the Lower Cretaceous basins of the Daqing Shan for the purpose of comparison in order to establish how basin geometry is affected by variability in the controlling structures.

Lower Cretaceous sedimentary basins above the detachment are interpreted to be syn-extensional for several reasons. First, Lower Cretaceous rocks are separated from older rocks by the Hohhot detachment or related normal faults, and occur only in the upper plate. Second, these rocks are cut by low and high angle normal faults as a result of southeast-directed extension, consistent with movement on the detachment. Third, volcanic rocks in the base of the Lower Cretaceous section have been dated at 125.2 ± 0.7 Ma, 125.7 ± 0.6 Ma, and 125.8 ± 0.6 Ma (sanidine single-crystal weighted mean $^{40}$Ar/$^{39}$Ar age), coincident with the age of faulting determined by cooling ages and cross-cutting relationships in the footwall of the detachment (Davis et al., 2002). Fourth, these rocks consist predominantly of coarse conglomerate derived from sources that include footwall mylonite and other metamorphic rocks common in the lower plate of the
detachment. Fifth, intraformational unconformities are present indicating rotation of strata due to continued upper-plate faulting after deposition.

Basins are located in several structurally distinct settings in the Daqing Shan, and now occur as unconnected basins. The basins are labeled N1, N2, S1, S2, S3, and S4 in this paper simply to facilitate discussion (Fig. 19). Basins N1 and N2 are located on the northern flank of the Daqing Shan, whereas basins S1, S2, S3, and S4 are located along the southern range front. Basins N2, S2, and S3 are located within the central part of the detachment system and adjacent to the Hohhot metamorphic core complex. Basins S2 and S3 are located in corrugations of the master Hohhot detachment and Basin N2 is located in the synformal keel, above the stacked and synformally folded detachment splays. Basin S4 is preserved in a corrugation of the master Hohhot detachment east of Basin S3 and outside the boundary of the Hohhot metamorphic core complex. The mylonitic front is mapped northwest of this basin where extension magnitude is greater within the bounds of the metamorphic core complex. Basin N1 is also located above the master Hohhot detachment, west of basin S2. The detachment fault sweeps to the northwest beyond basin S2 and the magnitude of extension is again less than that of the metamorphic core complex. Finally, basin S1 is located within the hanging wall of the master Hohhot detachment. This intra-hanging wall basin is bounded by a less extensive, low angle normal fault, which soles into the master detachment at depth.

The Hohhot basins comprise a dominantly clastic sedimentary section that is more than 1200 m thick (Fig. 3). We informally divide the basins into three lithostratigraphic members, K1a, K1b, and K1c from bottom to top. These units are recognized in most of
Fig. 19: Location of Lower Cretaceous basins.
Table 2: DISTRIBUTION OF SEDIMENTARY MEMBERS IN LOWER CRETAUCEOUS BASINS

<table>
<thead>
<tr>
<th>Member</th>
<th>Thickness</th>
<th>Lithofacies</th>
<th>Sedimentologic Interpretation</th>
</tr>
</thead>
</table>
| Kla    | 75 m      | • Red, unorganized, matrix-supported conglomerate  
• Interbedded bimodal volcanic rocks | • Debris flow deposits and volcanic flows in an alluvial fan setting |
| Klb    | 125 m     | • Red, unorganized, matrix-supported conglomerate  
• Contains lesser well-organized, clast supported conglomerate  
• Volcaniclastic detritus  
• Contains monolithologic blocks and breccias | • Dominantly debris flow deposits in an alluvial fan setting  
• Lesser subaqueous streamflow and sheetflood deposits  
• Gravity-driven slide blocks |
| Klc    | 200-400 m | • Well-organized, clast-supported conglomerate  
• Contains monolithologic blocks and breccias | • Subaqueous streamflow and sheetflood deposits in an alluvial fan setting  
• Gravity-driven slide blocks |

the Lower Cretaceous basins, although thickness and internal stratigraphy varies considerably throughout the study area (Table 2). Kla and Klb are composed dominantly of unorganized, red, matrix-supported conglomerate. Kla is distinguished by the presence of interbedded bimodal volcanic rocks, while Klb contains minor clast-supported lenticular conglomerate, lacks volcanic flows, and contains monolithologic blocks and megabreccia units (Fig. 7), and are most commonly composed of Proterozoic marble. Klc consists of well-organized, clast-supported conglomerate, and displays tabular to lenticular beds that can be traced laterally in the basin.
Basin N2

Basin N2 is located on the northern flank of the Daqing Shan antiform, east and slightly south of Wuchuan city (Fig. 19). Structurally, it occupies the synformal keel of the Hohhot metamorphic core complex, and lies above the second detachment splay and below the third detachment splay (Fig. 1 and 2) (Davis et al., 2002).

Sedimentology and Stratigraphy. Sedimentary strata are Early Cretaceous in age, defined by $^{40}\text{Ar}^{39}\text{Ar}$ ages on interbedded rhyolite flows (Davis et al., 2002). The sediments rest directly on the upper detachment splay, and this relationship can be seen in numerous locations around the basin. Pervasive normal faulting in this basin inhibits measurement of a complete section (Fig. 10); a maximum of only about 200 m of continuous section can be measured without crossing significant normal faults. However, a composite section has been constructed by correlating like-parts of repetitive lithostratigraphic sequences, and suggests a minimum basin thickness of 400 m (Fig. 20). Basin N2 contains three informally divided lithostratigraphic members, K1a, K1b, and K1c from bottom to top. The lowest two units, K1a and K1b, are difficult to separate in this basin and are generally considered one unit that is easily distinguished from the overlying unit, K1c.

K1a-b is composed dominantly of unorganized, red, matrix-supported conglomerate that has a minimum thickness of 175 m (Fig. 4, 6, and 20). Beds are 1 m to 2 m thick and have erosive bases particularly in the less common, more clast-supported portions of the sequence. Maximum clast size increases upwards within beds. Large monolithologic blocks and megabreccia units, most commonly composed of Proterozoic
Fig. 20: Basin N2 composite section.
marble, are contained in Klb. The marble can be fairly intact, but is usually intensely fractured and brecciated and may be injected with the silty, red matrix common in Klb (Fig. 6).

Kla-b is interpreted as dominantly debris flow deposits based on the matrix-supported, disorganized nature of the conglomerate beds, with lesser streamflow and sheetflood deposits marked by the well-organized, clast-supported, lenticular to tabular, and better organized conglomerates. The combination of minor waterlain deposits and debris flow deposits is interpreted to represent a proximal alluvial fan environment (Blair and McPherson, 1994). The monolithic blocks and megabreccia units are interpreted as gravity-driven slide blocks and rock-avalanche deposits because they are completely encased in Lower Cretaceous strata and exhibit characteristics of being emplaced as coherent to semi-coherent units (Friedmann, 1997). The contact with the overlying unit, Klc, is generally gradational and appears as an increasing amount of clast-support and sand content that replaces the fine, red matrix seen in Kla/b.

Klc is the uppermost unit dominantly consisting of well-organized, clast-supported conglomerate (Fig. 8). Beds are tabular to lenticular with erosive bases, 1 m to 2 m thick, and interbedded with coarse sandstone and rare mudstone ranging in thickness from 10 cm to 80 cm. Individual beds are organized into relatively tabular units on the order of a few meters to 10 m thick and that extend for at least hundreds of meters laterally. Packages of trough cross-stratified conglomerate fining upward to medium trough cross-stratified sandstone are preserved at the 20 cm to 80 cm scale, but are not as common as the dominant imbricated conglomerate and conglomerate displaying low-
angle cross-stratification. Imbrication is abundant, as is trough cross-stratification and planar lamination in the sandstone. Large monolithologic, brecciated, gravity-driven slide blocks are common in K1c, and reach >2 km (long axis) in size, and are typically composed of Proterozoic marble (Fig. 9). The minimum thickness of this unit is ~200 m, determined by the largest length of continuous section in this transect (Fig. 3 and 20).

These conglomerates are interpreted as subaqueous channelized and sheetflood deposits based on their clast-supported, well-organized character. These deposits are interpreted to have formed in an alluvial fan system, based on the uniformly coarse conglomeratic nature of K1c, dominance of streamflow and sheetflood processes, and association with gravity-driven slide blocks and rock-avalanche deposits (Blair and McPherson, 1994; Friedmann, 1997).

Normal faults that cut the strata are roughly east-west striking consistent with extensional slip on the detachment splay. Angular unconformities in this basin indicate syn-depositional rotation of Lower Cretaceous strata (Fig. 11).

*Paleocurrent and Provenance Data.* Paleocurrent data were collected around the basin (Fig. 14, 21). The average paleocurrent direction for K1a-b is 155°. The paucity of imbricated clasts within K1a-b makes paleocurrent measurement within theses units difficult. Well-imbricated conglomerate is abundant in K1c, and yields south-directed paleocurrents that average 187°. K1c paleocurrents show little variability in this basin. Stratigraphically, some variation in paleocurrent direction is seen, but paleocurrents are always confined to southern hemisphere (Fig. 20).
Fig. 21: Aerial distribution of paleocurrent data.
Areally distributed clast count data demonstrate the dominance of clast derived from the footwall of the detachment throughout the basin (Fig. 15, 22). Granitoid plutonic clasts are dominant, with foliated plutonic, conglomerate, and sandstone clasts distributed uniformly. Marble and volcanic clasts are locally important, with volcanic clasts, usually rhyolite and rare basalt, concentrated on the western side of the basin (where volcanic rocks of K1a are still preserved).

Clast composition vertically through the section varies little, although minor components show some important trends (Fig. 20). First, gneiss clasts are common in K1c, but not present in K1a-b. Second, sandstone clasts, some of which may be recycled Lower Cretaceous clasts, decrease in abundance up section. Finally, it should be noted that mylonite clasts, which are common in many of the other Lower Cretaceous basins are not present in this basin.

**Basin S3**

Basin S3 is located on the southern flank of the Daqing Shan antiform, just northeast of Hohhot, Inner Mongolia (Fig. 19). Lower Cretaceous strata overlie either the Hohhot detachment fault or an unconformity above older rocks (Fig. 5). Lower Cretaceous strata in this basin are cut, tilted, and/or folded by post-depositional normal faulting, and a large Neogene normal fault limits exposure of these rocks to within the Daqing Shan range front.

*Sedimentology and Stratigraphy.* Basin S3 contains a three-part stratigraphy as seen in surrounding basins. K1a, the lowest unit in the Lower Cretaceous section, is composed dominantly of unorganized, red, silty, matrix-supported conglomerate with
Fig. 22: Aerial distribution of clast count data.
interbedded bimodal volcanic rocks (Fig. 4). This unit is 75 m thick where the section was measured (Fig. 23). Beds are generally 1 m to several meters thick where defined.

K1a is interpreted as dominantly debris flow deposits with intermittent volcanic flows based on the matrix-supported, disorganized nature of the conglomerate beds. The dominance of debris flow deposits is interpreted to represent a proximal alluvial fan environment (Blair and McPherson, 1994).

Overlying this unit is K1b, composed dominantly of similar red, silty, matrix-supported conglomerate with beds 1 m to several meters thick (Fig. 6). This unit is distinguished from K1a by the lack of volcanic flows and the presence of minor clast-supported conglomerate, which appears as lenticular beds up to several meters thick (Fig. 6). The lenticular packages are generally not amalgamated, but are isolated within the matrix-supported conglomerate (Fig. 6). This unit also contains large (several meters to >10 m) monolithologic blocks and megabreccia units that are most commonly composed of Proterozoic marble (Fig. 7). The marble can be fairly intact, but is usually intensely fractured and brecciated and may be injected with the silty, red matrix common in K1b. K1b is ~125 m thick in this basin (Fig. 23).

K1b is interpreted as dominantly debris flow deposits based on the matrix-supported, disorganized nature of the conglomerate beds, with lesser streamflow and sheetflood deposits marked by the clast-supported lenticular to tabular, and better organized conglomerates. This combination of minor waterlain deposits and debris flow deposits is interpreted to represent a proximal alluvial fan environment (Blair and McPherson, 1994). Large blocks and megabreccia units are interpreted as slide blocks
Fig. 23 cont’d: Basin S3 composite section.
and rock-avalanche deposits, because they are completely encased in the K1b strata, and exhibit characteristics of being emplaced as coherent to semi-coherent units (Friedmann, 1997).

Although normal faults cut all of the units, K1a and K1b are more pervasively faulted and contain normal faults that cut only these units, and are consistent with south-southeast extension on the master detachment (Fig. 13).

The upper unit, K1c, is a well-organized, clast-supported conglomerate (Fig. 8). The unit is 900 m thick in this basin (Fig. 23). Beds are 1 m to several meters thick and are tabular to lenticular with erosive bases. Individual beds are organized into relatively tabular units on the order of a few meters to 10 m thick and that extend for at least hundreds of meters laterally. The conglomerate is interbedded with coarse sandstone beds that are decimeter to several meters thick and rare mudstone beds several cm to decimeters thick. Imbrication is abundant, as is cross-stratification and planer lamination in the sandstone. The section fines upward overall, but coarse conglomerate is seen even in the most distally exposed parts of the basin.

This unit has been interpreted as subaqueous channelized and sheetflood deposits based on the well-organized, clast-supported character. These deposits are interpreted to have formed in an alluvial fan system, based on the uniformly coarse conglomeratic nature of K1c and dominance of streamflow and sheetflood processes (Blair and McPherson, 1994).

Paleocurrent and Provenance Data. Paleocurrent data were collected aerially about the basin (fig. 14, 21). Average paleocurrent direction for combined K1a and K1b
is 214°. The paucity of imbricated clasts within K1a and K1b makes paleocurrent measurement for these units difficult. Well-imbricated conglomerate is abundant in K1c, and yields paleocurrents that average 187°. Stratigraphically, K1c paleocurrents show little variability, except in the upper 200 m of the section where sand content increases (Fig. 23).

Areally distributed clast count data clearly demonstrate the dominance of clasts derived from the footwall of the detachment (Fig. 15, 22). Granitoid plutonic clasts dominate, and foliated plutonic, conglomerate, and sandstone clasts are distributed uniformly. Volcanic clasts, usually rhyolite and rare basalt, are more concentrated on the western side of the basin (where volcanic rocks of K1a or older are still preserved). Stratigraphically, clast composition is fairly consistent with some exceptions (Fig. 23). First, gneiss clasts are common in K1c, but are not present in K1a or K1b (Fig. 15). Similarly, mylonite clasts are not observed in K1a or K1b, and are not seen in the lower part of K1c (Fig. 23). These mylonite clasts first appear at 850 m, and persist through the remaining stratigraphy. Finally, sandstone clasts, some of which may be recycled Lower Cretaceous clasts, decrease in abundance up section.

**Basin S4**

Basin S4 is the most easterly exposed Lower Cretaceous basin in the Daqing Shan (Fig. 19). It is located above the master Hohhot detachment fault, still a low-angle normal fault, but not within the main Hohhot metamorphic core complex. The eastern extent of the mylonitic front mapped in the Daqing Shan is located to the northwest of this basin in the lower plate (Fig. 3). Exposure in this area is limited by cover, which
prevents measurement of a complete section in this basin. Where measured, strata are tilted with beds dipping to the north, but the basin is cut by numerous normal faults. Exposure is limited to the range front. Maximum basin thickness is estimated at 2250 m from a cross-section using sparse stratal dips. The common occurrence of normal faults in the basin suggests that the actual basin thickness is thinner, probably similar to the thickness in Basin S3 ranging from 1200 m to 1500 m in thickness.

*Sedimentology and Stratigraphy.* Only lithostratigraphic member K1c is observed in this basin (Fig. 24). K1c is composed dominantly of well-organized, clast-supported conglomerate with tabular to lenticular beds with erosive-based bases (Fig. 8). Bedding thickness is 1 m to several meters thick. Individual beds are organized into relatively tabular units on the order of a few meters to 10 m thick. The conglomerate is interbedded with trough cross-stratified sandstone beds ranging from decimeters to meters in thickness and mud-to-siltstone beds that are several centimeters to decimeters thick. Imbrication is abundant, as is cross-stratification and planar lamination in the sandstone.

No monolithologic, brecciated, gravity-driven slide blocks were observed in this basin, though exposure is limited and slide blocks are less common in K1c than in K1b. The limited measured section at this locality is 333 m thick (Fig. 24).

The conglomerates are interpreted as subaqueous channelized and sheetflood deposits based on their well-organized, clast-supported character. These deposits are interpreted to have formed in an alluvial fan system, based on the uniformly coarse conglomeratic nature of K1c and dominance of streamflow and sheetflood deposits (Blair and McPherson, 1994).
Fig. 24: Basin S4 section.
Paleocurrent and Provenance Data. Paleocurrent data were collected areally around the basin (Fig. 21). Well-imbricated clasts within Klc are abundant and yield an average paleocurrent direction of 159°. Some variability is seen vertically in the section (Fig. 24). At ~100 m into the section, west directed paleocurrent indicators are seen, but this is a small subset of the data for this basin, and occurs in a part of the section with lots of fine mudstone that is not representative of the entire section.

Areally distributed clast count data clearly demonstrate the dominance of clasts derived from the footwall of the detachment (Fig. 22). Granitoid plutonic are dominant, with foliated plutonic, gneiss, marble, schist, and mylonite clasts. The clast count data are consistent through the section (Fig. 24). No obvious trends or changes are seen in the provenance data.

Basin N1

Basin N1 is located southwest of Wuchuan city (Fig. 19). This basin is located above a folded segment of the master Hohhot detachment fault, where the detachment abruptly cuts northward into the Daqing Shan (Fig. 1). Extension magnitude at this point in the detachment is less than within the metamorphic core complex proper.

Sedimentology and Stratigraphy. Basin N1 is again divided into three informal lithostratigraphic units, but these units differ from K1a, K1b, and K1c seen in the other Lower Cretaceous basin in the Daqing Shan. The total stratigraphy is 1140 m thick in this basin and can be divided into three lithostratigraphic units (Fig. 25). The first unit is 130 m thick and rests on the detachment fault. This unit consists of clast-supported and
Fig. 25: Basin N1 stratigraphic section.
clast composition remains the same to the top of the section
Fig. 25 cont’d: Basin N1 section.
lesser matrix-supported cobble to boulder conglomerate with boulders ranging in
diameter from 86 cm to 197 cm (Fig. 26). Beds are lenticular and erosive-based, ranging
from 80 cm to 2.5 m thick. The conglomerate is massive, but imbrication is common,
and large-scale trough cross-stratification is seen in some of the beds. The matrix is red
to maroon in color with very coarse sand and pebbles. Above the basal conglomerate,
numerous broad, trough cross-stratified sandstone beds are interbedded with pebble to
boulder, organized, clast-supported conglomerate. The sandstone beds display 20 cm to
30 cm upward fining packages from pebble to medium sand size. These deposits are
interpreted to be subaqueous channelized and sheetflood deposits based on clast-support,
lack of fine-grained material, imbrication and trough cross-stratification, and lenticular,
erosive nature of the bedding. These deposits are interpreted to have formed in an
alluvial fan system, based on the uniformly coarse conglomeratic nature and dominance
of streamflow and sheetflood deposits (Blair and McPherson, 1994).

The second unit is 170 m thick (Fig. 25). The unit dominantly consists of well-
imbricated, clast-supported cobbler to boulder conglomerate interbedded with trough-
cross-stratified sandstone (Fig. 27). The conglomerate beds are tabular to lenticular with
erosive bases and range from 1 m to 3 m in thickness. The sandstone beds are 10 cm to
20 cm thick, fining upward packages that contain occasional cobbles and boulders.
Maximum boulder diameter in this unit is 140 cm. Overall, this unit is finer than the
underlying unit.

This unit is interpreted as dominantly subaqueous channelized and sheetflood
deposits based on the presence of trough cross-stratified sandstone interbedded with
Fig. 26: Photographs of lowest unit in basin N1. This unit is clast-supported, pebble to boulder conglomerate. Large boulder in lower photo is basalt.
Fig. 27: Photographs of middle unit in basin N1. This unit is very coarse to pebble sand with pebble to boulder interbeds.
clast-supported conglomerate, and the lack of fine grain sediment. These deposits are interpreted to have formed in an alluvial fan system, based on the dominance of streamflow and sheetflood processes and the coarse nature of the deposits (Blair and McPherson, 1994). This unit and the lowest unit are consistent with units seen in the other Daqing Shan basins.

The third unit comprises the remaining stratigraphy in this basin (Fig. 25). The base of this unit is composed of poorly organized, yet predominantly clast-supported pebble-to-boulder conglomerate with a red, silty matrix (Fig. 28). The conglomerate, which consists of entirely of marble clasts, outcrops as 20 m to 40 m thick packages without well-defined bedding (Fig. 28). Clasts are generally angular and some of the boulders are fractured and injected with red matrix (Fig. 28). Higher in the section, the unit consists of boulder to cobble conglomerate with red, silty matrix, which remains clast-supported and poorly organized, but becomes locally well-imbricated and more organized in individual beds. Towards the top of the section, the matrix of the conglomerate was gradationally replaced with calcite-rich cement, resulting in resistant packages (Fig. 29). A high percentage of sand to pebble, marble derived clasts due to transport induced brecciation and cataclasis may contribute to the high calcite content in the matrix (Friedmann, 1997). Clast size in these conglomerate packages ranges from pebble to >2 m. Recrystalization of the matrix with calcite is common from this point upward in the stratigraphy, but red matrix is still present in the conglomerate when beds are traced laterally. Also at this point in the section, large monolithologic blocks contained in the conglomerate become common, some greater than >30 m in diameter.
Fig. 28: Photographs of upper unit in basin N1. Top photo is clast-supported, matrix-rich, angular, pebble to cobble conglomerate. Bottom photo shows thick package of this conglomerate.
Fig. 29: Top photo shows resistant pod of upper unit in basin N1. Lower photo is a closer shot of the pod (backpack is in same location on both photographs) showing the individual clasts within the bed.
These blocks are generally fractured and intensely brecciated. A monolithic block of marble that is 100-200 m thick caps the section.

This unit is interpreted as debris flow deposits, hyperconcentrated flow deposits, and rock-avalanche deposits with interbedded gravity-driven slide blocks. The debris flow interpretation is based on the presence of unorganized, matrix-rich conglomerate, some of which is well-imbricated, yet retains a significant amount of fine-grained matrix. The megabreccia units are interpreted as rock-avalanche deposits based on the coarse, angular, monolithologic clasts that are unorganized and both clast and matrix supported (Friedmann, 1997). Bedding is often difficult to see with in each package, but packages may represent individual flows or several amalgamated rock-avalanches. Large blocks are interpreted as gravity-driven slide blocks because they are completely contained within the Lower Cretaceous conglomerate and exhibit characteristics of being emplaced as coherent to semi-coherent units (Friedmann, 1997).

Paleocurrent and Provenance Data. Paleocurrent data were collected areally in this basin (Fig. 21). Well-imbricated clasts yield an average paleocurrent direction of 154°. Stratigraphically, paleocurrent data were difficult to obtain as well-imbricated conglomerate is rare due to the dominance of debris flow deposition (Fig. 25). Near the base of the section, southeastern paleocurrents are dominant with a significant east-directed component. At around 200 m, paleocurrents make a dramatic swing, becoming west directed. Between 410 m and 475 m, average paleocurrent direction from imbricated clasts is nearly south.
Fig. 31: Gravity-driven slide block near top of section in basin N1. Red lines mark top and bottom of block which is encased in red, Lower Cretaceous conglomerate.
Areally distributed clast-count data clearly demonstrate the dominance of clasts derived from the footwall of the detachment (Fig. 22). Granitoid plutonic clasts are dominant, with foliated plutonic, quartzite, and conglomerate representing minor percentages of the clast composition. Marble content decreases from west to east, and volcanic clasts (rhyolite and basalt ranging from pebbles to boulders) compose ~25% of the basin overall clast composition (Fig. 22). Stratigraphically, clast composition changes dramatically (Fig. 25). The base of the section contains high percentages (57%) of volcanic clasts, both rhyolite and large, well-rounded boulders (1 m to 2 m) of basalt. A large basalt flow is located near the base of the section and is the likely source of these boulders. Granitoid plutonic clasts are common and are accompanied by lesser quantities of marble, sandstone, quartzite, schist, and gneiss clasts. Up section, volcanic, gneiss, schist, and sandstone clasts are not seen, and granitoid plutonic clasts become dominant. The most dramatic change in clast composition occurs at a ~305 m where only marble, which is commonly silicified, is present within the conglomerate. Marble content remains constant through the remainder of the section.

Discussion

Tectonic Evolution of Lower Cretaceous Basins

The data from the supradetachment basins allow us to better understand the coupled structural and stratigraphic evolution of this extensional system. Comparison of controls emplaced by distinct basin settings highlights the more influential factors to supradetachment basin geometry.
The data from basin N2 and basin S3 allow us to establish a model for these basins that relates to the evolution of the Hohhot metamorphic core complex (Fig. 16). This model can be broadly subdivided into two phases, based on the contrasting depositional and deformational styles in K1a-b and K1c (Fig. 16). The bulk of the supradetachment basin fill consists of K1c, suggesting longer-lived basins later in the evolution of the system.

Units K1a and K1b were deposited by debris-flow and mass-wasting processes, with the onset of extension and concomitant creation of topographic relief and isolated basins. Volcanic flows were interbedded with these deposits as extension began, but ceased by the K1a-K1b boundary. Syn-depositional normal faulting consistent with extension direction deformed and dissected the basin. Further evidence of dissection consists of angular unconformities and abundant reworked volcaniclastic detritus in the sandstone and conglomerate (Fig. 11, 17). Intrabasinal breakup of these basins during K1a and K1b sedimentation, as well as the creation of intrabasinal graben (Fig. 13) resulted in variable paleocurrent directions, and local changes in stratigraphy and provenance (Fig. 14 and 15).

K1c is very consistent areally and stratigraphically, dominated by waterlain sheetflood and streamflow processes in an alluvial fan setting with additional rock-avalanche deposits and gravity-driven slide blocks. Paleocurrent indicators are uniformly south-directed in both basins indicating transverse transport of sediment away from the detachment breakaway. Gneiss clasts are common in K1c, but do not appear in K1a or K1b.
Data from the Lower Cretaceous sedimentary rocks suggests that the basins on both flanks of the Daqing Shan antiform were previously contiguous during deposition of K1a, K1b and the lower portion of K1c (Fig. 16). Both basins exhibit K1a-K1b strata of similar thickness that were deposited by debris flow and rock-avalanche processes. Units K1a and K1b are overlain by K1c sediment that was deposited by waterlain sheetflood and streamflow deposits in an alluvial fan setting. Mean transport direction in K1c summed for both basins is 187°, despite the presence of the current topographically-high metamorphic core complex that would have inhibited south-directed flow. Clast types in K1a, K1b, and the lower part of K1c are also similar. Granitoid plutonic clasts dominate and clasts of reworked Lower Cretaceous conglomerate and sandstone clasts are present. Also, gneiss clasts do not appear in either basin until K1c is deposited. Volcanic rocks are present along the west side of the basins and $^{40}\text{Ar}/^{39}\text{Ar}$ dates in basin N2 coincide with the age of movement on the master Hohhot detachment underlying basin S3 (Davis et al., 2002).

The appearance of higher-grade gneiss and mylonitic clasts high in the section suggests progressive unroofing of deeper crustal material as extension and uplift of the lower plate continued. The absence of such clasts in the northern basin implies that the northern basin had stopped receiving sediment by the time those clast types were exposed in the source terrane. The apparent shorter-lived deposition on the northern flank, supported by the much thinner K1c deposit in basin N2, is interpreted to record the uplift of the Daqing Shan antiform during unroofing of the metamorphic core complex. Uplift of the metamorphic core resulted in, not only deactivation of the folded northern splay...
of the Hohhot detachment, but also resulted in cessation of sedimentation in basin N2. Following uplift of the Daqing Shan antiform, extension was accommodated by propagation of a new detachment splay on the southern flank of the Daqing Shan antiform (Davis et al., 2002) that, created additional accommodation space in basin S3, and resulted in the thicker K1c deposit.

Basin S2 exhibits many similarities to basin S3. The basin consists of predominantly coarse conglomerate deposited by subaqueous channelized and sheetflood deposits in an alluvial fan setting. Paleocurrents are south-directed, indicating transport of sediment transversely away from the detachment fault (Fig. 21). Clast composition in basin S2 is similar to basin S3, but marble is much more common (Fig. 22). Sediment sources elsewhere in the Daqing Shan tend to be very localized, but the numerous brecciated, slide blocks composed of Paleozoic marble present in the strata may influence high marble content in this basin. We cannot determine if basin S2 and basin S3 were connected during their evolution, but were most likely deposited in separate corrugations of the detachment fault. The basins may be connected at some distance beyond where Lower Cretaceous rocks are exposed at the surface. If more distal exposure of these basins was available, the Daqing Shan basins may be found similar to the Esmarelda basin of Nevada, where sediments above the bounding detachment fault are deposited into a very broad, shallow lake, distal from the detachment breakaway (Diamond and Ingersoll, 2002; Stewart and Diamond, 1990).

The early history of basin S4 is not discernible because the only exposed unit is K1c. This unit is identical to the K1c seen in other basins. Paleocurrent directions are
south-directed indicating transverse transport of sediment away from the detachment. Clast composition in basin S4 is similar to other Lower Cretaceous basins, but mylonite content is much higher in this basin indicating a western source terrane where the mylonitic front of the metamorphic core complex is exposed. It should be noted that sedimentary processes and provenance in this basin are very similar to that in the basins further west, though the magnitude of extension is less.

Extension at this point in the detachment was not as great as in the basins directly adjacent to the Hohhot metamorphic core complex, but the resulting basin geometry is identical to the other K1c supradetachment basins described. The basin is bounded by a low-angle, corrugated normal fault that accommodated significant, rapid extension. With this extension, the lower plate was unloaded, triggering an isostatic response in the footwall. Uplift of these rocks minimized proximal accommodation space, promoting distal deposition of coarse sediment in an alluvial fan setting.

Basin S1 formed above a major low-angle fault, but this normal fault system is within the hanging wall of the Hohhot detachment fault. Coarse conglomerate was shed into the basin by alluvial fans that prograded into a shallow lacustrine environment. Paleocurrent indicators west of the lacustrine interval show southeast-directed flow into the lake. East of the lacustrine interval, paleocurrent directions are southwest directed again suggesting progradation into the lake.

Basin N1 differs from the other Lower Cretaceous basins in the Daqing Shan. Basin N1 does not contain the same lithologic members, K1a, K1b, and K1c, described in the other basins, and sedimentation in this basin is dominated by debris flow and rock-
avalanche deposition throughout the section. The upper portion of the section contains numerous monolithologic, brecciated, gravity-driven slide blocks that are hundreds of meters in diameter. Paleocurrent directions average near south, but significant east-west flow indicators are seen low in the section. Clast composition low in the stratigraphy is similar to that in other basins in this study, though they are high in volcanic clast content. Higher, the clast composition is nearly 100% marble, which persists through the top of the section.

Although Basin N1 displays some differences in sedimentary style when compared to the other Daqing Shan basins, it probably shares a similar history. The basin is thin (<1200 m), located above a low-angle normal fault, and dominated by debris flow and rock-avalanche deposits that were transported transversely away from the detachment. From these data, we cannot infer a similar period of hanging wall break up as seen in the other supradetachment basins, but the section studied strongly resembles a supradetachment basin based on the afore mentioned sedimentary characteristics.

The large presence of rock-avalanche and megabreccia deposits in basin N1 may be due to the characteristics of the source area. Generally, rock-avalanche source regions have three main requirements: slopes in excess of 25°, vertical falls in excess of 150 m, and a highly fractured source terrane (Friedmann, 1997; Keefer, 1984). Though the basin-bounding fault is low-angle, it may have exceeded 25° during the evolution of the basin, and high topography is common in regions that have experienced isostatic uplift of the lower plate with dramatic extension. Also, detachment faults commonly have breccia layers that form due to shear stress along the fault surface during tectonic transport.
As the footwall was elevated and exposed to surficial processes, the brecciated layer would have provided excellent source of fractured material to the basin. Any one, or combination, of these processes may have been responsible for the intense amount of rock-avalanche and megabreccia material in this basin.

Many studies have proposed that corrugated geometry of detachment faults is primary (Davis and Lister, 1988; John, 1987; Spencer and Reynolds, 1991). The paleocurrent data from the Hohhot basins neither supports nor refutes this statement, but the isolation of these basins from other Lower Cretaceous basins in the Daqing Shan and the differences in provenance characteristics implies that corrugations are primary. These corrugations would have been a strong geomorphologic control on Cretaceous drainage patterns, and which are still the major through-going drainages present in the Daqing Shan.

Supradetachment Basin Systems

The most widely cited and applied model for sedimentation in supradetachment basins is that of Friedmann and Burbank (1995), which classify supradetachment basins as an end-member basin style in extensional continental settings opposite the better-known half-graben rift basin of Leeder and Gawthorpe (1987) (Table 1). Friedmann and Burbank (1995) describe supradetachment basins as those that form “above a low-angle normal fault system.” More specifically, “the term also represents the end-member model presented [in Friedmann and Burbank, 1995].” These basins are thin, short-lived and are dominated by coarse, predominantly footwall-derived sediments delivered to the
basin by transverse drainages and often deposited by mass-wasting processes (Table 1). These basins generally are expected to lack either significant fine-grained, lacustrine deposits, or axial drainage systems, which are commonly found in half-graben basins (Leeder and Gawthorpe, 1987). Also, supradetachment basins tend to occur in back-arc regions where the crust has recently experienced dramatic thickening in rock that may be warmer and have had considerable radiogenic heat flow (Friedmann and Burbank, 1995). Most rifts occur in areas with cold normal crust lacking recent contractile tectonism (Friedmann and Burbank, 1995).

The Lower Cretaceous basins in the Daqing Shan all represent supradetachment basins though they are located in structurally distinct sub-settings. Our study basins may have formed within a variety of these settings and allow us to further understand how location within the detachment-metamorphic core complex system controls supradetachment basin geometry.

Basin S2, basin S3, and basin S4 were all formed in similar settings: they are in the upper plate of a metamorphic core complex that evolved during basin formation. The basins all display units from the Lower Cretaceous stratigraphy, best described in basin S3 (Fig. 25). Sediment in these basins was deposited directly above the Hohhot detachment, which rapidly accommodated high magnitudes of extension. The basin fill is thin and dominated by coarse conglomerate shed from the footwall by mass-wasting, sheetflood, and streamflow processes in an alluvial fan setting. Although exposure of Cretaceous rock is limited to within 5-6 km of the master detachment fault, coarse sediment is present everywhere in these basins, suggesting distal deposition of this
material. Rapid rates of footwall uplift relative to basin subsidence would exclude proximal accommodation space, promoting distal deposition of sediment. Basin S2, and basin S3 are located within the boundary of the Hohhot metamorphic core complex, an excellent indicator of the large amount of extension accommodated by the Hohhot detachment. Basin S4 is located east of the mylonitic front, which marks the edge of the metamorphic core complex. Though the amount of extension was less at this point in the detachment, the rates were probably comparable, and the detachment bounding this basin is low-angle and corrugated. These factors suggest a similar mechanism for proximal exclusion of sediment in this basin, and signify the importance of extension rate and fault geometry to supradetachment basin formation. Several studies have documented supradetachment basins of this type without the presence of an exposed mylonitic metamorphic core (Friedmann and Burbank, 1995; Diamond and Ingersoll, 2002; Miller and John, 1988, 1999; Stewart and Diamond, 1990).

Basin N2 is preserved in an interesting structural setting not generally observed in other metamorphic core complexes. Doming of the metamorphic core complex kinematically deactivated the detachment on this flank of the metamorphic core complex leading to the cessation of syn-extensional sedimentation. The geometry and depositional style of this basin clearly establish that this is a supradetachment basin, demonstrating that supradetachment basin geometry may form early during basin formation and does not require an exhumed metamorphic core complex or mid-crustal dome.

Basins located in the structural setting of basin N2 may have existed in other highly-extended regions of the world, but may not have been preserved, or are covered by
later sedimentation. In the Central Mojave metamorphic core complex, syn-extensional strata of the Pickhandle Formation are mapped overlying mylonitized footwall rocks of the metamorphic core (Fillmore et al., 1994; Fillmore and Walker, 1996). The sedimentary rocks of this formation are suggested to have formed in a basin adjacent to the detachment breakaway, but are not preserved in this adjacent locality (Fillmore et al., 1994; Fillmore and Walker, 1996). Basin N2 is provides an example of another structural setting for basin development within detachment metamorphic core complex settings that seems to be rarely preserved.

The intra-hanging wall setting of basin S1 is quite different than that of basins S2, S3, S4, which form directly above the detachment fault. However, many characteristics of a supradetachment basin are still present that clearly distinguish it from a typical rift. The basin is both bounded by a low-angle normal fault and underlain by the master Hohhot detachment. The basin is thin and dominated by coarse, footwall-derived conglomerate that was deposited dominantly by streamflow and sheetflood processes of an alluvial fan system, and displays predominantly transverse paleocurrents. The major difference this basin exhibits is the presence of a centrally located lacustrine interval. Extension magnitude in this basin may have been less and at a slower rate, which would have resulted in more basin subsidence, and made it possible for the lacustrine interval to form. This lacustrine interval is accompanied by variable paleocurrent patterns from alluvial fan progradation into the lake and possibly a minor axial component. If a large shallow lake was present south of the Daqing Shan, the lacustrine interval preserved in
basin S1 may be a factor of its southerly location, and not due to specific controls such as rate footwall uplift or rate of basin subsidence.

**Basin N1** is located in similar structural setting as basin N2. Both basins are located above a synformally folded detachment fault that has experienced doming of the lower plate to the south, but the basin stratigraphy is different. The stratigraphic thickness is greater than in basin N2, and the majority of the basin fill was deposited by debris flow processes as seen in K1a and K1b, but lacking a K1c waterlain unit. Doming of the detachment occurred as the upper plate was unloaded, but the extension magnitude was not great enough to exhume deep crustal material as in the Hohhot metamorphic core complex. Therefore, we again see a basin exhibiting supradetachment basin characteristics early in the basin history.

All of the Lower Cretaceous basins described in the Daqing Shan exhibit supradetachment basin characteristics (Friedmann and Burbank, 1995), regardless of location within the detachment-metamorphic core complex setting. The basins all formed above low-angle normal faults that accommodated rapid crustal extension in a region that has a complex tectonic history, including a period of significant contraction immediately prior to extension. These characteristics provide the conditions necessary to exclude proximal accommodation space and promote distal deposition of coarse sediment.

**Conclusions**

- Nonmarine extensional basins associated with the Hohhot detachment in the Daqing Shan of Inner Mongolia, China, are end-member supradetachment basins
(Friedmann and Burbank, 1995 *sensu stricto*) that are characterized by a definite structural style, thin basin fill, and prominence of mass-wasting and alluvial fan deposition of footwall-derived, coarse sediment through transverse transport paths.

- Supradetachment basins that form above the lower plate metamorphic dome evolve from being integrated early in the history of the detachment to separate as metamorphic core complex is exhumed and dissects the formerly contiguous basins. Accordingly, the basins that form above the youngest detachment splay are longer-lived as accommodation space is created by continued extension. Basins preserved in the synformal keel north of the structural culmination, do not continue to receive sediment because folding results in inactivation of their kinematically-linked detachment, and thus cessation in creation of accommodation space.

- Depositional environment, depositional processes, lithology, and transport patterns in the Daqing Shan supradetachment basins have little variation, but sediment sources are local and poorly mixed.

- Supradetachment basins associated with detachment faulting in the Daqing Shan are of the style described by Friedmann and Burbank (1995) regardless of the magnitude of extension by the time of K1c deposition. Metamorphic core complex exhumation is not a necessary requirement for end-member supradetachment basin geometry.
• Intra-hanging wall basins display Friedman and Burbank (1995) characteristics. They are controlled largely by the detachment and metamorphic core complex sediment supply, not local upper plate sources.
CHAPTER IV
CONCLUSIONS

Nonmarine extensional basins associated with the Hohhot detachment in the Daqing Shan of Inner Mongolia, China, are end-member supradetachment basins (Friedmann and Burbank, 1995 *sensu stricto*) that are characterized by a definite structural style, thin basin fill, and prominence of mass-wasting and alluvial fan deposition of footwall-derived, coarse sediment through transverse transport paths. These supradetachment basins associated with detachment faulting in the Daqing Shan are of the style described by Friedmann and Burbank (1995) regardless of the magnitude of extension by the time of Klc deposition. Metamorphic core complex exhumation is not a necessary requirement for end-member supradetachment basin geometry.

The supradetachment basins that form above the lower plate metamorphic dome evolve from being integrated early in the history of the detachment to separate as metamorphic core complex is exhumed and dissects the formerly contiguous basins. Accordingly, the basins that form above the youngest detachment splay are longer-lived as accommodation space is created by continued extension. Basins preserved in the synformal keel north of the structural culmination, do not continue to receive sediment because folding results in inactivation of their kinematically-linked detachment, and thus cessation in creation of accommodation space.
Intra-hanging wall basins also display Friedmann and Burbank (1995) characteristics. They are controlled largely by the detachment and metamorphic core complex sediment supply, not local upper plate sources.

Overall, depositional environment, depositional processes, lithology, and transport patterns in the Daqing Shan supradetachment basins have little variation, but sediment sources are local and poorly mixed.
REFERENCES


APPENDIX EXPLANATION

This appendix presents the field data collected in this study in table format.

Station refers to the numerical representation of a geographical location where data was collected. Latitude and longitude refer to the coordinates of that station given in decimal minutes. Strike and Dip values describe the attitude of bedding at that station in degrees. Imbrication is the corrected measurement of the plane of imbrication in degrees.

Paleocurrent roses presented in the thesis were created by plotting poles to these planes. Trough Axis refers to corrected trough axis in degrees, but may also represent data from imbrication that is corrected and recorded as a line instead of a plane. When used for paleocurrent roses they were plotted as lines or poles. Clast Type refers to the type of clast recorded in a clast count. Clast Count refers to the frequency of a particular clast type in a clast count. Max Clasts refers to the maximum long axes of the largest clasts found at a particular station.

In the Clast Count Data, the table is arranged by basin and shows the frequency of clast types for each station. These clast types were grouped from the raw data to present a standardized assemblage that is consistent for all of the basins. The data is provided in the raw groupings as well as by percentages for each clast count.
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The table lists the following data for various locations:
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- **X** and **Y** coordinates
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- **Plutonic Types**
- **Weathering Grades**

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- schist
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- 245.5 24.8N
- 259.6 28.3N
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**Foliated Plutonic:**
- 5

**Green Plutonic:**
- 2

**Weathered Plutonic:**
- 6

**Schist:**
- 1

**Gneiss:**
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- 10.54SE: Use 10.54SE for column 4.
- 111: Use 111 for column 3.
- 57.35SE: Use 57.35SE for column 5.
- 49.254: Use 49.254 for column 5.
- 35.28N: Use 35.28N for column 6.
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| Sandstone | 1 | 0 | 0 | 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Conglomerate | 1 | 11 | 10 | 8 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Clast Totals | 99 | 92 | 100 | 102 | 106 | 79 | 91 | 79 | 101 | 103 | 104 | 104 | 96 |

### Percentages

| Plutonic | 68.7 | 69.6 | 73.0 | 55.9 | 54.7 | 62.0 | 49.5 | 64.6 | 41.6 | 47.6 | 45.2 | 39.4 | 51.0 |
| Foliated Plutonic | 8.1 | 3.3 | 3.0 | 1.0 | 7.5 | 20.3 | 24.2 | 17.7 | 28.7 | 29.1 | 18.3 | 27.9 | 17.7 |
| Gneiss | 4.0 | 6.5 | 0.0 | 7.8 | 27.4 | 2.5 | 14.3 | 3.8 | 19.8 | 5.8 | 4.8 | 12.3 | 6.3 |
| Marble | 0.0 | 0.0 | 0.0 | 4.9 | 0.0 | 2.5 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 | 18.3 | 0.0 |
| Schist | 17.2 | 8.7 | 10.0 | 6.9 | 15.7 | 12.7 | 7.7 | 11.4 | 0.0 | 3.9 | 6.7 | 16.3 | 21.9 |
| Quartzite | 0.0 | 0.0 | 3.0 | 3.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.9 | 0.0 |
| Mylonite | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Volcanic | 0.0 | 0.0 | 1.0 | 5.9 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 |
| Sandstone | 1.0 | 0.0 | 0.0 | 5.9 | 0.9 | 0.0 | 4.4 | 2.5 | 8.9 | 13.6 | 6.7 | 1.0 | 3.1 |
| Conglomerate | 1.0 | 12.0 | 10.0 | 7.8 | 2.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Clast Totals | 99 | 92 | 100 | 102 | 106 | 79 | 91 | 79 | 101 | 103 | 104 | 104 | 96 |

### Basin S3

| Plutonic | 73 | 67 | 53 | 91 | 55 | 70 | 76 | 68 | 82 | 84 | 36 | 85 | 70 |
| Foliated Plutonic | 7 | 20 | 9 | 5 | 8 | 0 | 13 | 0 | 15 | 6 | 0 | 14 | 14 |
| Gneiss | 0 | 6 | 4 | 0 | 0 | 3 | 5 | 0 | 9 | 15 | 8 | 14 | 14 |
| Marble | 10 | 0 | 2 | 0 | 3 | 0 | 0 | 10 | 0 | 0 | 12 | 3 | 10 |
| Schist | 8 | 3 | 3 | 1 | 0 | 8 | 4 | 0 | 0 | 1 | 2 | 4 | 1 |
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| Mylonite | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Volcanic | 0 | 0 | 5 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| Sandstone | 1 | 3 | 6 | 3 | 0 | 5 | 2 | 7 | 0 | 0 | 0 | 0 | 0 |
| Conglomerate | 0 | 0 | 18 | 0 | 0 | 5 | 0 | 5 | 0 | 0 | 0 | 0 | 0 |
| Clast Totals | 99 | 92 | 100 | 81 | 92 | 101 | 94 | 106 | 108 | 59 | 114 | 100 |

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