Evolution of the Kingman Arch, southern Nevada

Juliana Marie Herrington

University of Nevada, Las Vegas

Follow this and additional works at: https://digitalscholarship.unlv.edu/rtds

Repository Citation
https://digitalscholarship.unlv.edu/rtds/1203

This Thesis is brought to you for free and open access by Digital Scholarship@UNLV. It has been accepted for inclusion in UNLV Retrospective Theses & Dissertations by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
EVOLUTION OF THE KINGMAN ARCH,
SOUTHERN NEVADA

by

Juliana Marie Herrington

Bachelor of Science
University of Nevada, Las Vegas
1993

A thesis submitted in partial fulfillment
of the requirements for

Master of Science Degree
Department of Geoscience
College of Sciences

Graduate College
University of Nevada, Las Vegas
December, 2000
The Thesis prepared by

Juliana Marie Herrington

Entitled

Evolution of the Kingman Arch, Southern Nevada

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Geoscience

Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

Evolution of the Kingman Arch, Southern Nevada
by
Juliana Herrington

Dr. Eugene I. Smith, Examination Committee Chair
Professor of Geoscience
University of Nevada, Las Vegas

The Kingman Arch is a structurally high area in southern Nevada and northwestern Arizona that lies partially within the Colorado River Extensional Corridor. Apatite fission track and $^{40}$Ar/$^{39}$Ar thermochronological analyses were conducted for granite samples collected from a 4.5 kilometer thick Precambrian section in the central McCullough Range. $^{40}$Ar/$^{39}$Ar data suggest slow cooling of the Kingman Arch between 1000 to about 560 Ma. Cessation of cooling is coincident with deposition of the Cambrian Tapeats Sandstone. Paleozoic and Mesozoic strata are absent on the Kingman Arch, but are present in areas adjacent to it. Thermal modeling suggests differential cooling of the crust, possibly caused by crustal refrigeration. The faster cooling of samples lower in the section compared to those in the upper part may be evidence of this refrigeration event. Nearly 5.5 kilometers of Mesozoic, Paleozoic, and Precambrian strata were removed from the Kingman Arch between the onset of Sevier thrust faulting (146 Ma) and deposition of the Peach Springs Tuff (18.5 Ma). The McCullough Spring conglomerate (MSC) was deposited in channels on the Precambrian basement between

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
40 and 18.5 Ma. The MSC contains Precambrian crystalline, Neoproterozoic quartzite, and Paleozoic carbonate clasts. Studies of clast type and provenance, together with qualitative analysis of paleoflow indicators, suggest that sediment was eroded from the Kingman Arch and highlands to the west and transported to the east and northeast.
TABLE OF CONTENTS

ABSTRACT ................................................................................................................................üi
LIST OF FIGURES ..................................................................................................................vü
ACKNOWLEDGEMENTS ......................................................................................................ix
CHAPTER 1 REGIONAL GEOLOGIC SETTING ................................................................1
Geologic Setting of the Kingman Arch ................................................................. 1
Geology of the Northern Colorado River Extensional Corridor ................... 2
Stratigraphy of the NCREC ............................................................................. 2
Structural Events Affecting the NCREC .......................................................... 4
   Thermal Uplift ...................................................................................... 4
   Sevier Thrusting ............................................................................... 5
   Laramide Deformation .................................................................. 6
   Cretaceous Extension ................................................................. 7
Denudation of the Kingman Arch and Sedimentation in
Southwestern Utah and Northwestern Arizona ........................................... 8

CHAPTER 2 FIELD RELATIONSHIPS OF THE NORTHERNMOST
KINGMAN ARCH ....................................................................................................... 18
The McCullough and Lucy Gray Ranges ........................................................... 18

CHAPTER 3 MCCULLOUGH SPRING CONGLOMERATE ......................................... 21
McCullough Range ............................................................................................... 21
Lucy Gray Range ................................................................................................. 23
Diagnostic Features and Discussion of the McCullough Spring Conglomerate... 24
Significance and Age of the McCullough Spring Conglomerate ................. 26

CHAPTER 4 GEOCHRONOLOGY ..................................................................................... 40
Introduction ................................................................................................................... 40
Fission-Track Dating ............................................................................................... 41
   Fission-Track Thermal Modeling ...................................................... 42
   40Ar/39Ar Analyses ........................................................................... 43
CHAPTER 5 EVOLUTION OF THE KINGMAN ARCH ..............................................49

Stage I - Slow Steady Cooling of the Kingman Arch ..............................................49
Stage II - Cooling (Laramide) and Denudation of the Kingman Arch ..................50
Stage III – Continued Refrigeration and Denudation, Deposition of the MSC, and Tertiary Extension and Volcanism .........................................................52

CHAPTER 6 CONCLUSION ...............................................................................................56

APPENDIX I GRANITE THIN SECTIONS MCCULLOUGH RANGE, NEVADA ....59

Sample MCM-1 ............................................................................................................59
Sample MCM-2 ............................................................................................................59
Sample MCM-3 ............................................................................................................61
Sample MCM-4 ............................................................................................................61
Sample MCM-5 ............................................................................................................61

APPENDIX II SAMPLE COLLECTION AND PREPARATION FOR GEOCHRONOLOGY .................................................................61

Introduction .................................................................................................................61
Mineral Separation Procedure .....................................................................................61
    Rock Crushing/Sieving ..............................................................................................61
    Wilfley Table ..........................................................................................................62
    Heavy Liquid Separation .........................................................................................62
    Franz Separator .......................................................................................................63
Fission-Track Methods ..............................................................................................63
    $^{39}$Ar/$^{40}$Ar Methods ............................................................................................64

APPENDIX III APATITE FISSION-TRACK DATA .......................................................67

APPENDIX IV NEVADA ISOTOPE GEOCHRONOLOGY LABORATORY PROCEDURES POTASSIUM FELDSPAR $^{40}$Ar/$^{39}$Ar STEP-HEATING DATA ..........................................................73

Nevada Isotope Geochronology Laboratory Procedures ........................................74

REFERENCES CITED .............................................................................................................76

VITA .........................................................................................................................................83
LIST OF FIGURES

Figure 1: Index map of the Colorado River extensional corridor.................................12

Figure 2: Paleogeographic map of the Lake Mead area prior to Miocene extension.......13

Figure 3: Stratigraphic column of the central McCullough Range and equivalent
stratigraphy in the Eldorado Mountains.................................................................14

Figure 4: Extent of the lower Cretaceous conglomerate (Cloverly Formation)
In the western interior or North America..............................................................15

Figure 5: Source areas for Late Cretaceous to early Tertiary sediments in southwestern
Utah..........................................................................................................................16

Figure 6: Composite cross-section of the Late Cretaceous to early Tertiary sediments in
Milkweed Canyon.................................................................................................17

Figure 7: Identified MSC locations in the McCullough and Lucy Gray ranges............20

Figure 8: Index of the McCullough and Lucy Gray ranges showing the locations
of the crustal section sampled for fission-track and $^{40}\text{Ar}^{39}\text{Ar}$
thermochronologic study.......................................................................................28

Figure 9: Photographs of the MSC debris flow deposit (including a large carbonate
block) in contact with the Precambrian crystalline basement within the lower
part of the McCullough Spring stratigraphic section, McCullough Range.............29

Figure 10: Photographs of the upper part of the McCullough Spring stratigraphic section
showing the MSC fanglomerate deposit in contact with the overlying Tertiary
volcanic section, McCullough Range................................................................30

Figure 11: Photograph of the McClanahan Spring stratigraphic section, McCullough
Range......................................................................................................................31

Figure 12: Photographs of an isolated ridge on the east flank of the Lucy Gray Range
showing the stratigraphic relationships and location of measured sections, and
the poorly sorted, non-bedded nature of the MSC..............................................32

Figure 13: McCullough Spring stratigraphic column, McCullough Range.................33
Figure 14: Southside McCullough Spring stratigraphic column, McCullough Range. .....35
Figure 15: McClanahan Spring stratigraphic column, McCullough Range. .................36
Figure 16: North stratigraphic column, Lucy Gray Range. ......................................................37
Figure 17: Middle stratigraphic column, Lucy Gray Range. ......................................................38
Figure 18: South stratigraphic column, Lucy Gray Range. ......................................................39
Figure 19: Apatite fission-track age, length, and precision data for the McCullough Range, Nevada. .........................................................................................................45
Figure 20: Apatite fission-track length modeling data for the McCullough Range, Nevada. ......................................................................................................................48
Figure 21: Samples MCM-1 and MCM-5 K-feldspar \(^{40}\text{Ar}/^{39}\text{Ar} \) step-heating diagrams and data. ......................................................................................................................49
Figure 22: Thermal history model for the Kingman Arch ....................................................54
Figure 23: Conceptual model for the Evolution of the Kingman Arch. ..............................55

viii
ACKNOWLEDGEMENTS

I would like to give special thanks to Dr. E. I. Smith for your patience and encouragement during the completion of my thesis. Your kind, gentle, mannerism and exceptional educational style provided me the guidance, courage, and persistence to overcome many challenges both personally and professional while working on this project.

Special thanks to Dr. Clay Crow for conducting X-ray Diffraction on my samples to determine K-spar content. Also, for your help with use of the rock and mineral laboratory equipment.

Dr. Terry Spell thank-you for your time and patience regarding my endless thermochronology questions. My sincere thanks to you and Kathy Zanetti for conducting the $^{40}\text{Ar}/^{39}\text{Ar}$ analyses for my samples.

I'm very grateful to my committee members Dr. Michael Wells, Dr. Stephen Rowland, Dr. Eugene Smith, and Dr. Diane Pyper-Smith who have challenged me to grow both personally and professionally during the completion of this thesis. Thanks for answering all my questions, trips to the field, comments to my thesis, your encouragement. You all have my deepest respect and admiration.

Dr. Michael Wells I really appreciate your guidance and the generous use of your equipment and supplies in order to conduct the mineral separations. I especially appreciate your thorough review and insightful comments regarding this thesis. Your
comments and discussions have been extremely thought provoking and inspiring.

Dr. Stephen Rowland thanks for taking Dr. Timothy Wallin’s place on my committee. I am grateful to you for naming the conglomerate and your help in the field identifying clasts and looking at paleoflow indicators. Your thoughtful questions and encouragement to complete this thesis is greatly appreciated.

Thanks to the all the folks in the Geoscience Department who have provided me encouragement and motivation to finish (especially Dr. Wanda Taylor). Special thanks to the Department and Bernada E. French for the scholarship and graduate assistantship I received during completion of this thesis. They were very useful in covering some of my expenses.

My sincere gratitude to Dr. David Foster, P. O’Sullivan, and Melinda Mitchell for conducting the fission track analyses and modeling.

To my mom, Anne Herrington, my family, and friends, thanks for your love and support. I dedicate this thesis to the loving memory of my father, Ray Herrington, who didn’t mind all the scratches I put on his explorer going to my field area. Special thanks to Jonathan Banks, my son, who helped me collect and carry rock samples and provided me with love and encouragement.

To my dearest husband, Michael Harris, it would not have been possible to finish my thesis without you. Thanks for keeping me company in the field, for your endless love, encouragement, and support. You have my deepest gratitude.
CHAPTER 1

REGIONAL GEOLOGIC SETTING

Geologic Setting of the Kingman Arch

The Precambrian basement within the Colorado River extensional corridor (CREC) (Figure 1), a 70 to 100 km wide zone of extended crust between the Colorado Plateau and the Spring and Old Woman Mountains, forms a structural high known as the Kingman Uplift (Lucchitta, 1966; Young and Brennan, 1974; Howard and John, 1987; Bohannon, 1984; Duebendorfer et al., 1998). In this thesis, however, this feature is referred to as the Kingman Arch. On the Kingman Arch (Figure 2), Precambrian basement is overlain by Tertiary volcanic rocks except in some areas where there is an intervening conglomerate. This conglomerate is the subject of the thesis and is herein named the McCullough Spring Conglomerate (MSC) (Figure 3). The Paleozoic and Mesozoic strata are absent from the CREC with the exception of a few isolated occurrences. More complete and thicker Paleozoic sections, however, occur to the east on the Colorado Plateau and to the west in the Spring Mountains (Figure 1). The reason for the absence of Paleozoic and Mesozoic strata on the Kingman Arch is a subject of current debate. Either the Paleozoic-Mesozoic strata were denuded in Late Cretaceous or early Tertiary (Young and Brennan, 1974; Bohannon, 1984; Duebendorfer et al., 1998), or the arch formed a topographic high that prevented deposition of Paleozoic and Mesozoic sediments.
The goal of this study is to determine the age and origin of the Kingman Arch. The principle tools used to attain this goal are thermochronologic studies of the Precambrian basement rocks of the arch and sedimentologic and stratigraphic studies.

The area of study consists of MSC exposures in the northernmost part of the Kingman Arch, within the McCullough and Lucy Gray Ranges of southern Clark County, Nevada (Figure 1). Samples for thermochronologic study were collected from a relatively structurally intact block of Precambrian basement near McCullough Spring in the central McCullough Range.

Geology of the Northern Colorado River Extensional Corridor

The following paragraphs provide general geologic information that is important to understanding the models of evolution of the Kingman Arch proposed in this study. Emphasis is placed on the distribution and thickness of stratigraphic units and significant structural events that may have contributed to uplift and/or denudation.

Stratigraphy of the NCREC

The stratigraphy within and adjacent to the NCREC is important because it may provide evidence of deposition (e.g., Paleozoic and Mesozoic strata) on the arch and also identifies potential source areas for MSC clasts (including Precambrian crystalline, Neoproterozoic quartzite, and Paleozoic carbonate clasts).

Precambrian crystalline basement rocks (2.5 to 1.4 Ga) in the northern part of the CREC herein referred to as the NCREC (including the Kingman Arch) are structurally complex and consist of a variety of lithologies including gneiss, schist, and granite.
Supracrustal sedimentary and volcanic rocks (1.4 to 0.9 Ga) overlie the Precambrian crystalline basement farther to the east in the Colorado Plateau area (lower Grand Canyon Supergroup) and in the Death Valley region (lower Pahrump Group) but are absent adjacent to the Kingman Arch (Stewart, 1992). In the northwestern part of the Grand Canyon, Neoprotozoic strata of the Grand Canyon Supergroup overlie the Precambrian basement (Stewart, 1992). This section is approximately 4 km thick in the western Colorado Plateau, but sediments of this age were apparently not deposited in the southern Nevada area (Burchfiel et al., 1992). Neoprotozoic strata also crop out to the west of the Kingman Arch, near Wheeler Pass, in the Spring Mountains, Nevada and at Mesquite Mountain, California and comprise the lower part of the Pahrump Group (Figure 1) (Longwell et al., 1965; Jennings et al., 1977). Neoprotozoic strata in the Spring and Mesquite Mountains include the Johnnie Formation and Stirling Quartzite (Longwell et al., 1965; Jennings et al., 1977).

Prior to deposition of Paleozoic strata, the paleotopography of the NCREC was relatively flat with the exception of broad, low Precambrian monadnocks that ranged from 5 m to 30 m high (McKee, 1945; Hardy, 1986). The thickness of Paleozoic strata originally deposited in the NCREC is controversial (see earlier discussion); however, at the present time this section are largely absent from the NCREC except for the occurrence of a few isolated, incomplete sections (Longwell et al., 1965; Timm, 1985; Feuerbach, 1986, Naumann, 1987; Sewall, 1988; Bridwell, 1991). Paleozoic exposures range in thickness from a few meters at Saddle Island, on the west shore of Lake Mead (Sewall, 1988), to about 1500 m at Sheep Mountain (Longwell et al., 1965; Hardy, 1986; S. Rowland, personal communication, 2000). In contrast to these NCREC sections,
Paleozoic sections are approximately 4-5 km thick to the east on the Colorado Plateau, to the west in the Spring Mountains, and to the north in Utah (Burchfiel et al., 1992). Importantly, the Paleozoic strata do not thin toward the arch.

Mesozoic strata are exposed to the east of the Kingman Arch near Peach Springs, Arizona, to the west in the Spring Mountains, Nevada and north in Utah; Mesozoic strata are absent from the Kingman Arch (Figure 1). These strata also do not thin toward the arch. West of the Kingman Arch, the Mesozoic sections in the Spring Mountains generally include the Moenkopi and Chinle formations, and Aztec (Navajo) Sandstone. The cumulative thickness of the Chinle and Moenkopi Formations in the Goodsprings District and near Blue Diamond, Nevada ranges from 456 to 550 m (Longwell et al., 1965). The maximum thickness of the Aztec Sandstone in Clark County, Nevada is approximately 762 m (Longwell et al., 1965).

Throughout the NCREC, the Precambrian basement is overlain by Tertiary volcanic rocks. The oldest of the volcanic rocks on the Kingman Arch is the 18.5 ± 0.2 Ma Peach Springs Tuff (Nielson et al., 1990).

Structural Events Affecting the NCREC

Structural events that may have resulted in the denudation of the Paleozoic and Mesozoic strata on Kingman Arch include Mesozoic (pre-Sevier) thermal uplift, Sevier thrusting, Laramide deformation, and Cretaceous shearing.

Thermal Uplift

Heller and Paola (1989), described a period of thermal uplift and regional doming prior to and during deposition of the Jurassic Morrison Formation between 156 and 144...
Ma that may have preceded Sevier thrusting. These events resulted in the deposition of a lower Cretaceous conglomerate (the Cloverly Formation) over a broad alluvial plain across 600 km of the western interior (Figure 4). The composition of the Cloverly Formation conglomerate indicates the source area consisted, in part, of upper Paleozoic marine sedimentary rocks that crop out in Nevada, west of the thrust belt (Heller and Paola, 1989). The conglomerates also contain chert fragments and, to a lesser extent quartzite and limestone clasts. The Heller and Paola (1989) study demonstrates that a regional northeast trending drainage system existed prior to or coeval with the Sevier Orogeny.

Sevier Thrusting

Thermal uplift and regional doming was followed by Sevier thrusting that was active primarily from 146 \( \pm \) 2 to 99 \( \pm \) 0.4 Ma in the southern Spring, Mesquite, and Clark Mountains. The 99 \( \pm \) 0.4 Ma date is based on \(^{40}\text{Ar}/^{39}\text{Ar}\) laser-fusion and incremental-heating studies of an interbedded tuff within the Lavinia Wash sequence (Fleck and Carr, 1990). The Lavinia Wash sequence consists of a conglomerate that was overridden by the Contact and Keystone thrust faults in the Spring Mountains (about 7 km south of Potosi Mountain). The 146 \( \pm \) 2 Ma date is based on U-Pb zircon dates of Late Jurassic plutons that bracket the Palchalka thrust in the Clark Mountains, California (Walker et al., 1995). Sevier thrusting produced a topographic high to the west of the present Kingman Arch (Figure 2) (Cameron, 1977). During the Sevier Orogeny, thick sections of Paleozoic strata were transported eastward tens of kilometers and thrust over younger Paleozoic and Mesozoic rocks (Armstrong, 1968). Locally, these thrust faults overrode conglomerates that unconformably overlie Triassic strata (Hewett, 1931; Longwell, 1926;
Secor, 1963; Davis, 1973; Carr, 1977; Cameron, 1977; Fleck and Carr, 1990; Fleck et al., 1994). These conglomerates, named the Lavinia Wash sequence by Carr (1980), contain clasts derived from the nearby 100.5 ± 2 Ma Delfonte volcanic terrane and from the thrust plates themselves (Fleck and Carr, 1990; Fleck et al., 1994).

In the eastern Spring Mountains at the base of Potosi Mountain, a chert-quartzite-carbonate pebble conglomerate occurs beneath the Contact Thrust and overlies the Aztec Sandstone (Cameron, 1977). In this conglomerate (maximum thickness about 30 m) the clasts of Precambrian chert and quartzite could have only been derived from sources farther to the west (Longwell, 1926; Cameron, 1977). Davis (1973) indicated that this conglomerate contains a greater abundance of carbonate clasts in the upper part of the section. This conglomerate, as well as the Lavinia Wash sequence, were thought to have been deposited on an erosional surface prior to Sevier thrusting (Cameron, 1977; Carr, 1980). However, subsequent work by Fleck and Carr (1990, 1994) have shown that these deposits are syn-thrusting deposits approximately 99 ± 0.4 Ma, based on $^{40}\text{Ar}/^{39}\text{Ar}$ laser-fusion and incremental heating studies of an interbedded tuff.

Laramide Deformation

Laramide deformation in western North America was active between about 80 and 40 Ma (Coney, 1973; Gresans, 1981; Young, 1982) and is characterized by basement-cored uplift commonly bordered by high-angle reverse and thrust faults (Cross, 1986). Laramide deformation produced large-scale compressional upwarps and monoclinal folds (Young, 1982). Several authors have suggested that intracrustal flow from an overthickened Sevier hinterland resulted in Laramide uplift and ultimately in the uplift of the proto-Colorado Plateau (Wernicke, 1990; Zandt et al., 1995; McQuarrie and
Chase, 2000). Others have suggested that Laramide deformation is due to the low-angle subduction of an aseismic ridge beneath a compressional arc-trench system resulting in basement-involved deformation within retroarc foreland basins (Dickinson and Snyder, 1978; Cross, 1986; Busby and Ingersoll, 1995). Another study by Dumitru et al. (1991) suggested that during Laramide subduction, the hot asthenospheric wedge was expelled and replaced by a cold subducting slab. Furthermore, they suggested that thermochronologic data, including K-Ar, ⁴⁰Ar/³⁹Ar, and fission-track, from the Sierra Nevada, Great Basin, Mojave Desert, western Arizona, and the Colorado Plateau record latest-Cretaceous-early Tertiary cooling. Cooling may be due to refrigeration related to this cold subducting slab. The regional crustal refrigeration effects from the cold slab would have caused metamorphism to wane and the thickening and strengthening of the crust. According to Dumitru et al. (1991), Late Cretaceous to early Tertiary isotopic cooling ages, therefore, probably are not indicative of regional uplift and unroofing.

Cretaceous Extension

Beyene (2000) suggested that regional extension was coeval with Laramide uplift in the Mojave Desert region. This Late Cretaceous extension is evidenced by deformation (73-66 Ma) and rapid cooling (44°C/m.y.) of the Pinto shear zone (Beyene, 2000). Initial cooling in the shear zone is thought to be associated with extension. Evidence includes microstructural studies of mylonite and ultramylonite that show deformation occurred over a broad range of decreasing temperatures (Beyene, 2000). Beyene (2000) suggested that the Pinto shear zone could be kinematically related to other Late Cretaceous extensional structures in the eastern Mojave Desert, including those in
the Old Woman and Funeral Mountains. However, no Cretaceous age structures have been identified in the study area.

Denudation of the Kingman Arch and Sedimentation In Southwestern Utah and Northwestern Arizona

Relevant to the study of the MSC are Late Cretaceous to early Tertiary conglomerates on the Colorado Plateau. These conglomerates may be coeval with the MSC (see Chapter 3) and also demonstrate east to northeast transport of sediment across the Kingman Arch. Young (1982, 1993) suggested that in Late Cretaceous to early Tertiary time there was enough erosion of both the Sevier thrust belt and the Kingman Arch to unroof the Mesozoic and Paleozoic sections and to expose and significantly erode the Precambrian basement. This unroofing sequence is reflected in conglomerates in canyons west of the Grand Canyon (Young, 1982; Young, 1993; Young, 2000). These conglomerates contain abundant Paleozoic clasts at their bases, with Precambrian quartzite and crystalline clasts increasing in abundance up section (Young, 1993). The uppermost part of these conglomerate sections contain exotic upper Cretaceous (63-80 Ma) volcanic clasts that exceed 50 percent of the total clasts (Young, 1993). The early Tertiary sediments were eroded from highlands to the west and transported 100 to 150 km north and east (Young, 1993; Young, 2000). These sediments accumulated to thicknesses ranging from 76 to 236 m in channels in the western Grand Canyon region (Young, 1982). Young (1993) concluded that these sediments record Laramide tectonism, erosion, and syntectonic sedimentation.

Additional support of Young’s model is provided by Goldstrand (1992), who
demonstrated that conglomerates in southern Utah could have been derived from sources in southern Nevada and southeastern California (Figure 5). Billingsley et al. (1999) also concluded that the deposits in southern Utah described by Goldstrand (1990, 1992, 1994) provide indirect support for the proposed Laramide origin of sediments in the western Grand Canyon region.

In southwestern Utah, Goldstrand (1992) described two upward-coarsening petrofacies (i.e., Kaiparowits-Canaan Peak and Iron Springs-Grand Castle) that range in age from late Cretaceous to Eocene. The cumulative thickness of these deposits ranges from about 450 to 1150 m (Goldstrand, 1992). These petrofacies record active Sevier-style thrust deformation, cessation of thrusting, and Laramide-style folding (Goldstrand, 1992). The depositional environments for these sediments include braided fluvial and muddy to meandering flow systems, alluvial fan, and floodplain. The predominant regional paleoflow direction for most of these deposits was northeast-to-east (Figure 5) (Goldstrand, 1992). The Maastrichtian to early Paleocene Canaan Peak Formation contains clasts that include the 100.5 ± 2 Ma Delfonte Volcanics (Fleck et al., 1994), Jurassic Aztec Sandstone, Neoproterzoic-Cambrian Prospect Mountain Quartzite (equivalent to Stirling and Wood Canyon formations), and Precambrian metamorphic and granitic rocks (Goldstrand, 1992). The most likely source of these clasts is the Mountain Pass region of southeastern California (Goldstrand, 1992). Clasts in the Canaan Peak Formation also contain radiolarian argillites and chert lithoarenites. These clasts may have originated from the Paleozoic rocks in southern Nevada (Figure 5) (Goldstrand, 1992).

Young (1982) described the unroofing sequence in exposures in Peach Springs
and Milkweed canyons on the western rim of the Grand Canyon (Figure 1). In these canyons, the Cambrian Muav Limestone is overlain by a sequence of well-rounded arkosic gravel-size conglomerates, fanglomerates, lacustrine limestones, and limestone conglomerates (Young and Brennan, 1974; R. Young, personal communication, 2000). These deposits crop out discontinuously and are overlain by Tertiary volcanic rocks including the Peach Springs Tuff on the Hualapai Indian Reservation from the Kingman area to Williams, Arizona (Figure 6) (R. Young, personnel communication, 2000). The lower section of arkosic conglomerate is weathered, iron-oxide stained, moderately to loosely consolidated, and lacks any volcanic clasts (Young, 1982). However, the upper section of the arkosic conglomerate is not significantly weathered, more consolidated, and contains volcanic clasts (Young, 1982). The volcanic clasts were dated between 129 Ma and 64 Ma, with most of the clasts about 72 Ma (R. Young, personal communication, 2000).

The closest source area for Late Cretaceous volcanic clasts is south of Prescott, Arizona near Bagdad and Copper Basin (Young, 1993). These volcanic clasts generally increase in abundance upsection in Peach Springs Canyon and may represent syntectonic erosion of the arc (Young, 1982; R. Young, personal communication, 2000). Volcanic clasts in Milkweed Canyon, however, are less abundant than those in Peach Springs Canyon (R. Young, personal communication, 2000). In Peach Springs Canyon a thin gravel lens containing Paleozoic carbonate clasts crops out between the upper and lower arkosic sections (Young, 1982). The scarcity of Paleozoic carbonate clasts in the arkosic deposits may be due to thick soil and vegetation cover under wetter climatic conditions (Young, 1982), or perhaps the source area for these deposits lacked Paleozoic rock. In
Milkweed Canyon, the conglomerate (i.e., Buck and Doe conglomerates) that lies directly below the Peach Spring Tuff, contains subangular clasts and was derived from the south and west (Billingsley et al., 1999; J. Faulds, personal communication, 2000). Paleozoic carbonate, Neoproterozoic quartzite, granitic gneiss, and megacrystic granite (1.4 Ga?) are the major clast types in the conglomerate (Billingsley et al., 1999; J. Faulds, personal communication, 2000). Faulds (personal communication, 2000) indicated that the conglomerate could be correlative to the MSC.

In summary, during Late Cretaceous to early Tertiary time sediments were transported across the Kingman Arch and deposited in channels on the western margin of the Colorado Plateau and in southwest Utah. Some of the clasts contained in these sediments originated to the west in the Mountain Pass (Mesquite Mountain) and Spring Mountains areas. These studies demonstrate that during the Late Cretaceous and early Tertiary east to northeast drainage channels were established. Conglomerates that occur on the western Colorado Plateau may be equivalent to the MSC (Chapter 3).
Figure 1: Index map of the Colorado River extensional corridor. The Kingman Arch lies between the Spring Mountains, Nevada and the Colorado Plateau. The study area is in the northernmost part of the Kingman Arch in the Lucy Gray and McCullough ranges (modified from Morikawa, 1993).
Figure 2: Paleogeographic map of the Lake Mead area prior to Miocene extension (from Beard, 1996). Inferred location of Kingman Arch from Lucchitta (1966) and Bohannon (1984). Paleo-Permian scarp inferred from Young (1985). Paleoflow directions shown by solid arrows based on preserved canyons and deposits; directions shown by dashed arrows are inferred from regional geologic relationships (Duebendorfer et al., 1998).
Figure 3: Stratigraphic column of the central McCullough Range and equivalent stratigraphy in the Eldorado Mountains. The McCullough Spring Conglomerate (MSC) overlies the Precambrian basement and is overlain by Tertiary volcanic rocks (Eldorado Mountains stratigraphy from Anderson, 1971; modified from Schmidt, 1987).
Figure 4: Extent of lower Cretaceous conglomerate (Cloverly Formation) in the western interior of North America. Heller and Paola (1989) indicate that the Cloverly Formation was derived from highlands formed by thermal uplift and regional doming during the Jurassic (156-144 Ma). Paleocurrent directions for lower Cretaceous gravels are shown by small arrows (modified from Heller and Paola, 1989). Note that regional drainage is toward the east and northeast.
Figure 5: Source areas for Late Cretaceous to early Tertiary sediments in southwestern Utah (Goldstrand, 1992).
Figure 6: Composite cross-section of Late Cretaceous to early Tertiary sediments in Milkweed Canyon (modified from Young and Brennan, 1974). These conglomerate deposits may be correlative to the MSC (Chapter 3).
CHAPTER 2

FIELD RELATIONSHIPS OF THE NORTHERNMOST KINGMAN ARCH

The McCullough and Lucy Gray Ranges

The McCullough and Lucy Gray Ranges lie in the northern part of the Kingman Arch (Figure 1). In the McCullough Range, the oldest Precambrian basement rocks consist of garnet-sillimanite-cordierite granulite gneiss interlayed with leucogranite, amphibolite, and ultramafic rock (Anderson et al., 1985). Intruding the granulite gneiss are granitic (e.g., monzogranite) and dioritic plutons. The youngest Precambrian units consist of pegmatite and aplite dikes (Anderson et al., 1985). Generally, the Precambrian basement is overlain by Tertiary volcanic rocks. However, at several locations throughout the McCullough Range (Figure 7) the MSC occurs between the Precambrian basement and Tertiary section. This 100 m thick conglomerate crops out discontinuously throughout the McCullough Range from McCullough Spring to McCullough Pass and contains clasts of Precambrian crystalline rocks and Stirling Quartzite, Neoproterozoic-Cambrian Wood Canyon quartzite, and Paleozoic carbonates (Anderson et al., 1985). On the northwest side of the McCullough Range, near McClanahan Spring (Figure 7), the Peach Springs Tuff overlies the MSC (Wells and Hillhouse, 1989).

In the northern part of the McCullough Range, Tertiary volcanic rocks about 1100 m thick overlie Precambrian basement (Anderson et al., 1985). However, in the
northwestern part of the range, near Interstate Highway 15, Tertiary volcanic rocks
overlie a Paleozoic section consisting of the Mississippian Monte Cristo Limestone and
the Pennsylvanian-Permian Birdspring Formation (Figure 1) (Longwell et al., 1965;

In the Lucy Gray Range, the Precambrian basement consists primarily of a 1.7 Ga
light gray to pink, fine- to medium-grained quartzofeldspathic orthogneiss and lesser
amounts of mafic gneiss (Christensen, 1994). In the northern and central parts of the
range, the orthogneiss is intruded by the Beer Bottle Pass Pluton, a 1.4 Ga rapakivi
granite (L.T. Silver, personal communication to Stewart and Carlson, 1978; Christensen,
1994). The Beer Bottle Pass Pluton consists of a coarse-grained, porphyritic, hornblende-
biotite granite with feldspar megacrysts up to 4-5 cm in length (Christensen, 1994). The
southern part of the Lucy Gray Range is primarily banded gneiss and mafic-megacrystic
granite (Christensen, 1994). Precambrian basement is locally overlain on the eastern side
of the range by Tertiary volcanic rocks (Longwell et al., 1965). However, immediately
north part of the Lucy Gray Range at Sheep Mountain (Figure 1), the Precambrian
basement is overlain by a Paleozoic section (about 1500 m thick). The Paleozoic section
includes the Cambrian Tapeats Sandstone, Bright Angel (Pioche) Shale, Bonanza King
Formation (Muav Formation equivalent), Devonian Sultan Formation, and Mississippian
Monte Cristo Limestone (S. Rowland, personal communication, 2000). The MSC is
exposed in the Lucy Gray Range about 2-3 km south of Sheep Mountain (Figure 7). The
MSC at this location is approximately 49 m thick.
Figure 7: Identified MSC locations in the McCullough and Lucy Gray Ranges (modified from Smith et al., 1988). Note that Tertiary geologic units are not shown for the Highland Spring Range or Eldorado Mountains.
CHAPTER 3

MCCULLOUGH SPRING CONGLOMERATE

McCullough Range

MSC localities in the McCullough and Lucy Gray ranges are shown in Figure 8.

In the central and northern parts of the McCullough Range, the MSC is discontinuous and variable in thickness (1-100 m). The most well preserved MSC deposits are those that are overlain by Tertiary volcanic rocks.

The MSC exposure near McCullough Spring (Figures 7 and 8) consists of a 100 m thick section of conglomerate. The lower 88 m of this section consists entirely of poorly sorted angular Precambrian clasts that range in size from pebble to cobble with the majority of the clasts ranging from 1 to 3 cm in diameter. Parts of this section exhibit iron oxide staining. Paleoflow indicators (i.e., clast imbrication patterns) show variable flow directions within the lower part of the section. At the top of the lower part of the section is a 1 m wide and 3 m long carbonate block (Figure 10). Based on the presence of stromatolites, this block appears to be middle Cambrian Bonanza King Formation (S. Rowland, personal communication, 2000). In a conglomerate that underlies Tertiary volcanic rocks and overlies the Precambrian basement, another large carbonate block has been observed (E. Smith and M. Wells; personal communications, 1998) in the Castle
Mountains, south of the McCullough Range.

Overlying the lower part of the section of MSC near McCullough Spring, is 12 m of conglomerate that contains clasts of Precambrian crystalline basement and quartzite and Paleozoic carbonate. In this section, the percentage of Precambrian crystalline clasts percentages are qualitative estimates) generally decrease upward to about 55% while the percentage of carbonate clasts increases to 44% (with about 1% quartzite). The upper part of the section of conglomerate (Figure 9) varies from poorly to moderately sorted. Anderson et al. (1985) identified Precambrian Stirling Quartzite as well as Precambrian-Cambrian Wood Canyon quartzite and Paleozoic carbonate clasts in the MSC conglomerate near McCullough Spring. The carbonate and quartzite clasts range in size from pebble to cobble and are generally subangular to rounded with matrix support. Paleoflow within the upper part of the section, based on qualitative analysis of clast imbrication patterns, generally indicates flow to the southeast. This 100 m thick exposure pinches out completely to the north about 1 km from McCullough Spring.

Another MSC exposure is near McClanahan Spring, in the northwest part of the McCullough Range (Figures 7 and 8). The section at this exposure is about 12 m thick; it overlies the Precambrian basement and is overlain by the 18.5 Ma Peach Springs Tuff (Figure 11). In this MSC exposure, Precambrian crystalline clasts decrease in abundance upsection while the Neoproterozoic quartzite (i.e., Stirling Quartzite) and Paleozoic carbonate clasts increase in abundance upsection. The paleoflow direction, based on qualitative analysis of clast imbrication patterns, appears to be eastward to southeastward. The McClanahan spring exposure pinches out just 100 m north of the thickest part of the section. The section also thins to the south but contacts are covered by alluvium. The stratigraphic columns for the McCullough Range are shown in Figures 13 through 15.
Lucy Gray Range

In the eastern part of the Lucy Gray Range, near Beer Bottle Pass, the MSC is exposed on an isolated ridge (Figures 7 and 8). Here the MSC is 46 to 61 m thick, consisting of both poorly sorted and well-sorted beds. At this locality the MSC can clearly be seen to overlie crystalline basement and to be overlain by Tertiary andesite (Figure 12). I measured three stratigraphic sections (north, middle, and south) and described the MSC for this exposure (Figure 12). These correspond to localities C, D, and E on Figure 8. In these sections, carbonate clast percentages generally increase upsection from 45 to 65 percent (percentages are based on qualitative observations). Quartzite clast percentages generally vary from 2 to 5 percent, but in the southernmost stratigraphic section (Figure 12) quartzite clasts increase upsection to about 30 percent. I identified some of the quartzite clasts as Precambrian Stirling Quartzite based on comparisons to Stirling Quartzite from Mt. Stirling, Nevada and Mesquite Mountain, California.

In the middle and southern stratigraphic sections (Figure 12), at about 7.5 m above the Precambrian crystalline contact there is a distinctive conglomerate containing very well-rounded, purple and rose quartzite clasts (about 2.5 cm in diameter). This distinctive bed is traceable to the east side of the MSC exposure (about 0.5 km). The Precambrian crystalline clasts tend to be angular while the quartzite and carbonate clasts are mostly subangular to rounded. Clast size ranges from pebble to boulder, but the majority of the clasts are about 0.2 to 3 cm. Paleoflow, based on qualitative analysis of clast imbrication patterns, was toward the south and southeast. These exposures thin to about 1 m thick approximately 1 km south of the southernmost section. The stratigraphic columns for the Lucy Gray Range are shown in Figures 16 through 18.
Diagnostic Features and Discussion of the McCullough Spring Conglomerate

The principle diagnostic features of the MSC are (1) the channel-like geometry of many of the exposures, (2) its stratigraphic position between the Precambrian basement and Tertiary volcanic rocks, (3) the predominance of Precambrian crystalline clasts in the lower part of the section, (4) the abundance of Neoproterozoic quartzite (i.e., Stirling Quartzite) and Paleozoic carbonate clasts in the upper part, and (5) the lack of any volcanic clasts or Mesozoic sandstone clasts.

Based on field observations at MSC exposures described in this thesis, I suggest that the MSC was deposited in broad channels. Although, speculative, these channels appear to be oriented roughly east-west.

In the McCullough Range near McCullough Spring, there appears to be a change in depositional environment between the lower and upper portions of the MSC. The lower portion has varied clast imbrication patterns, no bedding, angular clasts, is poorly sorted, and contains a large carbonate block. These features are consistent with a debris flow origin (Boggs, 1987; S. Rowland, personal communication, 2000). The clasts in the lower part of this deposit are probably from local sources. The carbonate block could not have been transported a great distance due to its large size. I suggest that it originates from a nearby Paleozoic remnant (butte or mesa). In comparison, the upper part of the section has consistent clast imbrication patterns, bedding with some channeling, angular-to-rounded clasts, and ranges from poorly to well sorted. These features are more characteristic of a widespread sheetflood and stream-channel (fanglomerate) deposits (Boggs, 1987; S. Rowland, personnel communication, 2000).

Debris flow, stream-channel, and sheetflood deposits are common in alluvial fan
environments (Boggs, 1987). Debris flows are common on fans in arid and semi-arid regions where rainfall is infrequent but violent, slopes are steep, and vegetation is sparse. However, fanglomerate is formed by stream-channel and sheetflood processes. Stream-channel sediments form deposits that are coarse to poorly sorted and are long and narrow in shape (Nilsen, 1985; Boggs, 1987). Sheetflood deposits are formed by surges of sediment laden with water that spread out from the terminus of the stream channel onto a fan (Boggs, 1987). These deposits tend to be well sorted, cross-bedded, laminated, or nearly structureless (Boggs, 1987).

Young (1982) suggested that the climate during the early to mid-Tertiary was wetter and more conducive to widespread erosion. Thus, the change in depositional environments recorded in the MSC may indicate the change in regional climate. However, the change from debris flow to fanglomerate deposits in the MSC could be due to a change in source areas from local to more distal. The debris flow deposits containing Precambrian crystalline basement clasts and the large carbonate block were derived from local sources on the arch. The fanglomerate deposits containing Neoproterozoic quartzite and more rounded Paleozoic carbonate clasts were derived from more distal sources to the west. Possible source areas for the Neoproterozoic quartzite clasts could be in the Wheeler Pass thrust plate, presently exposed discontinuously from the Las Vegas Range, Nevada southward to Clark Mountain, California (Figure 1). The most likely source for the Paleozoic carbonate clasts is from Sheep Mountain, and/or the Spring or Mesquite Mountains (Figure 1). Additionally, the source area(s) lacked volcanic and Mesozoic rocks.

Significance and Age of the McCullough Spring Conglomerate

MSC exposures in the Lucy Gray and McCullough Ranges and in other areas of the NCREC are significant because they provide the only stratigraphic evidence of the evolution the Kingman Arch. Anderson et al. (1985) suggested that the MSC was of regional extent and that
there were exposures in the Eldorado and River Mountains. Anderson et al. (1985) indicated the age of the MSC is most likely late Cretaceous to early Tertiary based on the comparison to stratigraphically equivalent channel-fill deposits described by Young and McKee (1978) to the northeast on the margin of the Colorado Plateau (i.e., Milkweed Canyon) and by Smith (1982) and Choukroune and Smith (1985) on Saddle Island, Lake Mead.

The age of the MSC cannot be determined precisely but it can be estimated from stratigraphic evidence. In the McCullough and Lucy Gray ranges, the MSC is older than the overlying 18.5 Ma ± 0.2 Ma Peach Springs Tuff. Regional stratigraphic evidence suggests the deposition of about 4-5 km of Paleozoic and 1-1.3 km of Mesozoic strata by the onset of Sevier thrust faulting (~146 ± 2 Ma) in the southern Spring, Clark, and Mesquite mountains, Nevada and California. These Paleozoic and Mesozoic strata were then locally removed, exposing Precambrian crystalline basement. Clearly, the MSC was deposited after the denudation of the Mesozoic and Paleozoic strata because it overlies Precambrian crystalline rock. Sevier thrust faulting in the southern Spring Mountains had ceased by ~99 Ma following the deposition of the Lavinia Wash sequence that contains volcanic and Mesozoic clasts. The MSC is not correlative to the Lavinia Wash sequence because these conglomerates overlie the Jurassic Aztec Sandstone and are overlain by the ~99 Ma Sevier thrust faults consisting of Paleozoic strata. The Lavinia Wash sequence is not considered a source area for the MSC because it contains volcanic and Mesozoic clasts. Therefore, the age of the MSC based on stratigraphic evidence is less than 99 Ma and is older than 18.5 Ma. The age of the MSC can be narrowed down further by thermochronological data presented later in this thesis.

Of interest is the Horse Spring Formation that occurs northeast of the Kingman Arch throughout the Lake Mead region and on Saddle Island (Bohannon, 1984; Sewall, 1988). As
described by Parolini (1986), the 17.2 Ma basal conglomerate of the Thumb Member is strikingly similar to the MSC fanglomerate near McCullough. However, a major difference is that the Thumb Member conglomerate in its type section contains rounded clasts of Aztec Sandstone and ash-flow tuff (Parolini, 1986). Also, the conglomerates and megabreccias of the Horse Spring Formation are never seen in depositional contact on the Precambrian crystalline basement. The fact that the conglomerate on Saddle Island lacks volcanic and Mesozoic clasts and is in contact with the Precambrian crystalline basement and has been intruded by Tertiary volcanic rocks suggests that it may be correlative to MSC rather than the Thumb Member.
Site Locations for the Lucy Gray and McCullough Ranges, Clark County, Nevada

Figure 8: Index of the McCullough and Lucy Gray Ranges showing the locations of the crustal section sampled for the fission track and $^{40}\text{Ar}^{39}\text{Ar}$ thermochronologic study. Also, shown are the MSC stratigraphic column locations.
Figure 9: The upper photograph (A) is a 1 x 3 m Paleozoic (Bonanza King Formation) carbonate block within the MSC debris flow deposit. The lower photograph (B) shows the contact (solid line) between the Precambrian basement and MSC. The MSC in this part of the section is a debris flow deposit composed entirely of Precambrian crystalline clasts (lens cap is about 4 cm in diameter). Photographs are of the McCullough Spring stratigraphic section (Figures 13 and 14).
Figure 10: The upper photograph (A) shows MSC fanglomerate with an overlying Tertiary volcanic section. The lower photograph (B) shows bedding within the MSC fanglomerate (for scale the GPS is 5 x 16 cm). The fanglomerate overlies the debris flow section containing the large carbonate block (Figure 9). Photographs are of the McCullough Spring stratigraphic section (Figure 14).
Figure 11: The McClanahan Spring site (Figure 8), in the McCullough Range is a 12 m thick section of MSC that overlies Precambrian basement and underlies Tertiary volcanic rocks. At this location the 18.5 Ma Peach Springs Tuff overlies the MSC channel deposit that pinches out toward the top of the photograph. See Figure 15 for the stratigraphic column.
Figure 12: The upper photograph (A) isolated ridge on the east flank of the Lucy Gray Range showing stratigraphic relationships and location of measured sections (north, middle, and south). View is eastward toward the McCullough Range. See Figures 16, 17, and 18 for stratigraphic columns. The lower photograph (B) shows the poorly sorted, non-bedded nature of the clasts in the middle MSC stratigraphic column in the Lucy Gray Range (for scale the GPS is 5 x 16 cm). See Figure 17 for stratigraphic column.
Tertiary? debris flow
Matrix is muddy sand (carbonate rich) to sandy mud;
30-50% matrix in some bedding; iron oxide staining near middle
of section; abundant pebbles (2.5 to 2.5 cm), some cobbles
(2.5 x 10 cm; 5 x 8 cm; 7 x 7 cm); clasts include Precambrian
granite, shist, amphibolite, and gneiss; 100% Precambrian
clasts; poorly sorted, clast orientation is random; alternating
beds of pebbles and cobbles.

Iron-oxide staining

Possible fault?

Tertiary? debris flow
Matrix is sandy mud (carbonate rich); clasts are angular to
subangular; abundant pebbles (.2 to 2.5 cm), few cobbles
(2.5 x 7 cm; 7 x 7 cm); clasts include Precambrian granite,
schist, amphibolite, and gneiss; 100% Precambrian clasts;
poorly sorted, alternating beds of pebbles and cobbles.

Precambrian basement

Figure 13: McCullough Spring stratigraphic column, McCullough Range. Clast
percentages are based on qualitative estimates. See Figure 9 for photographs.
Figure 13 (continued): McCullough Spring stratigraphic column, McCullough Range. Clast percentages are based on qualitative estimates. See Figures 9 and 10 for photographs.
Figure 14: Southside McCullough Spring stratigraphic column (adjacent to McCullough Spring stratigraphic column), McCullough Range. Clast percentages are based on qualitative estimates.
Figure 15: McClanahan Spring stratigraphic column, McCullough Range. Clast percentages are based on qualitative estimates. See Figure 11 for photograph of site.
Tertiary volcanic rock
Andesitic basalt slumps down onto conglomerate, contact is sharp.

Tertiary fanglomerate
Upper: Matrix is mud (carbonate rich) with some sand near top of section clasts are more matrix supported; poorly cemented; clasts are subrounded to rounded; abundant pebbles, cobbles (10 x 20 cm), and boulders (25 x 50 cm); clasts include Precambrian granite, shist, and gneiss, Paleozoic? carbonate, tan and red quartzite.

Lower: At bottom of section is a 25 cm thick silty-mud bed moderately cemented; matrix is sandy mud (carbonate rich) moderately cemented; clasts are subangular to rounded; abundant pebbles (0.2 x 2.5 cm) and cobbles with some boulders; clasts include 15% Precambrian granite, shist, and gneiss, 83% Paleozoic? carbonate, 2% quartzite; poorly sorted.

Tertiary fanglomerate/debris flow
Upper: Matrix is sandy mud; and pebbly, sandy, mud (carbonate rich); clasts are angular to subrounded; alternating beds of abundant pebbles (0.2 to 2.5 cm) with few cobbles (2.54 x 10 cm; 5 x 8 cm) and abundant cobbles with pebbles and few boulders (10 x 26 cm; 15 x 38 cm; 25 x 50 cm); clasts include 33% Precambrian granite, schist, amphibolite, and gneiss; 65% Paleozoic? carbonate, 2% tan quartzite; poorly to moderately sorted; paleoflow appears to be southeast.

Middle: Matrix is sandy mud (carbonate rich); clasts are angular to subrounded; abundant pebbles (0.2 to 1.5 cm) and few cobbles; clasts include Precambrian granite, schist, amphibolite, gneiss; Paleozoic? carbonate; poorly sorted.

Lower: Matrix is sandy mud to muddy sand (carbonate rich); clasts are angular to subangular; alternating beds of abundant pebbles (0.2 to 2.5 cm) with few cobbles (2.54 x 7 cm; 2 x 10 cm) and abundant cobbles with pebbles and few boulders; clasts include 50% Precambrian granite, schist, amphibolite, and gneiss, 48% Paleozoic? carbonate, 2% tan and purple quartzite; poorly sorted.

Precambrian basement
Rapakivi granite sharp contact with conglomerate.

Figure 16: North stratigraphic column, Lucy Gray Range. Clast percentages are based on qualitative estimates. See Figure 12 for photograph of site location.
Tertiary volcanic rock
Andesitic basalt; clasts at contact include rounded cobbles and boulders; soil is an orange-red color.

Tertiary? fanglomerate

Upper: Matrix is sandy mud (carbonate rich); well-cemented, clasts are subangular to rounded; poorly to moderately sorted; abundant pebbles (0.2 to 2.5 cm), cobbles (5 x 7 cm; 7 x 7 cm; 8 x 15 cm), and boulders (23 x 45 cm; 30 x 60 cm); clasts include 30% Precambrian granite, schist, amphibolite, and gneiss, 65% Paleozoic? carbonate, 5% tan and purple quartzite; paleoflow appears to be southward.

Lower: Matrix is sandy mud to muddy sand (carbonate rich); clasts are subangular to slightly rounded; alternating layers of abundant pebbles (0.2 to 2.5 cm) and cobbles (2.5 x 2.5 cm; 2.5 x 13 cm; 7 x 15 cm); clasts include 35% Precambrian (generally smallest clasts), 60% Paleozoic? carbonate, and 5% red and tan quartzite; poorly sorted with some well sorted beds.

Tertiary? fanglomerate/debris flow

Upper: Matrix is sandy mud (carbonate rich); moderately cemented; mudflow with abundant boulders (15 x 25 cm; 30 x 75 cm); clasts are angular to rounded; near top of section matrix is muddy sand with alternating beds of pebbles with some cobbles and cobbles with some pebbles; 49% Precambrian, 49% Paleozoic? carbonate, 2% red, tan, and purple quartzite.

Middle: Matrix is sandy mud (carbonate rich); well cemented; clasts are angular to subangular except for some well-rounded quartzite; abundant pebbles (0.2 to 2.5 cm) with some to few cobbles; Clasts include 45% Precambrian granite, white granite with garnets, schist, amphibolite, and gneiss, 51% Paleozoic? carbonate, 4% tan, purple-brown quartzite, including a distinctive well-rounded rose and purple quartzite (1 x 3 cm); paleoflow appears to be southeast.

Lower: Matrix is muddy sand and grades upward to sandy mud (carbonate rich); clasts are angular to subangular; abundant cobbles (5 x 15 cm; 2.5 x 15 cm; 10 x 10 cm) near bottom grading upward to abundant pebbles (0.2 to 2.5 cm); clasts include 60% Precambrian granite, schist, amphibolite, and gneiss; 30% Paleozoic? carbonate; 10% tan quartzite; poorly to moderately sorted.

Precambrian basement
Contact with conglomerate is erosional

Figure 17: Middle stratigraphic column, Lucy Gray Range. Clast percentages are based on qualitative estimates. See Figure 12 for photograph of site location and clasts in part of the section.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 18: South stratigraphic column, Lucy Gray Range. Clast percentages are based on qualitative estimates. See Figure 12 for photograph of the site location.
CHAPTER 4

GEOCHRONOLOGY

Introduction

In order to determine the thermal history of the Kingman Arch, five Precambrian granite samples (Appendix I) were collected from a relatively unfaulted structural section between McCullough Spring and McClanahan Spring, in the McCullough Range (Figure 8). This 4.5 km thick structurally intact crustal block is tilted eastward about 68 degrees (see cross-section on Figure 8). Apatite separates from the Precambrian granite samples were used for fission-track dating (Appendices II and III) and K-feldspar for $^{40}\text{Ar}^{39}\text{Ar}$ analyses (Appendices II and IV). The samples were numbered MCM-1 through MCM-5. Sample MCM-1 is structurally the highest and sample MCM-5 the deepest (~ 4.5 km).

Fission tracks are formed and retained in each mineral over a range of specific temperatures (temperature zones). The temperature range over which fission tracks form and then begin to anneal is the partial annealing zone (PAZ) (Wagner, 1972; Wagner and Van Den Haute, 1992). Typically, the PAZ for apatite lies between 110°C and 60°C. In the case of the McCullough Range section, all samples originated below 110°C as indicated by steepness of the track length histogram (Figure 19). Sequential cooling of the samples (MCM-1 through MCM-5) through 60°C would result in samples nearest the surface to have older dates than samples at depth. The upper part of the section cools first followed by the lower section. Therefore, the rocks nearest the surface should
exhibit older dates than those at depth. The dates shown in Table 1 for samples MCM-2 through MCM-5 are consistent with this model except for sample MCM-1. The younger date for sample MCM-1 may suggest that it represents a deeper level of the crust, but was brought to its current location during Tertiary faulting. However, no fault has been identified.

**Fission-Track Dating**

Fission track ages are determined by the density and length of microscopic fission tracks for each mineral. The accumulation, retention, and erasure of fission tracks within minerals are highly temperature dependent. Therefore, minerals such as apatite are sensitive thermochronometers and are useful in the location of paleothermal boundaries.

The length of a fission track indicates how quickly a mineral has passed through the PAZ (Wagner, 1972; Wagner and Van Den Haute, 1992). Generally, longer tracks are indicative of a mineral moving quickly through the PAZ. Shorter tracks indicate that a mineral moved through the PAZ slowly. A bimodal length pattern indicates that tracks were moved in and out of the PAZ on more than one occasion. This pattern occurs when a mineral moves through the PAZ and then becomes reheated causing new tracks to form but the temperature is not high enough to completely anneal the older tracks (Wagner, 1972; Wagner and Van Den Haute, 1992). Finally, the mineral is moved upward through the PAZ and both sets of tracks are retained. Fission-track length data are often used to reconstruct the paleodepth and thermal history for the mineral. In Figure 13, the fission-track age, length, and precision data are shown. The track length data show steep peaks on the histograms indicative of minerals moving through the PAZ.
quickly (Wagner 1972; Wagner and Van Den Haute, 1992). Fission track data are summarized in Table 1 and provided in detail in Appendix III.

Fission-Track Thermal Modeling

The fission-track data were modeled to determine thermal paths (Figure 20) were calculated using Monte Trax, Version 8, under genetic algorithm (GA) control using 50 simulations of 50 groups matching the age, mean track length, and standard deviation (Gallagher, 1995). The annealing model is only valid between temperatures of 110°C to 60°C. For a comprehensive explanation of the Monte Trax thermal modeling program refer to Gallagher (1995).

The apatite fission-track modeling data was used to interpret the thermal history of the Precambrian section. In Figure 20, these data show that the samples cooled through the PAZ generally between 85 and 40 Ma. However, between 40-23 Ma and 40-30 Ma in samples MCM-2 and MCM-3, respectively, there was reheating. Sample MCM-2 shows reheating from 60 to 75°C. Sample MCM-3 shows reheating from 50 to 65°C, but this was not significant enough to create a bimodal pattern in the track-length data (Figure 19). However, the track lengths for sample MCM-2 are shorter than any of the other samples and may indicate slight annealing. My interpretation for the period of heating between 40-23 Ma is that it represents subsidence and may be the time of deposition of the MSC. After 23 Ma, these two samples show cooling, perhaps related to the onset of Tertiary extension and volcanism.
$^{40}$Ar/$^{39}$Ar Analyses

Samples MCM-1 and MCM-5 were selected for $^{40}$Ar/$^{39}$Ar dating because they represented the uppermost and lowest parts of the tilted Precambrian block. $^{40}$Ar/$^{39}$Ar analyses were conducted on these samples to determine the age of the samples. If the two samples yielded Precambrian ages, then no further analyses on the additional samples would be required because it would be clear that Phanerozoic tectonism had not been heated the Precambrian K-feldspars to a younger age. However, if the samples yielded ages that were younger than Precambrian, then additional K-feldspar samples could be analyzed to estimate the cooling history. The total gas age for sample MCM-1 is 909.54 Ma and for sample MCM-5 the total gas age is 893.28 (Figure 21). No additional sample analysis was required because the ages of these two samples were Precambrian.

The closure temperature for the small diffusion domains of K-feldspar for sample MCM-1 is estimated to be 220°C by modeling of the fractional $^{39}$Ar lost, heating temperature, and heating duration (T. Spell, personal communication, 2000). The $^{40}$Ar/$^{39}$Ar data infers that K-feldspar in sample MCM-1 has not been heated to temperatures exceeding 220°C since the Precambrian (~1000 Ma). The closure temperature for K-feldspar in sample MCM-5 was not modeled, however its closure temperature is estimated to be between 150-250°C (T. Spell, personal communication, 2000). Data for MCM-1 and MCM-5 indicate slow steady cooling or slight reheating based on the convex upward shape of the age spectrum for K-feldspar (Figure 21) (McDougall and Harrison, 1988). Sample MCM-1 shows the cessation of cooling or the
initiation of heating between 560-500 Ma and sample MCM-5 between 375-300 Ma based on projected Y-intercepts.
Figure 19: Apatite fission-track age, length, and precision data for the McCullough Range, Nevada
Table 1: Apatite Fission-Track Statistical and Age Data, McCullough Range, Nevada

<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>Sample 1*</th>
<th>Sample 2*</th>
<th>Sample 3*</th>
<th>Sample 4*</th>
<th>Sample 5*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of basic unit (cm&lt;sup&gt;-2&lt;/sup&gt;)</td>
<td>7.803E-07</td>
<td>7.803E-07</td>
<td>7.803E-07</td>
<td>7.803E-07</td>
<td>7.803E-07</td>
</tr>
<tr>
<td>P (CHI Squared)</td>
<td>78.8%</td>
<td>21.5%</td>
<td>44.8%</td>
<td>24.0%</td>
<td>70.6%</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>0.914</td>
<td>0.941</td>
<td>0.978</td>
<td>0.954</td>
<td>0.914</td>
</tr>
<tr>
<td>Variance of Square (Ns)</td>
<td>2.09672</td>
<td>3.096781</td>
<td>8.027153</td>
<td>4.528946</td>
<td>1.656845</td>
</tr>
<tr>
<td>Variance of Square (Ni)</td>
<td>7.356659</td>
<td>7.341695</td>
<td>25.86461</td>
<td>16.61926</td>
<td>6.809265</td>
</tr>
<tr>
<td>Ns/Ni</td>
<td>0.291+0.010</td>
<td>0.339±0.012</td>
<td>0.309±0.012</td>
<td>0.290±0.014</td>
<td>0.240±0.008</td>
</tr>
<tr>
<td>Mean Ratio</td>
<td>0.295±0.008</td>
<td>0.336±0.017</td>
<td>0.315±0.015</td>
<td>0.301±0.018</td>
<td>0.243±0.008</td>
</tr>
<tr>
<td>Mean Length</td>
<td>12.92±0.12μm</td>
<td>12.88±0.12μm</td>
<td>13.19±0.12μm</td>
<td>13.20±0.15μm</td>
<td>13.11±0.11μm</td>
</tr>
<tr>
<td><strong>Pooled Age</strong></td>
<td>61.9±2.3 Ma&lt;sup&gt;1&lt;/sup&gt;</td>
<td>73.0±2.9 Ma&lt;sup&gt;2&lt;/sup&gt;</td>
<td>67.4±2.8 Ma&lt;sup&gt;3&lt;/sup&gt;</td>
<td>64.2±3.3 Ma&lt;sup&gt;4&lt;/sup&gt;</td>
<td>53.9±2.0Ma&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Mean Age</strong></td>
<td>62.8±2.1 Ma&lt;sup&gt;1&lt;/sup&gt;</td>
<td>72.4±3.9 Ma&lt;sup&gt;2&lt;/sup&gt;</td>
<td>68.8±3.5 Ma&lt;sup&gt;3&lt;/sup&gt;</td>
<td>66.6±4.0 Ma&lt;sup&gt;4&lt;/sup&gt;</td>
<td>54.5±2.0 Ma&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Central Age</strong></td>
<td>61.9±2.3 Ma&lt;sup&gt;1&lt;/sup&gt;</td>
<td>73.0±3.0 Ma&lt;sup&gt;2&lt;/sup&gt;</td>
<td>67.7±3.1 Ma&lt;sup&gt;3&lt;/sup&gt;</td>
<td>65.0±3.8 Ma&lt;sup&gt;4&lt;/sup&gt;</td>
<td>53.9±1.9 Ma&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
<tr>
<td>% Variation</td>
<td>0.89%</td>
<td>4.00%</td>
<td>7.72%</td>
<td>10.17%</td>
<td>0.47%</td>
</tr>
</tbody>
</table>

*See Figure 8 for sample locations

<sup>1</sup>Sample 1: Ages calculated using a zeta of 379.2±3 for CN 5 glass 12.5 ppm; RHO D = 1.126E+06cm<sup>-2</sup>; ND=4364

<sup>2</sup>Sample 2: Ages calculated using a zeta of 379.2±3 for CN 5 glass 12.5 ppm; RHO D = 1.142E+06cm<sup>-2</sup>; ND=4364

<sup>3</sup>Sample 3: Ages calculated using a zeta of 379.2±3 for CN 5 glass 12.5 ppm; RHO D = 1.167E+06cm<sup>-2</sup>; ND=4364

<sup>4</sup>Sample 4: Ages calculated using a zeta of 379.2±3 for CN 5 glass 12.5 ppm; RHO D = 1.173E+06cm<sup>-2</sup>; ND=4364

<sup>5</sup>Sample 5: Ages calculated using a zeta of 379.2±3 for CN 5 glass 12.5 ppm; RHO D = 1.188E+06cm<sup>-2</sup>; ND=4364

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 20: Apatite fission-track length modeling data for the McCullough Range, Nevada.
Figure 21: Samples MCM-1 and MCM-5 K-spar $^{40}$Ar-$^{39}$Ar step-heating diagrams and data.
CHAPTER 5

EVOLUTION OF THE KINGMAN ARCH

Models of the cooling history and evolution of the Kingman Arch are depicted in Figures 22 and 23. Stage 1 is not shown in Figure 23, however, stages 2-3 are depicted in five diagrams.

Stage I – Slow Steady Cooling of the Kingman Arch

Based on $^{40}$Ar/$^{39}$Ar evidence that the Precambrian section has not been heated to temperatures exceeding $220^\circ$C since the Precambrian (~1000 Ma) and the lack of deposition of late-Precambrian sediments in southern Nevada, I suggest that the time between 1000 and about 560-500 Ma was a period of slow and steady cooling. The cooling of the Kingman Arch during this period may be attributed in part to uplift and exhumation of a rift shoulder during continental rifting (900-600 Ma) along the North American continental margin (Burchfiel et al., 1992; M. Wells, personal communication, 2000). At about 540 Ma the Cambrian Tapeats Sandstone was deposited on the Kingman Arch. By the end of the Mesozoic at least 4 km of Paleozoic section and 1 km of Mesozoic sediments were deposited (Figure 22A). Evidence for the deposition of these sediments on the arch is suggested by the presence of relatively thick sections of Paleozoic (4-5 km) and of Mesozoic (1-1.3 km) strata to the east, west, and north of the Kingman Arch that shows no indication of thinning towards the arch (Burchfiel et al., 1992; M. Wells, personal communication, 2000).
Additionally, the presence of remnant Paleozoic deposits found on or adjacent to the Kingman Arch including the large Paleozoic carbonate block in the MSC are evidence of the deposition of this section. It is interesting that the Y-intercept of the age spectrum of sample MCM-1 at between 500 and 560 Ma (Figure 21) corresponds to the time of deposition of the Cambrian Tapeats Sandstone. Based on these observations, I suggest that at about 560 Ma slow cooling of the arch changed to heating related to the deposition of the Paleozoic and Mesozoic sedimentary sections. An implication of this interpretation is that the model that considers the Kingman Arch a significant barrier to the deposition of Paleozoic and Mesozoic strata is invalid. Furthermore, the thermal model (Figure 22A) suggests that by 146 Ma deposition had ended and cooling on the Kingman Arch had resumed and by 85 Ma the Mesozoic section (1-1.3 km) appears to have been denuded from the arch.

An alternative interpretation of the data is that the projected Y-intercept ages (Figure 21) reflect a heating event related to pluton emplacement. I argue against this model for the Kingman Arch, because the Y-intercept ages for sample MCM-1 and MCM-5 are different. Pluton emplacement would most likely result in relatively instantaneous heating of the crust and thus the Y-intercepts for the samples should be similar. Furthermore, no plutons in the age range between 300 and 600 Ma are known to exist in the Kingman Arch region.

Stage II - Cooling (Laramide) and Denudation of the Kingman Arch

Cooling of the Kingman Arch continued from 85 Ma to 40 Ma (late Cretaceous to late Eocene) as evidenced by apatite fission-track data (Figures 20, and 22A and 22B). 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
The age of cooling is consistent with the age of Laramide deformation between 80-40 Ma (Cross, 1986) and is most likely related to denudation of about 2 km of Paleozoic strata and/or crustal refrigeration (Figure 22A and 22B). At the onset of Sevier thrusting (~146 Ma) there is approximately a 112°C temperature difference between the lowermost (MCM-5) and the uppermost (MCM-1) samples. However, at 80 Ma only a 10°C temperature difference separates the samples. Because evidence for Laramide structural deformation (faulting, shearing, or tilting) is lacking in the McCullough and Lucy Gray Ranges the convergence of the cooling curves must be due to sample MCM-5 cooling at a faster rate than sample MCM-1 (Figure 22A and 22B). A reasonable explanation for this variance in the thermal gradient may be crustal refrigeration (Dumitru et al., 1991). Refrigeration throughout the southwestern United States may have been caused by the subduction of a cold oceanic slab beneath the continental lithosphere.

The thickness of the Paleozoic strata removed during this period was calculated by assuming a 25°C/km geothermal gradient and using a 220°C closure temperature for K-feldspar for sample MCM-1 and a 150-250 °C closure temperature range for sample MCM-5 (Figure 22A and 22B). This calculation indicates that the maximum cumulative thickness of the Paleozoic section removed between 85 to 40 Ma did not exceed 2 km (Figure 22A and 22B). This calculation is in agreement with studies by Kelley et al. (2000) that suggest 2.7 to 4.5 km of Laramide and post-Laramide exhumation in the Grand Canyon area (Kelley et al., 2000). Therefore, my data support removal of Paleozoic strata from the Kingman Arch between the late Cretaceous and early Tertiary (Figure 23A, 23B, and 23C).
Stage III – Continued Refrigeration and Denudation, Deposition of the MSC, and Tertiary Extension and Volcanism

By 40 Ma, the cooling model (based on fission-track data) shows that the deepest samples (MCM-4 and MCM-5) had cooled to less than 60°C by 40 and 30 Ma (late Eocene to Oligocene), respectively (Figure 22B). At this time (40-30 Ma), data for sample MCM-1 (Figure 22A and 22B) indicate that about 2.5 km of Paleozoic section is present on the arch. I suggest that by 40 Ma this Paleozoic section had been dissected by east and northeast trending channels and formed plateaus on the arch (Figure 23C). Because the MSC contains clasts of Precambrian crystalline, Neoproterozoic quartzite, and Paleozoic carbonate rocks, I assume that these channels have incised into the Precambrian basement and served to transport Neoproterozoic quartzite from sources to the west and onto the Kingman Arch (Figure 23C). At 23 Ma (early Miocene), fission-track data for sample MCM-1 indicate that there was 2 km of Paleozoic section remaining on the arch and that only 0.5 km of strata had been removed between 40 and 23 (Figure 22B). Also during the period between 40 and 23 Ma, the fission-track data for samples MCM-2 and MCM-3 suggest heating, possibly related to subsidence (Figure 22B). This period of heating may correspond in part to the timing of MSC deposition (Figures 23C and 23D). Therefore, between 23 and 18.5 Ma, 2 km of Paleozoic section was stripped from the arch, and only channels with MSC remained on the Precambrian basement. At about 18.5 Ma the Peach Spring Tuff was erupted and deposited on the MSC. Following the eruption of Tertiary volcanic rocks from (about 18.5 to 15 Ma), widespread extension began throughout the CREC. The Kingman Arch was tilted,
elevated (with respect to surrounding topography), and faulted (Duebendorfer et al., 1998).
Figure 22: (A) Thermal model for the Kingman Arch. The model assumes a 4.5 km stratigraphic separation of samples MCM-1 and MCM-2, an initial thermal gradient of 25°C/km, and a closure temperature for K-feldspar of 220°C for sample MCM-1. The closure temperature for sample MCM-5 ranges from 150-250°C. The model assumes that a minimum of 0.5 km of Precambrian basement is present at the onset of Paleozoic deposition. (B) Detail of cooling model between 85 and 5 Ma. This part of the model is a summary of fission-track model data shown in Figure 20.
Figure 23: Stages II and III of the evolution for the Kingman Arch are depicted for five time periods. (A) Crustal refrigeration continues and Mesozoic section is denuded by east northeast channels, (B) Cooling of crust continues and Paleozoic section continues to be denuded and incised, (C) Cooling continues, Paleozoic section forms distinct plateaus, channels have incised into the Precambrian basement (D) MSC is deposited between 40 and 20 Ma (E) Tertiary volcanic rocks are deposited over the MSC. Onset of widespread Tertiary extension in the CREC and elevation of the Kingman Arch to its present position.
CHAPTER 6

CONCLUSION

The Kingman Arch forms a structural high in southern Nevada and northwestern Arizona that lies partially within the CREC. The age and origin of the Kingman Arch was evaluated through the consideration of two models. The first model assumes that the Paleozoic and Mesozoic strata were deposited on the Kingman Arch then subsequently eroded during Cretaceous contraction or Tertiary extension. The second model assumes that the Kingman Arch formed during the Precambrian and was a barrier to Paleozoic and Mesozoic deposition. These models were tested through the use of thermochronologic and stratigraphic data. Granite samples were collected from a 4.5 thick relatively intact Precambrian section for thermochronologic analyses. Stratigraphic data were obtained from the MSC that overlies the Precambrian basement and underlies Tertiary volcanic rocks.

The Kingman Arch experienced slow and steady cooling from about 1000 to about 560 Ma based on $^{40}\text{Ar}/^{39}\text{Ar}$ data. These $^{40}\text{Ar}/^{39}\text{Ar}$ data also suggest the cessation of cooling between 560-500 Ma that is consistent with the onset of deposition of the Cambrian Tapeats Sandstone. Thermal modeling data suggest the cumulative deposition of about 5 km of Paleozoic and Mesozoic strata on the Kingman Arch between 560 Ma
and about 146 ± 2 Ma (the onset of the Sevier Orogeny). The Paleozoic and Mesozoic sections (including up to 0.5 km of Precambrian basement) were subsequently denuded from the arch between the onset of the Sevier Orogeny and eruption of the Peach Springs Tuff (~18.5 Ma). At about 146 Ma, the thermal history model shows that cooling resumed on the arch and that the Mesozoic section (1-1.3 km) was removed from the Kingman Arch by 85 Ma. From 146 Ma, differential cooling, perhaps related to crustal refrigeration, may have caused the lowermost samples of the transect to cool more quickly than samples higher in the section. Apatite fission-track data suggest denudation of about 2 km of Paleozoic section between 85 and 40 Ma. By 40 Ma, east and northeast trending channels probably cut the Paleozoic section and exposed the Precambrian basement. Sediment was transported from the arch and from sources to the west through these channels and deposited in southwestern Utah and western Arizona. Crustal refrigeration continued through about 30 Ma and an additional 0.5 km of Paleozoic/Precambrian section was removed between 40 and 23 Ma. However, while data for the deepest sample indicates cooling at 30 Ma, samples MCM-2 and MCM-3 indicate heating (apatite fission-track data) that could be attributed to the deposition of the MSC. The MSC contains clasts of Precambrian crystalline, Neoproterozoic quartzite, and Paleozoic carbonate clasts; it lacks any volcanic or Mesozoic clasts. At 23 Ma (earliest Miocene), apatite fission-track data for sample MCM-1 indicates the presence of a 2.5 km-thick Paleozoic/Precambrian section on the arch. Between 23 and 18.5 Ma (early Miocene), most of the remaining 2 km of Paleozoic section was removed and at 18.5 Ma the eruption of the Peach Springs Tuff covered the channels containing MSC. Tertiary volcanism occurred between about 18 and 12 Ma (mid-Miocene) throughout the
CREC. After 15 Ma, Tertiary extension resulted in stratal tilting and faulting of the rocks of the Kingman Arch to a higher elevation with respect to surrounding topography.
APPENDIX I

GRANITE THIN SECTIONS MCCULLOUGH RANGE, NEVADA

The five granite samples (Figure 8) were cut into billets on an oil saw in the UNLV Geoscience Laboratory under the supervision of Clay Crow, Ph.D. The samples were then shipped to Quality Thin Sections in Tucson, Arizona. Quality Thin Sections prepared a standard thin section (27 X 46 mm) with a cover glass and stained for potassium feldspar for each billet. The thin sections were observed using a polarizing microscope. Percentages are based on qualitative estimates.

Sample MCM-1

Minerals present: 40% quartz, 35% K-spar (including microcline, perthitic orthoclase), 20% plagioclase with sercitic alteration, 5% biotite and muscovite, trace zircon, chlorite as secondary alteration

Texture: Myrmekite (quartz and plagioclase), poikioblastic (quartz and feldspar)

Sample MCM-2

Minerals present: 40% K-spar (including microcline), 30% quartz, 15% plagioclase, 5% biotite, trace zircon

59

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Texture: Lepioblastic biotite, gneissic banding

Sample MCM-3

Minerals present: 40% quartz, 25% K-spar (including microcline and perthitic orthoclase), 30% plagioclase with sericitic alteration, 5% biotite, trace apatite

Texture: intergrown quartz, micro-shearing of biotite (cataclastic deformation)

Sample MCM-4

Minerals present: 30% quartz, 35% K-spar (including microcline, perthitic orthoclase), 29% plagioclase with sericitic alteration, 6% biotite and muscovite, trace zircon, trace chlorite

Texture: recrystalized and intergrown quartz, gneissic banding with evidence of shearing (fine-grained bands of plagioclase, quartz, and K-spar)

Sample MCM-5

Minerals present: 55% K-feldspar (including microcline), 30% quartz, 10% plagioclase (fresh and small), 5% biotite (some altered to chlorite), trace zircon (euhedral), trace iron oxide

Texture: Myrmekite, intergrown and interlocking quartz, some cataclasis around k-feldspar, some fine-grained shearing
APPENDIX II

SAMPLE COLLECTION AND PREPARATION FOR GEOCHRONOLOGY

Introduction

Five rock samples were collected from the McCullough range for fission-track and $^{40}$Ar/$^{39}$Ar analyses (Figure 8). The purpose of these analyses was to determine the cooling history of the Precambrian basement in this region. The samples were collected east to west across the central McCullough Range. These samples (MCM-1 through MCM-5) represent a relatively intact structural block representing approximately the upper 4.5 km of the Precambrian basement. The samples were collected from locations described in Table 2 and shown in Figure 8. The rock samples (20-60 pounds each) were collected with a rock and/or sledge hammer and care was taken to remove any weathered surface from the samples.

Mineral Separation Procedure

Rock Crushing/Sieving

The samples were processed separately and the equipment was cleaned thoroughly between each sample. Each rock sample was broken with a sledge hammer into manageable fist size pieces before being crushed. The sample was placed in a cone
rock-crusher and milled into chips about 1-2 cm in diameter. The chips were then placed into a disk mill and ground to about 2 mm diameter. The sample was disk milled again to obtain a smaller 1 mm diameter (except for sample 4 which did not require a second milling). After the disk mill, the sample was placed in a stack of rock sieves (#10, #30, #60, and #80 mesh). The stack of sieves was placed in an automatic shaker until the sample was separated by mesh size.

**Wilfley Table**

Using the #80 mesh or smaller size mineral fraction, each sample was then further processed on a Wilfley Table to aid in separating the heavier from the lighter minerals. The Wilfley Table uses water, gravity, and a gentle shaking motion to separate the minerals. The Wilfley process takes several hours for each sample. The Wilfley Table was cleaned thoroughly between each sample. The heaviest mineral fractions (WT positions generally 1-3 and sometimes 1-6) were then taken to the laboratory and washed thoroughly with R.O. water followed by an acetone rinse. The heavier mineral fraction was allowed to dry overnight and placed in clean containers for later use. Lighter fractions from the Wilfley Table (typically WT positions 7-8) were allowed to dry by evaporation and then stored in clean containers for later use.

**Heavy Liquid Separation**

The heavier mineral fraction of each sample was further separated by use of heavy liquids (i.e., methyl iodide and bromoform). The specific gravity of Methyl Iodide is designed for the initial separation of zircon from apatite (MeI). Then subsequent
separation of the apatite fraction was conducted using Bromoform to separate apatite from quartz and feldspar. Because mineral densities vary in the Precambrian granite samples it was necessary to repeat the heavy liquid separation process more than once per sample.

Franz Separator

The Franz technique is generally the final step used for mineral separation. The technique utilizes the magnetic properties of minerals to separate mineral grains from each other into pure mineral fractions. The sample is poured through the Franz magnetic separator a few grains at a time for several runs (approximately thirteen). For each run, an electric current is applied at varying amperages and tilt angles to magnetically separate the desired mineral. After the minerals were separated using the Franz, it was sometimes necessary to run the mineral fractions through the heavy liquid separation process again to remove any persistent undesirable minerals to obtain as pure of a mineral separate as possible. The minerals separated for this thesis were zircon and apatite for fission-track analyses and K-feldspar as determined by X-ray diffraction analysis and biotite for \(^{40}\text{Ar}/^{39}\text{Ar}\) analysis.

Fission Track Methods

Zircon and apatite separates were sent to David Foster, Ph.D., at La Trobe University (also University of Florida), Australia for fission-track analysis. Melinda Mitchell prepared the zircon minerals for analyses, however, the zircon were metamict (i.e., crystal structure destroyed by too many nuclear fissions). The preparation and
analysis of the apatite grains was conducted as follows by P. O'Sullivan. Analytical procedures for apatite fission-track analysis followed the techniques described in detail by Green (1986). Apatite grains were separated from crushed samples using conventional magnetic and heavy liquid techniques, mounted in epoxy resin on glass slides, ground and polished to reveal an internal surface, and etched in 5N HNO₃ at room temperature for 20 seconds to reveal fossil fission-tracks. Samples were irradiated in the X-7 position of the Australian HIFAR Research Reactor. Thermal neutron fluences were monitored in a muscovite detector adjacent to discs of the NBS standard glass SRM612 and ages were determined using the external detector method. Fission-tracks were counted at a magnification of 1250x (dry objective) using automated Zeiss Axiotron microscopes, and only those grains orientated parallel to the c-axis that displayed sharp polishing scratches were counted. Ages were calculated using the zeta calibration method (Hurford and Green, 1983) and the central age is reported (Galbraith and Laslett, 1993). Lengths of horizontal confined fission-tracks were measured in apatite grains oriented approximately parallel to the c-axis using a drawing tube and digitizing tablet.

\[ ^{40}\text{Ar}/^{39}\text{Ar} \text{ Methods} \]

Feldspar and biotite minerals separates were provided to Terry Spell, Ph.D., University of Nevada, Las Vegas for analysis. Kathy Zanetti prepared and conducted the \[ ^{40}\text{Ar}/^{39}\text{Ar} \] analysis as follows using a MAP-215-50 mass spectrometer. Only two K-feldspar samples were analyzed because the total gas ages of the samples were very old, 910 Ma for Sample 1 (nearest the surface) and 893 Ma for Sample 5 (about 4.5 km below the surface). The individual feldspars were placed in a double vacuum furnace and
subjected to step-heating. See Appendix V for additional details on the $^{40}\text{Ar}^{39}\text{Ar}$ analysis method and procedures.
Table 2: Granite Sample Numbers and Coordinates.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>UTM</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCM-1</td>
<td>11 S 0668850</td>
<td>N35°38.811</td>
<td>W115°08.095</td>
</tr>
<tr>
<td></td>
<td>3946383</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCM-2</td>
<td>11 S 0668552</td>
<td>N35°38.750</td>
<td>W115°08.314</td>
</tr>
<tr>
<td></td>
<td>3946188</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCM-3</td>
<td>11 S 0668108</td>
<td>N35°38.645</td>
<td>W115°08.607</td>
</tr>
<tr>
<td></td>
<td>3946047</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*11 S 0668085</td>
<td>*N35°38.624</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3946021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCM-4</td>
<td>11 S 0667732</td>
<td>N35°38.671</td>
<td>W115°08.827</td>
</tr>
<tr>
<td></td>
<td>3946116</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*11 S 0667716</td>
<td>*N35°38.633</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3946031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCM-5</td>
<td>11 S 0664572</td>
<td>N35°39.821</td>
<td>W115°10.848</td>
</tr>
<tr>
<td></td>
<td>3948172</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Additional rock sample was collected from this location in order to collect a sufficient quantity of the mineral type needed for analysis. The separated minerals from the additional rock sample were combined with the mineral grains from the original sample. The additional rock sample was collected from as near the original sample location as possible.
APPENDIX III

APATITE FISSION-TRACK DATA

Apatite fission-track preparation and analyses conducted by P.O. Sullivan
LaTrobe University, Australia

Apatite fission-track modeling conducted by David Foster, Ph.D.
LaTrobe University, Australia
University of Florida, United States
(See Figure 20)
<table>
<thead>
<tr>
<th>No.</th>
<th>Ns</th>
<th>Ni</th>
<th>Na</th>
<th>Ratio (ppm)</th>
<th>Rho</th>
<th>F.T.</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>73</td>
<td>100</td>
<td>0.301</td>
<td>10.4</td>
<td>2.819E+05</td>
<td>9.355E+05</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>55</td>
<td>80</td>
<td>0.309</td>
<td>9.8</td>
<td>2.723E+05</td>
<td>8.811E+05</td>
</tr>
<tr>
<td>3</td>
<td>56</td>
<td>167</td>
<td>100</td>
<td>0.335</td>
<td>23.8</td>
<td>7.177E+05</td>
<td>2.140E+05</td>
</tr>
<tr>
<td>4</td>
<td>58</td>
<td>167</td>
<td>100</td>
<td>0.347</td>
<td>23.8</td>
<td>7.433E+05</td>
<td>2.140E+05</td>
</tr>
<tr>
<td>5</td>
<td>59</td>
<td>173</td>
<td>100</td>
<td>0.341</td>
<td>24.6</td>
<td>7.561E+05</td>
<td>2.171E+05</td>
</tr>
<tr>
<td>6</td>
<td>42</td>
<td>126</td>
<td>100</td>
<td>0.333</td>
<td>17.9</td>
<td>5.383E+05</td>
<td>1.615E+05</td>
</tr>
<tr>
<td>7</td>
<td>17</td>
<td>78</td>
<td>100</td>
<td>0.218</td>
<td>11.1</td>
<td>2.179E+05</td>
<td>9.996E+05</td>
</tr>
<tr>
<td>8</td>
<td>56</td>
<td>179</td>
<td>100</td>
<td>0.313</td>
<td>25.5</td>
<td>7.177E+05</td>
<td>2.294E+05</td>
</tr>
<tr>
<td>9</td>
<td>67</td>
<td>201</td>
<td>100</td>
<td>0.333</td>
<td>35.7</td>
<td>1.073E+06</td>
<td>3.220E+06</td>
</tr>
<tr>
<td>10</td>
<td>68</td>
<td>214</td>
<td>100</td>
<td>0.318</td>
<td>30.4</td>
<td>8.715E+05</td>
<td>2.743E+05</td>
</tr>
<tr>
<td>11</td>
<td>9</td>
<td>26</td>
<td>100</td>
<td>0.346</td>
<td>3.7</td>
<td>1.153E+05</td>
<td>3.322E+05</td>
</tr>
<tr>
<td>12</td>
<td>56</td>
<td>195</td>
<td>100</td>
<td>0.287</td>
<td>27.7</td>
<td>7.177E+05</td>
<td>2.499E+05</td>
</tr>
<tr>
<td>13</td>
<td>28</td>
<td>97</td>
<td>100</td>
<td>0.289</td>
<td>33.8</td>
<td>3.588E+05</td>
<td>1.243E+05</td>
</tr>
<tr>
<td>14</td>
<td>50</td>
<td>196</td>
<td>100</td>
<td>0.255</td>
<td>59.1</td>
<td>1.335E+06</td>
<td>5.233E+06</td>
</tr>
<tr>
<td>15</td>
<td>48</td>
<td>161</td>
<td>100</td>
<td>0.258</td>
<td>22.9</td>
<td>6.151E+05</td>
<td>2.063E+05</td>
</tr>
<tr>
<td>16</td>
<td>55</td>
<td>221</td>
<td>100</td>
<td>0.349</td>
<td>31.4</td>
<td>7.049E+05</td>
<td>2.832E+05</td>
</tr>
<tr>
<td>17</td>
<td>35</td>
<td>157</td>
<td>60</td>
<td>0.223</td>
<td>37.2</td>
<td>7.476E+05</td>
<td>3.353E+05</td>
</tr>
<tr>
<td>18</td>
<td>56</td>
<td>213</td>
<td>100</td>
<td>0.263</td>
<td>30.3</td>
<td>7.177E+05</td>
<td>2.730E+05</td>
</tr>
<tr>
<td>19</td>
<td>63</td>
<td>197</td>
<td>100</td>
<td>0.320</td>
<td>28.0</td>
<td>8.074E+05</td>
<td>2.525E+05</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
<td>83</td>
<td>100</td>
<td>0.301</td>
<td>11.8</td>
<td>3.204E+05</td>
<td>1.064E+05</td>
</tr>
<tr>
<td>21</td>
<td>59</td>
<td>196</td>
<td>100</td>
<td>0.301</td>
<td>27.9</td>
<td>7.561E+05</td>
<td>2.512E+05</td>
</tr>
<tr>
<td>22</td>
<td>47</td>
<td>153</td>
<td>100</td>
<td>0.307</td>
<td>21.8</td>
<td>6.023E+05</td>
<td>1.961E+05</td>
</tr>
<tr>
<td>23</td>
<td>45</td>
<td>223</td>
<td>100</td>
<td>0.202</td>
<td>31.7</td>
<td>5.767E+05</td>
<td>2.858E+05</td>
</tr>
<tr>
<td>24</td>
<td>30</td>
<td>88</td>
<td>100</td>
<td>0.341</td>
<td>12.5</td>
<td>3.845E+05</td>
<td>1.128E+05</td>
</tr>
<tr>
<td>25</td>
<td>57</td>
<td>225</td>
<td>80</td>
<td>0.253</td>
<td>40.0</td>
<td>9.131E+05</td>
<td>3.604E+05</td>
</tr>
</tbody>
</table>

1125 3864 23.4 6.140E+05 2.109E+06

Area of basic unit = 7.803E-07 cm-2

CHI SQUARED = 9.14977 WITH 24 DEGREES OF FREEDOM
P(chi squared) = 78.8 %
CORRELATION COEFFICIENT = 0.914
VARIANCE OF SQR(Ns) = 2.09672
VARIANCE OF SQR(Ni) = 7.356659

Ns/Ni = 0.291 ± 0.010
MEAN RATIO = 0.295 ± 0.008

**Pooled Age** = 61.9 ± 2.3 Ma  **Mean Length** = 12.92 ± 0.12 µm

Mean Age = 62.8 ± 2.1 Ma
Central Age = 61.9 ± 2.3 Ma
% Variation = 0.89%

Ages calculated using a zeta of 379.2 ± 3 for CN 5 glass 12.5 ppm
RHO D = 1.126E+06 cm-2; ND = 4364

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
### MCM-2 Apatite

**IRRADIATION LU539-08 COUNTED BY: P. O'SULLIVAN (8/19/98)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Ns</th>
<th>Ni</th>
<th>Na</th>
<th>Ns/Ni</th>
<th>RATIO</th>
<th>U(ppm)</th>
<th>rhoS</th>
<th>rhoI F.T.</th>
<th>AGE(Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52</td>
<td>143</td>
<td>100</td>
<td>0.364</td>
<td>20.1</td>
<td>6.66E+05</td>
<td>1.83E+06</td>
<td>78.3 ± 12.7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>42</td>
<td>100</td>
<td>0.143</td>
<td>5.9</td>
<td>7.68E+04</td>
<td>5.38E+05</td>
<td>30.9 ± 13.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>91</td>
<td>48</td>
<td>0.286</td>
<td>26.6</td>
<td>6.94E+05</td>
<td>2.43E+05</td>
<td>61.6 ± 13.7</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>103</td>
<td>264</td>
<td>100</td>
<td>0.390</td>
<td>37.0</td>
<td>1.32E+06</td>
<td>3.38E+05</td>
<td>83.9 ± 9.9</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>96</td>
<td>80</td>
<td>0.303</td>
<td>9.3</td>
<td>2.56E+05</td>
<td>8.45E+05</td>
<td>58.4 ± 12.9</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>83</td>
<td>48</td>
<td>0.313</td>
<td>24.3</td>
<td>6.94E+05</td>
<td>2.21E+05</td>
<td>67.5 ± 15.2</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>66</td>
<td>100</td>
<td>0.303</td>
<td>9.3</td>
<td>2.56E+05</td>
<td>8.45E+05</td>
<td>58.4 ± 12.9</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>51</td>
<td>123</td>
<td>48</td>
<td>0.415</td>
<td>35.9</td>
<td>1.36E+06</td>
<td>3.29E+05</td>
<td>89.2 ± 14.9</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>60</td>
<td>100</td>
<td>0.267</td>
<td>8.4</td>
<td>2.05E+05</td>
<td>7.69E+05</td>
<td>57.5 ± 16.2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>35</td>
<td>67</td>
<td>36</td>
<td>0.522</td>
<td>26.1</td>
<td>1.24E+06</td>
<td>3.85E+05</td>
<td>112.1 ± 23.5</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>69</td>
<td>235</td>
<td>80</td>
<td>0.294</td>
<td>41.2</td>
<td>1.10E+06</td>
<td>3.76E+05</td>
<td>63.3 ± 8.7</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>43</td>
<td>137</td>
<td>100</td>
<td>0.314</td>
<td>19.2</td>
<td>5.51E+05</td>
<td>1.76E+05</td>
<td>67.6 ± 11.9</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>60</td>
<td>90</td>
<td>0.200</td>
<td>9.4</td>
<td>1.70E+05</td>
<td>5.54E+05</td>
<td>43.2 ± 13.7</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>55</td>
<td>131</td>
<td>80</td>
<td>0.420</td>
<td>23.0</td>
<td>8.81E+05</td>
<td>2.99E+05</td>
<td>90.3 ± 14.6</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>37</td>
<td>79</td>
<td>48</td>
<td>0.468</td>
<td>23.1</td>
<td>9.87E+05</td>
<td>2.10E+05</td>
<td>100.6 ± 20.1</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>19</td>
<td>45</td>
<td>72</td>
<td>0.422</td>
<td>8.8</td>
<td>3.38E+05</td>
<td>8.01E+05</td>
<td>90.8 ± 24.9</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>20</td>
<td>76</td>
<td>60</td>
<td>0.263</td>
<td>17.8</td>
<td>4.27E+05</td>
<td>1.62E+05</td>
<td>56.7 ± 14.3</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>32</td>
<td>105</td>
<td>100</td>
<td>0.305</td>
<td>14.7</td>
<td>4.10E+05</td>
<td>1.34E+05</td>
<td>65.7 ± 13.3</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>69</td>
<td>237</td>
<td>80</td>
<td>0.291</td>
<td>41.6</td>
<td>1.10E+05</td>
<td>3.79E+05</td>
<td>62.7 ± 8.6</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>35</td>
<td>107</td>
<td>40</td>
<td>0.327</td>
<td>37.5</td>
<td>1.12E+05</td>
<td>3.42E+05</td>
<td>70.4 ± 13.8</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>43</td>
<td>111</td>
<td>80</td>
<td>0.367</td>
<td>26.0</td>
<td>9.18E+05</td>
<td>2.37E+05</td>
<td>83.3 ± 15.0</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>59</td>
<td>185</td>
<td>80</td>
<td>0.319</td>
<td>43.3</td>
<td>1.26E+05</td>
<td>3.95E+05</td>
<td>68.7 ± 10.3</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>46</td>
<td>148</td>
<td>80</td>
<td>0.311</td>
<td>26.0</td>
<td>7.36E+05</td>
<td>2.37E+05</td>
<td>66.9 ± 11.4</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>67</td>
<td>183</td>
<td>100</td>
<td>0.366</td>
<td>25.7</td>
<td>8.56E+05</td>
<td>2.34E+05</td>
<td>78.8 ± 11.3</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>33</td>
<td>74</td>
<td>48</td>
<td>0.446</td>
<td>21.6</td>
<td>8.11E+05</td>
<td>1.97E+05</td>
<td>95.8 ± 20.1</td>
<td></td>
</tr>
</tbody>
</table>

| 1000 | 2948 | 22.3 | 6.89E+05 | 2.03E+06 |

**Area of basic unit** = 7.803E-07 cm²

**Chi Squared** = 14.56376 WITH 24 DEGREES OF FREEDOM

P(chi squared) = 21.5 %

**Correlation Coefficient** = 0.941

**Variance of SQR(Ns)** = 3.096781

**Variance of SQR(Ni)** = 7.341695

Ns/Ni = 0.339 ± 0.012

Mean Ratio = 0.336 ± 0.017

**Pooled Age** = 73.0 ± 2.9 Ma  **Mean Length** = 12.88 ± 0.12 μm

Mean Age = 72.4 ± 3.9 Ma

Central Age = 73.0 ± 3.0 Ma

% Variation = 4.00%

Ages calculated using a zeta of 379.2 ± 3 for CN 5 glass 12.5 ppm

RHO D = 1.142E+06 cm⁻²; ND = 4364

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
**MCM-3 Apatite**

**IRRADIATION LU539-09** COUNTED BY: P. O'SULLIVAN (8/19/98)

<table>
<thead>
<tr>
<th>No.</th>
<th>Ns</th>
<th>Ni</th>
<th>Ratio</th>
<th>U(ppm)</th>
<th>RHo S</th>
<th>RHo I</th>
<th>F.T.</th>
<th>AGE(Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>34</td>
<td>0.382</td>
<td>5.9</td>
<td>2.083E+05</td>
<td>5.447E+05</td>
<td>83.3 ± 27.2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>46</td>
<td>126</td>
<td>0.365</td>
<td>21.8</td>
<td>7.369E+05</td>
<td>2.018E+06</td>
<td>79.6 ± 13.8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>99</td>
<td>0.374</td>
<td>13.7</td>
<td>4.742E+05</td>
<td>1.269E+06</td>
<td>81.5 ± 15.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>31</td>
<td>0.387</td>
<td>5.4</td>
<td>1.922E+05</td>
<td>4.966E+05</td>
<td>84.4 ± 28.7</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>76</td>
<td>0.197</td>
<td>13.2</td>
<td>2.403E+05</td>
<td>1.217E+06</td>
<td>43.2 ± 12.2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>20</td>
<td>0.450</td>
<td>2.8</td>
<td>1.153E+05</td>
<td>2.563E+05</td>
<td>98.0 ± 39.4</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>27</td>
<td>0.296</td>
<td>3.7</td>
<td>1.025E+05</td>
<td>3.460E+05</td>
<td>64.7 ± 26.1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>117</td>
<td>404</td>
<td>0.290</td>
<td>55.9</td>
<td>1.499E+06</td>
<td>5.177E+06</td>
<td>83.3 ± 6.7</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td>40</td>
<td>0.325</td>
<td>5.5</td>
<td>1.666E+05</td>
<td>5.126E+05</td>
<td>70.9 ± 22.7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>23</td>
<td>0.174</td>
<td>3.2</td>
<td>5.126E+04</td>
<td>2.948E+05</td>
<td>38.0 ± 20.6</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>15</td>
<td>36</td>
<td>0.417</td>
<td>8.3</td>
<td>7.404E+05</td>
<td>3.096E+06</td>
<td>90.8 ± 27.9</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>48</td>
<td>0.229</td>
<td>6.6</td>
<td>1.410E+05</td>
<td>6.151E+05</td>
<td>50.1 ± 16.8</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>73</td>
<td>335</td>
<td>0.218</td>
<td>46.4</td>
<td>9.355E+05</td>
<td>4.293E+06</td>
<td>47.6 ± 6.2</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>8</td>
<td>43</td>
<td>0.186</td>
<td>6.0</td>
<td>1.025E+05</td>
<td>5.511E+05</td>
<td>40.7 ± 15.7</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>94</td>
<td>293</td>
<td>0.321</td>
<td>50.7</td>
<td>1.506E+06</td>
<td>4.694E+06</td>
<td>70.0 ± 8.4</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>70</td>
<td>179</td>
<td>0.391</td>
<td>31.0</td>
<td>1.121E+06</td>
<td>2.867E+06</td>
<td>85.2 ± 12.1</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>89</td>
<td>273</td>
<td>0.326</td>
<td>37.8</td>
<td>1.141E+06</td>
<td>3.499E+06</td>
<td>71.1 ± 8.8</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>11</td>
<td>51</td>
<td>0.216</td>
<td>8.8</td>
<td>1.762E+06</td>
<td>8.170E+06</td>
<td>47.1 ± 15.7</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>7</td>
<td>20</td>
<td>0.350</td>
<td>4.3</td>
<td>1.402E+05</td>
<td>4.005E+05</td>
<td>76.3 ± 33.5</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>13</td>
<td>41</td>
<td>0.317</td>
<td>8.9</td>
<td>2.603E+05</td>
<td>8.210E+05</td>
<td>69.2 ± 22.1</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>137</td>
<td>421</td>
<td>0.325</td>
<td>58.3</td>
<td>1.756E+06</td>
<td>5.395E+06</td>
<td>71.0 ± 7.1</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>35</td>
<td>98</td>
<td>0.357</td>
<td>32.3</td>
<td>1.068E+06</td>
<td>2.990E+06</td>
<td>77.9 ± 15.4</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>26</td>
<td>85</td>
<td>0.306</td>
<td>19.6</td>
<td>5.553E+05</td>
<td>1.816E+06</td>
<td>68.8 ± 15.0</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>19</td>
<td>59</td>
<td>0.322</td>
<td>12.8</td>
<td>3.805E+05</td>
<td>1.181E+06</td>
<td>70.3 ± 18.6</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>17</td>
<td>47</td>
<td>0.362</td>
<td>6.5</td>
<td>2.179E+05</td>
<td>6.023E+05</td>
<td>73.9 ± 22.4</td>
<td></td>
</tr>
</tbody>
</table>

| 899 | 2909 | 19.1 | 5.450E+05 | 1.764E+06 |

Area of basic unit = 7.803E-07 cm-2

**Chi Squared** = 12.12338 with 24 degrees of freedom

**P(Chi squared)** = 44.8 %

**Correlation Coefficient** = 0.978

**Variance of SQR(Ns)** = 0.027153

**Variance of SQR(Ni)** = 25.86461

Ns/Ni = 0.309 ± 0.012

**Mean Ratio** = 0.315 ± 0.015

**Pooled Age** = 67.4 ± 2.8 Ma

**Mean Length** = 13.19 ± 0.12 μm

Mean Age = 68.8 ± 3.5 Ma

Central Age = 67.7 ± 3.1 Ma

% Variation = 7.72%

Ages calculated using a zeta of 379.2 ± 3 for CN 5 glass 12.5 ppm

RHO D = 1.157E+06 cm-2; ND = 4364

Central Age = 67.7 ± 3.1 Ma

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
<table>
<thead>
<tr>
<th>No.</th>
<th>Ns</th>
<th>Ni</th>
<th>Na</th>
<th>RATIO</th>
<th>U(ppm)</th>
<th>RHOs</th>
<th>RHOI F.T.</th>
<th>AGE(Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>99</td>
<td>42</td>
<td>0.354</td>
<td>32.2</td>
<td>1.068E+06</td>
<td>3.021E+06</td>
<td>78.2 ± 15.4</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>40</td>
<td>72</td>
<td>0.350</td>
<td>7.6</td>
<td>2.492E+05</td>
<td>7.120E+05</td>
<td>77.4 ± 24.1</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>71</td>
<td>60</td>
<td>0.366</td>
<td>16.2</td>
<td>5.553E+05</td>
<td>1.517E+05</td>
<td>80.9 ± 18.6</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>24</td>
<td>50</td>
<td>0.208</td>
<td>6.6</td>
<td>1.282E+05</td>
<td>6.151E+05</td>
<td>46.2 ± 22.7</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>71</td>
<td>80</td>
<td>0.239</td>
<td>12.1</td>
<td>2.723E+05</td>
<td>1.137E+05</td>
<td>53.0 ± 14.3</td>
</tr>
<tr>
<td>6</td>
<td>19</td>
<td>88</td>
<td>60</td>
<td>0.216</td>
<td>20.0</td>
<td>4.058E+05</td>
<td>1.880E+05</td>
<td>47.8 ± 12.1</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>49</td>
<td>42</td>
<td>0.204</td>
<td>15.9</td>
<td>3.051E+05</td>
<td>1.495E+05</td>
<td>45.2 ± 15.7</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>77</td>
<td>48</td>
<td>0.195</td>
<td>21.9</td>
<td>4.005E+05</td>
<td>2.056E+05</td>
<td>43.2 ± 12.2</td>
</tr>
<tr>
<td>9</td>
<td>17</td>
<td>47</td>
<td>60</td>
<td>0.362</td>
<td>10.7</td>
<td>3.631E+05</td>
<td>1.004E+05</td>
<td>79.9 ± 22.7</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>37</td>
<td>90</td>
<td>0.405</td>
<td>5.6</td>
<td>2.136E+05</td>
<td>5.269E+05</td>
<td>89.5 ± 27.4</td>
</tr>
<tr>
<td>11</td>
<td>81</td>
<td>378</td>
<td>100</td>
<td>0.214</td>
<td>51.6</td>
<td>1.038E+06</td>
<td>4.844E+06</td>
<td>47.5 ± 5.9</td>
</tr>
<tr>
<td>12</td>
<td>33</td>
<td>103</td>
<td>100</td>
<td>0.320</td>
<td>14.1</td>
<td>4.229E+05</td>
<td>1.320E+06</td>
<td>70.9 ± 14.2</td>
</tr>
<tr>
<td>13</td>
<td>27</td>
<td>69</td>
<td>80</td>
<td>0.391</td>
<td>11.8</td>
<td>4.325E+05</td>
<td>1.105E+06</td>
<td>86.4 ± 19.7</td>
</tr>
<tr>
<td>14</td>
<td>59</td>
<td>183</td>
<td>56</td>
<td>0.322</td>
<td>44.6</td>
<td>1.350E+06</td>
<td>4.188E+06</td>
<td>71.3 ± 10.7</td>
</tr>
<tr>
<td>15</td>
<td>65</td>
<td>213</td>
<td>64</td>
<td>0.305</td>
<td>45.5</td>
<td>1.302E+06</td>
<td>4.265E+06</td>
<td>67.5 ± 9.6</td>
</tr>
<tr>
<td>16</td>
<td>97</td>
<td>309</td>
<td>90</td>
<td>0.314</td>
<td>46.9</td>
<td>1.381E+06</td>
<td>4.400E+06</td>
<td>69.4 ± 8.2</td>
</tr>
<tr>
<td>17</td>
<td>25</td>
<td>71</td>
<td>100</td>
<td>0.352</td>
<td>9.7</td>
<td>3.204E+05</td>
<td>9.099E+05</td>
<td>77.8 ± 18.2</td>
</tr>
</tbody>
</table>

Area of basic unit = 7.803E-07 cm-2

CHI SQUARED = 9.783471 WITH 16 DEGREES OF FREEDOM
P(chi squared) = 24.0 %
CORRELATION COEFFICIENT = 0.954
VARIANCE OF SQR(Ns) = 4.528946
VARIANCE OF SQR(Ni) = 16.61926

Ns/Ni = 0.290 ± 0.014
MEAN RATIO = 0.301 ± 0.018

Pooled Age = 64.2 ± 3.3 Ma  Mean Length = 13.20 ± 0.15 μm
Mean Age = 66.6 ± 4.0 Ma
Central Age = 65.0 ± 3.8 Ma
% Variation = 10.17%

Ages calculated using a zeta of 379.2 ± 3 for CN 5 glass 12.5 ppm
RHO D = 1.173E+06 cm-2;  ND = 4364

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
**MCM-5** Apatite

**IRRADIATION LU539-11 COUNTED BY: P. O'SULLIVAN (8/20/98)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Ns</th>
<th>Ni</th>
<th>Na</th>
<th>RATIO</th>
<th>U(ppm)</th>
<th>RHOS</th>
<th>RHOi F.T.</th>
<th>AGE(Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44</td>
<td>191</td>
<td>80</td>
<td>0.230</td>
<td>32.2</td>
<td>7.049E+05</td>
<td>3.060E+06</td>
<td>51.7 ± 8.7</td>
</tr>
<tr>
<td>2</td>
<td>64</td>
<td>244</td>
<td>100</td>
<td>0.262</td>
<td>32.9</td>
<td>8.202E+05</td>
<td>3.127E+06</td>
<td>58.8 ± 8.3</td>
</tr>
<tr>
<td>3</td>
<td>69</td>
<td>251</td>
<td>100</td>
<td>0.275</td>
<td>33.8</td>
<td>8.843E+05</td>
<td>3.217E+06</td>
<td>61.6 ± 8.4</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>194</td>
<td>100</td>
<td>0.247</td>
<td>26.2</td>
<td>6.151E+05</td>
<td>2.486E+06</td>
<td>55.5 ± 9.0</td>
</tr>
<tr>
<td>5</td>
<td>42</td>
<td>157</td>
<td>80</td>
<td>0.268</td>
<td>26.5</td>
<td>6.728E+05</td>
<td>2.515E+06</td>
<td>60.0 ± 10.5</td>
</tr>
<tr>
<td>6</td>
<td>34</td>
<td>123</td>
<td>64</td>
<td>0.276</td>
<td>25.9</td>
<td>6.808E+05</td>
<td>2.463E+06</td>
<td>62.0 ± 12.1</td>
</tr>
<tr>
<td>7</td>
<td>37</td>
<td>121</td>
<td>100</td>
<td>0.306</td>
<td>16.3</td>
<td>4.742E+05</td>
<td>1.551E+06</td>
<td>45.6 ± 6.8</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>143</td>
<td>100</td>
<td>0.175</td>
<td>19.3</td>
<td>3.204E+05</td>
<td>1.833E+06</td>
<td>39.3 ± 8.5</td>
</tr>
<tr>
<td>9</td>
<td>53</td>
<td>253</td>
<td>80</td>
<td>0.209</td>
<td>42.6</td>
<td>8.430E+05</td>
<td>4.053E+06</td>
<td>47.0 ± 7.1</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>238</td>
<td>100</td>
<td>0.252</td>
<td>32.1</td>
<td>7.699E+05</td>
<td>3.050E+06</td>
<td>56.5 ± 8.2</td>
</tr>
<tr>
<td>11</td>
<td>15</td>
<td>89</td>
<td>100</td>
<td>0.169</td>
<td>12.0</td>
<td>1.922E+05</td>
<td>1.141E+06</td>
<td>37.9 ± 10.6</td>
</tr>
<tr>
<td>12</td>
<td>68</td>
<td>279</td>
<td>100</td>
<td>0.244</td>
<td>37.6</td>
<td>8.715E+05</td>
<td>3.576E+06</td>
<td>54.7 ± 7.5</td>
</tr>
<tr>
<td>13</td>
<td>54</td>
<td>266</td>
<td>100</td>
<td>0.203</td>
<td>35.9</td>
<td>6.920E+05</td>
<td>3.409E+06</td>
<td>45.6 ± 6.8</td>
</tr>
<tr>
<td>14</td>
<td>35</td>
<td>133</td>
<td>100</td>
<td>0.263</td>
<td>17.9</td>
<td>4.485E+05</td>
<td>1.704E+06</td>
<td>59.0 ± 11.3</td>
</tr>
<tr>
<td>15</td>
<td>28</td>
<td>140</td>
<td>80</td>
<td>0.200</td>
<td>23.6</td>
<td>4.485E+05</td>
<td>2.243E+06</td>
<td>44.9 ± 9.3</td>
</tr>
<tr>
<td>16</td>
<td>58</td>
<td>209</td>
<td>100</td>
<td>0.278</td>
<td>28.2</td>
<td>7.433E+05</td>
<td>2.678E+06</td>
<td>62.2 ± 9.3</td>
</tr>
<tr>
<td>17</td>
<td>30</td>
<td>139</td>
<td>100</td>
<td>0.216</td>
<td>18.7</td>
<td>3.845E+05</td>
<td>1.781E+06</td>
<td>48.4 ± 9.8</td>
</tr>
<tr>
<td>18</td>
<td>73</td>
<td>281</td>
<td>100</td>
<td>0.260</td>
<td>37.9</td>
<td>9.355E+05</td>
<td>3.601E+06</td>
<td>58.3 ± 7.7</td>
</tr>
<tr>
<td>19</td>
<td>53</td>
<td>233</td>
<td>100</td>
<td>0.227</td>
<td>31.4</td>
<td>6.792E+05</td>
<td>2.986E+06</td>
<td>51.0 ± 7.8</td>
</tr>
<tr>
<td>20</td>
<td>55</td>
<td>232</td>
<td>80</td>
<td>0.237</td>
<td>39.1</td>
<td>8.811E+05</td>
<td>3.717E+06</td>
<td>53.2 ± 8.0</td>
</tr>
<tr>
<td>21</td>
<td>18</td>
<td>60</td>
<td>60</td>
<td>0.300</td>
<td>13.5</td>
<td>3.845E+05</td>
<td>1.282E+06</td>
<td>67.2 ± 18.1</td>
</tr>
<tr>
<td>22</td>
<td>63</td>
<td>280</td>
<td>100</td>
<td>0.225</td>
<td>37.8</td>
<td>8.074E+05</td>
<td>3.588E+06</td>
<td>50.5 ± 7.1</td>
</tr>
<tr>
<td>23</td>
<td>54</td>
<td>169</td>
<td>50</td>
<td>0.320</td>
<td>45.6</td>
<td>1.384E+06</td>
<td>4.323E+06</td>
<td>71.8 ± 11.3</td>
</tr>
<tr>
<td>24</td>
<td>39</td>
<td>161</td>
<td>100</td>
<td>0.242</td>
<td>21.7</td>
<td>4.998E+05</td>
<td>2.063E+06</td>
<td>54.3 ± 9.7</td>
</tr>
<tr>
<td>25</td>
<td>65</td>
<td>339</td>
<td>100</td>
<td>0.192</td>
<td>45.7</td>
<td>8.330E+05</td>
<td>4.344E+06</td>
<td>43.0 ± 5.9</td>
</tr>
</tbody>
</table>

Area of basic unit = 7.803E-07 cm^-2

CHI SQUARE = 9.916311 WITH 24 DEGREES OF FREEDOM
P(chi squared) = 70.6 %
CORRELATION COEFFICIENT = 0.914
VARIANCE OF SQR(Ns) = 1.656845
VARIANCE OF SQR(Ni) = 6.809265

Ns/Ni = 0.240 ± 0.008
MEAN RATIO = 0.243 ± 0.008

**Pooled Age = 53.9 ± 2.0 Ma**  **Mean Length = 13.11 ± 0.11 µm**

Mean Age = 54.5 ± 2.0 Ma
Central Age = 53.9 ± 1.9 Ma
% Variation = 0.47%

Ages calculated using a zeta of 379.2 ± 3 for CN 5 glass 12.5 ppm
RHO D = 1.188E+06 cm^-2; ND = 4364

---

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
APPENDIX IV

NEVADA ISOTOPE GEOCHRONOLOGY LABORATORY PROCEDURES

POTASSIUM FELDSPAR $^{40}\text{Ar}/^{39}\text{Ar}$ STEP-HEATING DATA

(Terry Spell, Ph.D., personal communication, 2000)
Samples analyzed by the $^{40}$Ar/$^{39}$Ar method contained approximately 1 mg of potassium feldspar. Each sample package was wrapped in aluminum foil and stacked in a 6 mm (inside diameter) Pyrex(r) tube. Individual packets averaged 3 mm thick and neutron fluence monitors (ANU 92-176, Fish canyon Tuff sanidine) were placed every 5-10 mm along the tube. Synthetic K-glass and optical grade CaF$^2$ were included in the irradiation packages to monitor neutron induced argon interferences from K and Ca. Loaded tubes were packed in an aluminum container for irradiation. Samples were irradiated for 3 hours in the D3 position on the core edge (fuel rods on three sides, moderator on the fourth side) of the 1MW TRIGA type reactor at the Nuclear Science Center at Texas A&M University. Irradiations are performed in a dry tube device, shielded against thermal neutrons by a 5 mm thick jacket of B$^4$C powder, which rotates about its axis at a rate of 0.7 revolutions per minute to mitigate horizontal flux gradients. Correction factors for interfering neutron reactions on K and Ca were determined by repeated analysis of K-glass and CaF$^2$ fragments. Measured ($^{40}$Ar/$^{39}$Ar)K values were $1.38 \times 10^{-2} \pm 22.0\%$. Ca correction factors were ($^{36}$Ar/$^{37}$Ar) Ca = $2.782 \times 10^{-4} \pm 1.2\%$ and ($^{39}$Ar/$^{37}$Ar) Ca = $6.919 \times 10^{-4} \pm 1.6\%$. J factors were determined by fusion of 4-5 individual crystals of 92-176 which gave reproducibilities better than 0.5% at each standard position. Variation in the neutron flux along the 100 mm length of the irradiation tube was <4%. An error in J of 0.5% was used in age calculations. No significant neutron flux gradients were present within individual packets of samples as indicated by the excellent reproducibility of the single crystal flux monitor fusions. Neutron fluence monitors were analyzed in a Cu sample tray in a high vacuum extraction.
line and were fused using a 20 W CO\textsuperscript{2} laser. Sample feldspars were analyzed by the furnace step-heating method which uses a double vacuum resistance furnace. Reactive gases were removed by single MAP and two GP-50 SAES getters prior to being admitted to a MAP 215-50 mass spectrometer by expansion. The relative volumes of the extraction line and mass spectrometer allow ~80% of the gas to be admitted to the mass spectrometer. Peak intensities were measured using a Blazers electron multiplier by peak hopping through 7 cycles; initial peak heights were determined by linear regression to the time of gas admission. Mass spectrometer discrimination and sensitivity were monitored by repeated analysis of atmospheric argon aliquots from an on-line pipette system. Measured \(^{40}\text{Ar}/^{36}\text{Ar}\) ratios were 290.03 +/- 0.17% and 290.73 +/- 0.48% during this work, thus discrimination corrections of 1.01641 and 1.01886 were applied to measure isotope ratios. The sensitivity of the mass spectrometer was ~6 x 10^{-17} \text{ mol mV}^{-1} with the multiplier operated at a gain of ~30 over the Faraday. Furnace blanks averaged 1.98 x 10^{-16} \text{ mol} for mass 40 and 7.2 x 10^{-18} for mass 36. Discrimination, sensitivity, and blanks were relatively constant over the period of data collection. Computer automated operation of the sample stage, laser, extraction line, and mass spectrometer as well as final data reduction were conducted using LabVIEW software written by B. Idleman (Lehigh University). 

An age of 27.9 Ma (Steven et al. 1967; Cebula et al., 1986) was used for the Fish Canyon Tuff sanidine flux monitor in calculating ages for samples. All analytical data are reported at the confidence level of 1\sigma (standard deviation). Total gas age is based on a weighted calculation:

\[ \%^{39}\text{Ar for each step/ S} \times \%^{39}\text{Ar released} \times \text{Age (Ma)} \text{ for each step} \]
REFERENCES CITED


Cebula, G.T., Kunk, M.J., Mehnert, H.H., Naeser, C.W., Obradovich, J.D., and Sutter, 1986, The Fish Canyon Tuff, a potential standard for the $^{40}\text{Ar}/^{39}\text{Ar}$ and fission-track dating methods (abstract), Terra Cognita (6th International Conference on Geochronology, Cosmochronology, and Isotope Geology), v. 6, p. 139.


Lucchitta, Ivo, 1966, Cenozoic geology of the upper Lake Mead area adjacent to the Grand Wash Cliffs, Arizona [Ph. D. dissert.]: University Park, Pennsylvania State University.
McDougall, I., and Harrison, T.M., 1988, Geochronology and thermochronology by the $^{40}$Ar/$^{39}$Ar Method: Oxford University Press, 212 p.


Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.


VITA

Graduate College
University of Nevada, Las Vegas

Juliana Marie Herrington

Local Address:
Henderson, Nevada 89015

Degrees:
Bachelor of Science, Geology, 1993
University of Nevada, Las Vegas

Special Honors and Awards:
Bernada E. French Scholarship, 1998

Publications:

Thesis Title: Evolution of the Kingman Arch, southern Nevada

Thesis Examination Committee:
Chairperson, Dr. Eugene I. Smith, Professor, Ph.D.
Committee Member, Dr. Michael Wells, Associate Professor, Ph.D.
Committee Member, Dr. Stephen Rowland, Professor, Ph.D.
Committee Member, Dr. Diane Pyper-Smith, Associate Professor, Ph.D.

83