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Climatic and Structural Controls on the Geomorphology of Wadi Sana, Highland Southern Yemen

Joshua Michael Anderson
University of South Florida

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Climatic and Structural Controls on the Geomorphology of Wadi Sana, Highland Southern Yemen

by

Joshua Michael Anderson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science Department of Geology College of Arts and Sciences University of South Florida

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Date of Approval: April 12, 2007

Keywords: Yemen, RASA, Wadi Hadramawt, paleoclimate, geochronology, paleohydrology

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Dedication

I would like to dedicate this work to my loving family who supported my efforts with love, understanding, and compassion. I would especially like to dedicate this research to my daughter Ysabella.
Acknowledgments

I would like to thank Dr. Rick Oches for being a great friend and mentor. Without his patience and understanding, this thesis would not be possible. I would like to thank all of the members of the RASA team including Dr. Joy McCorriston, Mike Harrower, Catherine Heine, and others. My experience in Yemen would not have been so inspiring without our Yemeni colleagues from GOAMM including, Abdulazziz Bin’ Aquil, and Abdal Bassat Noman. I thank Nexen Inc. for their support of the project in Yemen. Finally, I would like to thank the National Science Foundation for their grant BCS-0211490 in support of this project.
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Joshua Michael Anderson

ABSTRACT

Middle Holocene climate change forced significant environmental response and influenced human activities throughout southern Arabia. Climate models and proxy data indicate that climate along the southern Arabian peninsula changed from a moist phase, spanning the early to middle Holocene, to an arid phase, which persisted for the last ca. 5,000 years. A weakening and southward shift of the Southwest Indian Monsoon System, forced by northern hemisphere insolation variations in the precession band and/or glacial boundary conditions, is suggested as the mechanism for the abrupt shift to more arid conditions. Geoarchaeological evidence suggests that agriculture was more widespread and evolved alongside the development of irrigation technologies during a period when rainfall was more plentiful than today. Here we investigate the surficial record of the dynamic fluvial response to the late Quaternary climate shift and reconstruct the geochronology of the geomorphic evolution of a significant portion of the ca. 125 km length of Wadi Sana, a north-flowing tributary to the Wadi Hadramout system. Using differential-corrected GPS-based survey, combined with analysis of the sedimentary record, the RASA (Roots of Agriculture in Southern Arabia) Project has created a paleohydrologic reconstruction of Wadi Sana in order to provide a context for understanding how fluvial landscapes, hydrologic regime, and human activity reacted to changing middle Holocene climate. Radiocarbon and luminescence dating of remnant silt terraces suggests that fine-grained sediment began accumulating on an older (late-Pleistocene) coarse cobble surface between 12,000-7,000 years ago and continued aggrading until about 5,000 years ago. Paralleling the climate shift, Wadi Sana began incising and eroding the thick sediment infilling about 4,500 years ago, which has continued to the present time. Field reconnaissance and map analysis reveals structural and lithologic controls on the source and availability of these fluvial sediments for
downstream deposition during the late Pleistocene and Holocene. Hydrologic modeling of active present-day channels within Wadi Sana estimates stream velocities at 2.2 m/s and stream discharges of 444 m³/s. We propose that a change in hydrologic regime, driven by the monsoon shift, is the cause of the middle Holocene channel adjustment from an aggradational to incising mode in Wadi Sana.
1. Introduction

Middle Holocene climate change forced significant environmental response and influenced human activities throughout southern Arabia. Climate models and proxy data indicate that climate along the southern Arabian peninsula changed from a moist phase, spanning the early to middle Holocene, to an arid phase, which persisted for the last ca. 5,000 years (Burns et al. 1998, Kutzbach 1981, Kutzbach et al. 1998, Prell & Kutzbach 1987, McClure 1976, 1984, Roberts & Wright 1993, Prell & Van Campo 1986, Van Campo et al. 1982, Fontugne & Duplessy 1986, Whitney 1983, Fleitmann et al., 2003, 2007). A weakening and southward shift of the Southwest Indian Monsoon System (see Figure 1), forced by northern hemisphere insolation variations in the precession band and/or post-glacial boundary conditions, is suggested as the mechanism for the shift to more arid conditions (Kutzbach 1981, Kutzbach et al. 1998, Prell & Kutzbach 1987, COHMAP 1988). Geoarchaeological evidence from Wadi Sana, a north-flowing tributary to the Wadi Hadramout system in highland southern Yemen (see Figure 2), suggests that agriculture was more widespread and evolved alongside the development of irrigation technologies during the early to middle Holocene, when rainfall was more plentiful than today (McCorriston & Oches 2001, McCorriston et al. 2002, Harrower 2006). Recent investigations by the RASA (Roots of Agriculture in Southern Arabia) Project aim to provide information on the response of Wadi Sana’s fluvial geomorphology to late Quaternary climatic variations in a region where terrestrial paleoclimate records, paleohydrologic data, and depositional histories have not been previously studied.

Through geoarchaeological survey, the RASA Project has investigated the surficial record of the dynamic fluvial response to the middle Holocene climate shift and documented an archaeological record of Neolithic artifacts, human settlement, and water management structures (Harrower 2006) along the ca. 125 km length of Wadi Sana (Figure 3). This research focuses on the paleohydrologic and geomorphic response to documented late Quaternary climate
change in the Wadi Sana drainage basin. The primary hypothesis that we are testing is that a change in hydrologic regime, driven by climate change, is the cause of a channel adjustment from an aggrading to incising mode in Wadi Sana. Radiocarbon and luminescence dating of remnant silt terraces suggests fine-grained sediment accumulated on an earlier (late Pleistocene) coarse cobble terrace surface between about 12,000 - 5,000 years ago. Incision and erosion of the thick fine-grained sediment infilling began about 5,000 years ago and has continued to the present. Eroded sandy-silt terraces, underlying coarse gravel deposits, and active channels throughout the studied reach provided the geomorphic framework necessary to reconstruct the depositional history for the study area. Regional climatic history, modern precipitation data,
structural geology and lithology provide additional context in the reconstruction of the Wadi Sana drainage evolution during the late Quaternary.

1.1 Research Questions

The research questions posed to address the main hypothesis as well as the approach used are listed below:

- Based on the geochronological ages for wadi sediments, what controls the timing of deposition and incision? What mechanisms control the downstream deposition and incision of wadi silts? High-resolution geochronology, climatic proxy records, and existing maps for the area are tools used to investigate this research question.
What flow regimes existed within the fluvial system throughout the late quaternary evolution of Wadi Sana? Estimates of flow conditions based on present rainfall data, grain-size, channel slope, and hydraulic geometry assist in determining how changing climatic regimes shaped the fluvial landscape of Wadi Sana.

In the context of sediment production, availability and transport, what are likely sources of the sandy silt deposits that infilled Wadi Sana along the study reach? The complex drainage network, lithology, stratigraphy and bedrock structural features in the upper reaches of Wadi Sana provide the necessary materials for investigating this research question. The timing and processes of wadi silt deposition contributes to our understanding of the relationship between paleoenvironment and the archaeological record.

1.2 Research Objectives

The objectives of this research attempt to reconstruct paleoenvironments of human occupation and define geomorphological mechanisms operating during changing hydrological regimes throughout the Holocene. The following research objectives are central to our investigation of the hypothesis:

- Develop high-resolution chronology for the sedimentary paleorecord of environmental changes associated with the changing Holocene climatic regime in Wadi Sana.
- Analyze existing precipitation data and estimate hydraulic flow conditions for the present hydrologic regime in order to better understand the late-Holocene arid phase fluvial geomorphology.
- Develop a conceptual model to explain the mechanisms and controls involved in the reconstruction of the geomorphological evolution of the fluvial system.

Massive remnant sandy silt deposits in the floor of Wadi Sana preserve a time-series of local environmental histories and sedimentary processes in the study area. With a high-resolution chronology of the sedimentary sequences in Wadi Sana, developed using radiocarbon and luminescence dating techniques, Geographic Information System (GIS) mapping tools, and
field reconnaissance; we have reconstructed the Holocene geomorphic and climatic history of Wadi Sana. This research area in southern Yemen, with its well-preserved landscapes shaped by late Quaternary environmental processes, provides an innovative context to resolve highland southern Yemen’s terrestrial record of past climate, environmental change and the human adaptive response.

1.3 Study Area and Regional Geology

Geologic maps provided by Nexen Inc., RASA Project satellite imagery, and GIS were used to create a digital elevation model and map of the drainage basin (Figure 3) and cross-section (Figure 4) of the region, illustrating the structural, lithological, and stratigraphic sequences. Wadi Sana is the main trunk of a 3,294 km² north-south trending drainage basin located in the Hadramout Province of highland southern Yemen (Figures 2 and 3). A brief summary of the regional geologic setting is described here, synthesized from Beydoun (1964). The peninsula of southern Arabia is situated adjacent to the tectonic triple junction of the Red Sea, Arabian Sea, and east African rifts. Uplift, faulting and erosion have produced a dissected landscape in a desolate and largely inaccessible region in the highlands of southern Yemen (Figure 2). A long, east-west fault in the South Hadramout structural arch of Paleocene limestones produced rugged mountains adjacent to the coastal plain, a steep limestone escarpment, and a large uplifted plateau known as the Southern Jol. The Southern Jol, 150 km (N-S) x 500 km (E-W), dips to the north and east, with its watershed extending through headward erosion close to the southern escarpment. Long drainage channels, or wadis, have incised the bedrock and flow northward into the west-east flowing Wadi Hadramout, formed in the synclinal structural depression near the northern boundary of the Southern Jol plateau.

Erosion impacted the rock units of the plateau differently. The Rus and Jeza formations, consisting of Eocene shales, marls, thin limestone and gypsum deposits, comprise the highest elevations in the southern regions of the plateau. The Rus and Jeza formations have been eroded, producing sediment that was transported northward, where aeolian and fluvial action deposited thick sediments derived from Rus and Jeza formations in the wadi bottoms. Underlying the Jeza Fm is the more indurated Paleocene Umm-ar-Rhaduma Limestone. This
unit eroded more slowly to produce bare rock plateaus, karstic dissolution features, and entrenched wadis north of the Southern Jol escarpment. Wadi Sana is an entrenched drainage network, incised into bedrock since Miocene uplift of the southern Arabian carbonate platform. A cross sectional schematic of Wadi Sana is shown on Figure 4.

The Wadi Sana drainage basin study area is not well documented due, in part, to the remote setting, sparse population, and limited access to the region. Literature is limited, and small-scale maps and air photos have been historically difficult to obtain. Prior to the Yemen unification in 1991, the study area was part of communist South Yemen, and availability of maps was closely restricted. Today, the region lies with the concession blocks of several oil companies, which consider detailed geologic information to be proprietary data. Generalized geologic maps obtained from RASA Project supporter, Nexen, Inc, provide local lithology and structure for the Wadi Sana drainage system in a geographic region where little geo-spatial data are otherwise available. From those maps and ground-based observations, we identified structural features crossing Wadi Sana that act as significant geologic controls on fluvial processes. Most importantly, structural control of the Wadi Sana drainage system is most significant along the upstream reaches of the fluvial system. The drainage system is divided into an upper and lower sub-basin by a series of east-west trending normal faults, located north of the town of Ghayl bin Yumain (see Figures 3 and 4). The faulting produced two different geomorphic landscapes on the north (footwall) block and on the south (hanging wall) block. The area north of the north block consists of expansive, uplifted terraces of Jeza and Umm-ar-Rhaduma limestone, downcut by steep-walled canyons; we refer to this as the lower sub-basin (Figures 5 and 6). The fluvial geomorphology of the area south of the faults is described here as an uplifted sedimentary basin with components of the Rus and Jeza formations still present in the upstream reaches of the drainage network. Large volumes of carbonate and siliciclastic sediment are located within this sedimentary basin (Figure 7). A generalized channel cross section is shown on Figure 8. A structural restriction at the boundary between the upper and lower sub-basins was created by the normal faulting, resulting in significant differences in the landscapes and fluvial geomorphology in each sub-basin. This structural restriction also regulates the timing and mode of sediment transport between the upper and lower sub-basins.
Figure 3. Wadi Sana drainage basin. Points A, B, and C correspond to locations shown in figures 7, 5, and 6, respectively.
**Figure 4. Drainage basin cross section (Nexen, Inc.)**

**Legend:**
- **TERTIARY**
  - Ts: Units not depicted below
  - Tm
  - Th
  - Tr
  - Tj1
  - Tu

**CRETACEOUS**
- K: Tawilah or Mahra Group - mixed sandstone and carbonate

**JURASSIC**
- J: Amran Group - Sandstone, siltstone, shale, marl and limestone.

**Lithology:**
- Rus Fm: Thin bedded dolomite, limestone marl, gypsum & anhydrite - dominantly evaporite. (Lower to mid-Eocene)
- Jeza Fm (Upper Member): Well bedded limestone and dolomite with chert nodules. (Lower Eocene)
- Jeza Fm - Nodular, chalky, fossiliferous limestone, thin beds of shale. (Upper to lower Eocene)
- Umm er Radhuma Fm - Massive limestone, partly nodular and chalky. Dolomite in the lower part. (Paleocene)
Figure 5. Photo of canyon section of Wadi Sana north of the normal fault system.
Figure 6. Photo of Wadi Sana looking downstream from Khuzma.
Figure 7. Photos of the upper Wadi Sana sub-basin showing incised sediments in Figure 7A and Rus formation lithology in Figure 7-B.
Changing sedimentary and fluvial processes are ultimately driven by late Quaternary climatic variations in the southern Arabian region.

1.4 Evolution of Climate and the Environment

The evolution of climate and the environment in southern Arabia during the Holocene is interpreted to be a transition from moister conditions, with enhanced precipitation, in the early Holocene to drier conditions from the middle Holocene to present. Modern precipitation data for the Hadramout Province in Yemen is limited. No local precipitation data for Wadi Sana is available. However, monthly totals of precipitation from 1981 to 2002 were obtained from a government gauging station approximately 70 km northwest from the study area, in the city of Seiyun. Details are summarized in Table 1. The collection methodology is unknown for this data set. Analysis of these data reveals a 22 year average of 74.2 mm/yr (± 42.8mm) with a range of 8.4 mm (1988) to 175.6 mm (1989). The 1989 maximum annual total of 175.6 mm represents 11% of the total 22 year precipitation record. Figure 9 shows annual rainfall totals.
Table 1. Monthly precipitation totals recorded in Seiyun, Yemen.

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<td>0.0</td>
<td>0.0</td>
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<td>79.6</td>
</tr>
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</table>

Sum 54.0 130.4 373.1 268.5 70.2 96.5 172.0 323.3 44.0 90.7 7.7 2.5 1632.8
Hist. Maximum 33.0 57.4 111.5 61.2 37.8 65.8 38.9 68.1 34.1 38.5 4.5 2.5 175.6
Mean 2.5 5.9 17.0 12.2 3.2 4.4 7.8 14.7 2.0 4.1 0.4 0.1 74.2
Stand. Dev. 7.1 15.5 30.4 20.2 8.7 14.6 10.7 17.7 7.3 9.3 1.1 0.5 42.8
Figure 9. Annual precipitation totals for Seiyun dataset.

Figure 10. Mean of monthly precipitation from 1981-2002 for Seiyun dataset.
for the period of record. Annual precipitation distribution is summarized by plotting the monthly mean over the period of record on Figure 10. Analysis of Figure 10 shows a bimodal distribution of precipitation occurring during the spring months, March and April, and the late summer month of August. Mediterranean climatic influence causes Arabian Peninsula precipitation and cloud cover during winter and spring. Late summer precipitation shows a linkage with the Southwest Indian Monsoon. A histogram showing monthly precipitation totals (Figure 11) (months with no precipitation are outliers and omitted) and their frequency distribution. The March 1989 total is the highest magnitude event occurring over the 22 year period, and the lowest magnitude interval class (0.1 mm to 5 mm) shows the greatest frequency (Figure 12).

![Figure 11. Histogram of months reporting precipitation and their frequency distribution.](image-url)
Holocene climatic variability is documented through terrestrial and marine proxy data from the southern Arabian Peninsula and surrounding regions. General circulation models (GCMs) indicate that a mid-Holocene shift in precipitation conditions over the southern Arabian Peninsula is due to changes in orbital parameters with subsequent effects on the Southwest Indian Monsoon. Proxy data and GCM reconstructions are summarized below.

Few land-based proxy records of late-Pleistocene and Holocene climate change exist in the southern Arabian peninsula (Roberts & Wright 1993, Hoelzmann et al. 1998). The terrestrial proxy records that do exist show a period of increased moisture during the early to middle-Holocene, from about 10 kya to 6 kya. During that period, higher lake levels (McClure 1976, 1984, Lezine et al. 1998), paleoclimate signatures derived from stable isotope geochemistry of groundwater carbonates (Clark & Fontes, 1990), and paleosols (de Maigret et al. 1989, Fedele 1992, Wilkinson 1997, Brinkmann 1996) within the study region, show increased moisture.

Figure 12. Monthly precipitation maximums for the Seiyun 1981-2002 dataset.
Speleothem research in adjacent Oman provides an innovative tool for reconstructing paleoclimates and paleohydrology in southern Arabia. U-Th age dating and stable isotope measurements of speleothems from caves in Oman yield high-resolution, precisely dated paleoclimate information from the region (Burns et al. 1998, 2001, Neff et al. 2001, Fleitmann et al. 2003, 2007). Paleoclimate information is derived from stalagmites from several proxies, including oxygen and carbon isotope ratios of speleothem carbonate (Bar-Matthews et al. 1997; Dorale et al. 1998). Thickness variations of growth layers can be related to climate in near surface caves in areas with a strong annual climate cycle (Baker et al. 1993). Stalagmite samples from near-surface caves in Oman are proximal to the study area and precisely dated producing an excellent proxy for comparison of other paleoclimate research within the study region (Burns et al. 1998, 2001, Neff et al. 2001, Fleitmann et al. 2003, 2007). Speleothem research in southern Arabia demonstrates that precipitation conditions for southern Arabia are found to reflect wetter conditions during the early Holocene than for the present arid climatic regime (Burns et al. 1998, 2001, Neff et al. 2001). The timing of precipitation decline has been documented by Fleitmann et al. (2003, 2007) through work from stalagmites in Southern Oman and Yemen. A gradual decrease in precipitation beginning after ~8 ky B.P. is inferred from a shift toward modern δ18O values along the stalagmite (Figure 13). This decline in monsoonal intensity indicates southward migration of the mean summer ITCZ in response to changing Northern Hemisphere summer solar insolation. Decadal to multi-decadal variations in monsoon precipitation are linked to solar activity fluctuation throughout the overall decline where increases in solar activity have been correlated with increases in Southwest Indian Monsoon precipitation (Bhattacharyya & Narasimha 2005).

and Arabian Sea provide the best evidence for changing climate since the last glaciation (e.g., Clemens & Prell 1990, Anderson & Prell 1993, Prell & Van Campo 1986, Van Campo et al. 1982, Sirocko et al. 1993, Overpeck et al. 1996, Cullen et al. 2000, Sarkar et al. 2000, Luckge et al. 2001, Gupta et al. 2003), but they do not typically show the resolution of land-based records. These marine records consistently show a pattern of weaker monsoon during glacial times, significantly enhanced early-to-middle Holocene monsoon, followed by a distinctly weaker monsoon since about 5 ky B.P.

Climate models combined with paleoclimate proxy data suggest that precipitation over the Arabian Peninsula is largely regulated by the strength of the southwest Indian Monsoon (Roberts & Wright 1993, Prell & Kutzbach 1987). The strength of the monsoon appears to be
controlled by precession-forced northern hemisphere insolation and glacial boundary conditions (SST’s, ice volume, albedo, CO₂) (summarized by Overpeck et al. 1996, Braconnot et al. 2000). Periods of abrupt change in moisture balance in continental paleoclimate records from the Arabian peninsula and adjacent regions coincide with shifts in the intertropical convergence zone (ITCZ) and monsoon intensity documented in continuous sediment cores from the Indian Ocean and Arabian Sea (deMenocal & Bloemendal 1995, Cullen et al. 2000). The timing of the climate shifts during the late Quaternary on a regional scale was found to include an abrupt initial monsoonal enhancement, while decline in monsoonal precipitation was gradual (Kutzbach et al. 1996, Naqvi & Fairbanks 1996). Geochronologic reconstruction in the fluvial sediments of Wadi Sana stands to provide a terrestrial context for comparison with model predictions.

General circulation models (GCMs) of climate and regional paleoenvironmental proxy records of the middle-Holocene indicate a major climatic shift with the southward displacement of the ITCZ and retreat of the southwest Indian monsoon, accompanied by a decline in precipitation across southern Arabia 8-5 ky B.P. (Burns et al. 1998, Kutzbach 1981, Kutzbach et al. 1998, Prell & Kutzbach 1987, COHMAP 1988, McClure 1976, 1984, Roberts & Wright 1993, Prell & Van Campo 1986, Van Campo et al. 1982, Fontugne & Duplessy 1986, Whitney 1983). Sensitivity studies of GCMs coupled with vegetation models suggest that there are significant positive feedbacks between vegetation and climate that may be important in explaining middle-Holocene climate changes in East Africa and Arabia (Ganopolski et al. 1998, Hoelzmann et al. 1998, Kutzbach et al. 1998, deNoblet-Ducoudre et al. 2000). Locally, this feedback mechanism is important to consider, because a decrease in vegetation cover in Wadi Sana will contribute to erosion and sediment yield.
2. Field and Laboratory Research Methods

Our working hypotheses and specific research objectives of this study were addressed through geoarcheological survey of the ca. 125 km length of Wadi Sana. Using differential-corrected GPS-based survey, combined with field and lab analysis of the sedimentary record, this research reconstructs the fluvial geomorphology and paleohydrology of Wadi Sana in order to provide a context for understanding how fluvial landscapes, hydrologic regime, and human activity reacted to changing Holocene climate.

2.1 Geochronology

Reconstruction of high-resolution geochronology for representative sediment profiles evaluates details of the timing and rates of sediment aggradation, incision and paleosol formation. 30 samples were collected at selected sediment profiles along the wadi to provide age constraints on the longitudinal and vertical extent of silts distributed throughout the reach. Accelerator Mass Spectrometry (AMS) radiocarbon dating and Optically Stimulated Luminescence (OSL) dating techniques were employed in the reconstruction. Radiocarbon samples consisted of 19 charcoal fragments sampled and a single terrestrial gastropod shell (Table 2). 10 OSL samples were collected from selected sediment profiles and provide ages when sediment profiles lack organic material suitable for radiocarbon dating (Table 3). The University of Arizona AMS Radiocarbon Lab analyzed the radiocarbon samples and OSL analyses were performed at the Leibnitz Institute of Applied Geosciences, Hannover, Germany, under the supervision of Dr. Manfred Frechen.

A generalized view of Wadi Sana stratigraphy is shown in Figure 8. Selected sediment profile locations sampled for geochronological data along Wadi Sana are shown in Figure 14. The profiles were investigated for evidence of dateable material and sampled in situ. AMS samples were collected from interpreted slackwater deposits within caves and erosional notches
and wadi silt terraces (including paleochannels within the terraces); that stratigraphically overlie the gravel terrace. Seven OSL samples were collected from sand lenses within the gravel terrace. Three OSL samples were collected from wadi silt sections to provide age constraints when no organic material was available for $^{14}$C dating. The dominantly carbonate composition of wadi silt sediments, with only minor amounts of feldspar and quartz, increases the range of

Table 2. RASA project radiocarbon ages for silts along Wadi Sana.

<table>
<thead>
<tr>
<th>#</th>
<th>RASA SAMPLE #</th>
<th>LAB #</th>
<th>ENVIRONMENTAL SETTING</th>
<th>STRATIGRAPHIC CHARACTERIZATION</th>
<th>$^{14}$ C yr BP</th>
<th>cal yr BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>04 WS 4(1)</td>
<td>AA61078</td>
<td>Fluvial slackwater cave deposit</td>
<td>Upper WS sandy silt</td>
<td>4545 ± 45</td>
<td>5195 ± 101</td>
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<tr>
<td>2</td>
<td>04WS 17(1)</td>
<td>AA59756</td>
<td>Fluvial slackwater cave deposit</td>
<td>Upper WS sandy silt</td>
<td>4633 ± 40</td>
<td>5386 ± 58</td>
</tr>
<tr>
<td>3</td>
<td>04WS 17(4)</td>
<td>AA59757</td>
<td>Fluvial slackwater cave deposit</td>
<td>Upper WS sandy silt</td>
<td>4721 ± 56</td>
<td>5458 ± 98</td>
</tr>
<tr>
<td>4</td>
<td>04WS 7(0.7)</td>
<td>AA59763</td>
<td>Fluvial slackwater deposit</td>
<td>Middle WS sandy silt</td>
<td>5329 ± 42</td>
<td>6110 ± 73</td>
</tr>
<tr>
<td>5</td>
<td>04 WS 6</td>
<td>AA59763</td>
<td>Fluvial slackwater &quot;oxbow&quot; deposit</td>
<td>Middle WS sandy silt</td>
<td>5402 ± 42</td>
<td>6208 ± 61</td>
</tr>
<tr>
<td>6</td>
<td>04 WS 18</td>
<td>AA61077</td>
<td>Fluvial slackwater deposit</td>
<td>Middle WS sandy silt</td>
<td>5765 ± 45</td>
<td>6571 ± 58</td>
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<tr>
<td>7</td>
<td>04WS 7(3.6)</td>
<td>AA59760</td>
<td>Fluvial slackwater deposit</td>
<td>Middle WS sandy silt</td>
<td>5842 ± 43</td>
<td>6653 ± 63</td>
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<tr>
<td>8</td>
<td>04WS 8</td>
<td>AA59762</td>
<td>Fluvial slackwater &quot;oxbow&quot; deposit</td>
<td>Middle WS sandy silt</td>
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<td>6815 ± 87</td>
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<tr>
<td>9</td>
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<td>AA59764</td>
<td>Fluvial slackwater deposit</td>
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<td>7334 ± 62</td>
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<tr>
<td>10</td>
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<td>AA59765</td>
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<td>9252 ± 52</td>
<td>10417 ± 89</td>
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<tr>
<td>11</td>
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<td>Fluvial sand</td>
<td>Lower WS sandy silt</td>
<td>10254 ± 55</td>
<td>12028 ± 184</td>
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Note: Samples shown above are from the 2004 field season (collected by Anderson & Oches). Samples shown below were not collected by Anderson and are taken with permission from previous RASA research along Wadi Sana.

<table>
<thead>
<tr>
<th>#</th>
<th>98 Hearth #13</th>
<th>OS16947</th>
<th>Fluvial slackwater deposit</th>
<th>Middle WS sandy silt (contamination problem?)</th>
<th>680 ± 35</th>
<th>624 ± 46</th>
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<td>12</td>
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<td>OS16958</td>
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<td>5368 ± 70</td>
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<td>OS18691</td>
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<td>5530 ± 70</td>
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<td>14</td>
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<td>AA38380</td>
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<td>6293 ± 69</td>
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<td>5750 ± 45</td>
<td>6560 ± 60</td>
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<td>Middle WS sandy silt</td>
<td>5880 ± 55</td>
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<td>6933 ± 52</td>
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<tr>
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<td>AA38381</td>
<td>Fluvial slackwater deposit</td>
<td>Middle WS sandy silt</td>
<td>6246 ± 58</td>
<td>7149 ± 90</td>
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</tbody>
</table>

Note: Samples shown above are from the 2004 field season (collected by Anderson & Oches). Samples shown below were not collected by Anderson and are taken with permission from previous RASA research along Wadi Sana.

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error of OSL dating results. At one section, a suite of samples consisting of charcoal and gastropod carbonate material were collected in combination with an OSL sediment sample from the same stratigraphic layer in an attempt to better understand the geochronological accuracy of the different sample materials and techniques.

2.2 Wadi Sediment Supply

Research questions pertaining to sediment availability, source, and transport mechanisms were investigated through field reconnaissance during the RASA 2004 and 2005 field seasons and analysis of available maps. Previous investigations were concentrated within the central Khuzma as Shumlya (Khuzma) region of drainage network and were unable to locate a source for the fine grained wadi silt terrace sediments prevalent throughout the study reach. Field observations were made upstream of the Khuzma and along the expansive plateaus surrounding Wadi Sana. Details of sediment availability and source lithology were observed, interpreted and documented. Geologic maps and satellite imagery were analyzed for wadi sediment source locations and basic geologic and structural controls.
Figure 14. RASA geochronology sample locations. Numbers correspond to sample identification numbers on Tables 2 and 3.
2.3 GPS-Based Survey

Differential-corrected GPS-based surveying technology was utilized to map cross sectional channel transects and longitudinal profiles along Wadi Sana. Transect locations are shown on Figure 15. A Trimble Pro-XRS GPS backpack system was used to record data points in the field. GPS-based survey provided the geographic data necessary to map relevant fluvial geomorphic surfaces and channel hydraulic geometry rapidly. Cross sectional transects perpendicular to the flow direction and longitudinal profiles were recorded throughout the study reach by logging a 3-dimensional point every second while traversing the wadi. Geomorphic features within transects were recorded by standing stationary at a point and taking an average of approximately 30 multiple readings (at one second intervals) to obtain a 3-dimensional location with better confidence and thus minimizing the impact of outlier points created by insufficient satellite information.

Geomorphic surfaces, reflecting stages of deposition, fluvial incision and dissection of the wadi sediments were categorized and recorded into a database during the GPS-based survey. The classification scheme included the following geomorphic surfaces and their descriptions. A schematic diagram and representative stratigraphic sequence of the wadi sediment profiles is shown in Figure 8:

- **Active Channel Gravels (ACG)** – the currently incising portion of the wadi that resides at the deepest point along a perpendicular transect across the wadi. The grain size of the carbonate sediments within the ACG unit ranges from pebbles to boulders;
- **Gravel Terrace (GT)** – a laterally continuous bed of carbonate pebbles through boulders that originates at the flanks of the ACG unit. The gravel terrace is the lowest stratigraphic unit in the wadi sediment profile sequence;
- **Wadi Silts (WS)** – interpreted flood deposits dominantly consisting of carbonate grains ranging from silt to sand, with the majority of the grains classified as silts. These silts are stratigraphically overlying the GT unit and are also well preserved within erosional notches and caves found throughout the wadi canyon walls. Wadi silts were separated into three major stratigraphic subdivisions in order to estimate the timing of deposition. The stratigraphically highest wadi silt sediments, found in caves and erosional notches
Figure 15. GPS-based survey locations for the ACG flow surface in Wadi Sana.
along the canyon wall, are interpreted to be the upper limit of deposition and are
classified as the upper wadi silt unit. Dates from incised wadi silt terrace profiles are
divided into middle wadi silt unit and lower wadi silt unit based on their relative
stratigraphic position within the unit;

- **Bedrock Slope (BS)** – portions of the canyon walls that form steep angles from the
  plateaus residing above the canyon down into the active wadi;
- **Paleostage Indicator (PSI)** – a continuous erosional notch identified throughout the
  lower Wadi Sana sub-basin. The PSI erosional notch is hypothesized here to be
  caused by historical flooding along this elevation above the current streambed. Caves
  and notches along the PSI contain upper wadi silt unit sediments representing the
  uppermost distribution of fine-grained sediments.

### 2.4 GIS Analysis

GIS systems provide the fluvial geomorphologist with innovative tools for river system
mapping and spatial analysis. ArcGIS technologies were utilized in spatial analysis of the fluvial
system and figure production from satellite imagery and GPS-based survey data. Fluvial system
characteristics including stream length, drainage area, and drainage pattern analysis were
investigated using GIS technologies. Other GIS analyses included remote sensing techniques
(Harrower 2006), such as satellite imagery mapping and georectification, and Digital Elevation
Model (DEM) production. These tools were integral to the spatial analysis of Wadi Sana.

### 2.5 Fluvial Hydrology Estimation Techniques

The primary hypothesis to be tested contends that a change in hydrologic regime is the
cause of channel adjustment in Wadi Sana. An understanding of Wadi Sana’s fluvial hydrology
is critical in evaluating how flow regimes might have operated throughout the late Quaternary.
The remote location of the study area and infrequent flow events require dry-channel estimation
techniques of flow conditions. Flow regime estimation included the field measurement of
channel hydraulic geometry, channel gradient, and channel sediment grain size. In the absence
of measured flow data, Shield’s dimensionless shear stress equation was used to estimate a
water column depth and the Manning equation was used to estimate flow velocity. Monthly precipitation data from the town of Seiyun were analyzed by techniques described previously to determine patterns in precipitation events for the present hydrologic regime.

Field measurement techniques and calculations for channel geometry and grain size measurements are summarized below:

- **Three-dimensional hydraulic geometry data necessary for discharge calculations** were obtained by using GPS survey data for channel width of the ACG flow surface and Shield’s dimensionless shear stress equation (Shield’s 1936) for water column depth above the streambed. Hydraulic geometry parameter measurements are described below:
  
  Wetted perimeter (P) values are the sum of the GPS-surveyed channel width and 2H (height of fluid column from Shield’s equation):

  \[
P = W + 2H
  \]

  ACG channel cross sectional area (A) is the mathematical product of the total measured width, W, of the channel and the height of the fluid column, H (Shield’s 1936):

  \[
  A = W \times H
  \]

  Hydraulic radius (R) is the mathematical quotient of (A) divided by (P):

  \[
  R = \frac{A}{P}
  \]

- **The friction slope, **S_f** or energy gradient was calculated from geotransect ACG channel elevations and the total distance of the study reach.** These measurements and calculations were completed using GIS analysis combined with GPS-based survey data.

- **Grain size dimensions of channel sediments were measured to obtain a median grain size (d_{50}) value for the active channel bed and the gravel terrace in Wadi Sana.** A straight section of channel was selected for measurement at one active channel surface and one gravel terrace surface. At each location, a measuring tape was
extended parallel to flow direction along the bed of Wadi Sana and gravels, cobbles and boulders were measured for their length, width, and height at every 0.5 meter interval for 25 total meters. Grain size measurements at these locations are assumed to be a representative value for Wadi Sana.

➢ Shield’s dimensionless shear stress equation (Shields 1936) was applied to assist in the estimation of the channel depth parameter and to test the hypothesis that the present ACG channel is currently being incised. The shear stress equation is shown below:

\[ \Theta = \frac{(H \cdot s)}{(\rho_f / \rho - 1) \cdot d_{50}} \]

where \( \Theta \) is a dimensionless critical shear stress value that is equal to 0.045 for most hydraulically rough channel beds (Komar, 1988), \( H \) is the height of the fluid column above the channel bed, \( s \) is the slope or energy gradient, \( \rho_s \) is the density of the sediment grain composing the channel bed, \( \rho \) is the density of the fluid, and \( d_{50} \) is the median grain size of the sediment at the channel bed fluid interface. Rearrangement of the above equation to solve for the height of the fluid column, \( H \), provides a critical channel depth necessary to entrain and move the median grain size sediment composing the channel bed:

\[ H = \frac{(\rho_f / \rho - 1) \cdot d_{50} \cdot \Theta}{s} \]

➢ Arid system (mid-Holocene to present) channel velocity was estimated for the ACG flow surface using the one-dimensional Manning’s equation technique:

\[ V = \frac{a}{n} \cdot R^{2/3} \cdot S^{1/2} \]

where \( V \) is velocity, \( a \) is a constant that is equal to 1 for metric units, \( n \) is a roughness coefficient called Manning’s \( n \), and \( S \) is friction slope or energy gradient (Chow 1959). The hydraulic radius, \( R \), is equal to \( A/P \), where \( A \) is cross sectional area and \( P \) is the wetted perimeter. Cross sectional area, hydraulic radius, and wetted perimeter were measured during the GPS-based survey of Wadi Sana, whereas Manning’s \( n \) was
estimated based on streambed roughness and field measurements of grain size, including the median grain size.

- Stream discharge \((Q)\) is calculated as the product of cross sectional area \((A)\) and stream velocity \((V)\). Discharge estimates for the ACG flow surface are made to estimate the minimal flow necessary to incise the channels and construct the current geomorphology of the study reach.

\[
Q = V \times A
\]

Quantification of discharge, velocity and shear stress assist in the understanding of how the current fluvial regime is operating and incising the lower reach of Wadi Sana. The difficulty of reconstructing paleochannel geomorphology and fluvial paleo-discharge estimates is well documented (summarized by Williams 1988). The current state of fluvial incision within Wadi Sana has removed much of the required material necessary for paleodischarge estimation over the past ca. 4,500 years. However, dated fluvial sediments within the wadi provide a qualitative framework for comparison with the current fluvial system. Attempts are made here to analyze the distribution of interpreted flood sediments deposited during the early Holocene moist phase and compare them with the current fluvial hydrology reconstruction.
3. Results

3.1 Geochronology

Using radiocarbon and OSL dating techniques, the geochronology of late Quaternary sediment deposition was reconstructed throughout the studied reach of Wadi Sana. AMS radiocarbon and OSL dating results are summarized on Table 1 and Table 2, respectively. Radiocarbon ages were calibrated using the CalPal radiocarbon calibration program (Weninger, B., Jöris, O, and Danzeglocke, U., 2004: www.calpal.de). OSL samples have larger standard deviations compared with radiocarbon data. The reported errors for OSL ages are inherent for the technique. Geochronology samples (04WS-3 a, b, and c) were taken for age control from approximately the same horizontal position within the middle wadi silt unit. An OSL sample was taken from fluvial sands adjacent to a gastropod shell and charcoal material sampled for 14C dating. Results indicate that the charcoal (7,334 ± 62 cal yr BP) and OSL (7,040 ± 1,100) samples are in general geochronologic agreement, and the gastropod shell (12,028 ± 184 cal yr BP) yields a much older age estimate (Tables 2 and 3). Uptake of older carbon by the gastropod shell during growth is likely to be the source of this discrepancy. Alternatively, the shell might have been reworked from older sediments. Figure 14 shows the geographic distribution of age estimates along the studied reach, and Figure 13 presents the frequency distribution of those ages. Geochronology results are summarized below from the lowest (earliest) to the highest (latest) stratigraphic units. The succession of stratigraphic units progresses from the gravel terrace unit up through the lower, middle, and upper wadi silt terrace.

Fluvial sediments exposed through incision reveal an abrupt contact between the gravel terrace (GT) and wadi silt (WS) stratigraphic units throughout the study reach. Dating results from six OSL samples taken from sand lenses in the upper part of exposed GT sediment ranged from 6,550 ± 1400 (04 WS 19) to 22,400 ± 3,300 (04 WS 13) yr BP. Three samples from
the lower WS yield $^{14}$C age estimates ranging from $7,334 \pm 62$ (98 Hearth #14) to $12,028 \pm 184$ (04 WS 3b) cal yr BP. The contact between the GT and lower WS represents the beginning of WS deposition throughout the late Pleistocene to early Holocene.

WS profiles interpreted in the field to represent the middle to upper WS layers were dated, and ages are correlative throughout the study reach of Wadi Sana. Eleven middle Wadi Silts charcoal samples were collected, and $^{14}$C age estimates ranged from $624 \pm 46$ (98 Hearth #13) to $7,149 \pm 55$ cal yr BP. 98 Hearth #13 is in stratigraphic disagreement with the rest of the samples. That age is considered anomalous and could be related to the shallow depth of the sample located on an erosional surface or contamination. Five charcoal were taken from upper Wadi Silts throughout the reach and range in age from $5,195 \pm 101$ (98 Cave Sed #1) to $5,530 \pm 70$ (04 WS 17 [4]) cal yr BP. Voids in the limestone above the PSI elevation did not contain sediments or dateable material while caves and erosional notches contained sediment available for sampling (Figure 16). The absence of sediment within the higher elevation caves indicates the upper limit of middle-Holocene wadi silt deposition.

3.2 Wadi Sana Field Reconnaissance and Map Analysis

Field reconnaissance and map analysis were employed to address the research questions associated with the potential source for wadi silt sediments and transport availability. Research questions pertaining to sediment availability, source, and transport mechanisms were investigated through field reconnaissance during the RASA 2004 field season. No source for wadi silts was located within the previously studied reach because the plateaus adjacent to the channel system are covered in thin desert pavement surfaces overlying the Jeza and Uhmm-a-Rhadumma limestone. Field observations upstream of the study reach identified different stratigraphy and lithology near the town of Ghayl bin Yumain. Date palm farming operations and other agricultural activities are presently ongoing throughout a wide sediment-filled basin surrounded by highlands consisting of erodable limestone, shales, marls and evaporites characteristic of the Rus and Jeza formations. Figure 7 shows expansive silt deposits and evaporitic lithology within the upper Wadi Sana sub-basin illustrated on Figure 3. Beydoun 1964 identified the Jeza formation as the source for thick wadi sediment infilling throughout the
Figure 16. Stranded wadi silts located in caves (16-A) and erosional notches (16-B,C) in Wadi Sana (Photos Oches 2004).
southern Jol. The Rus Formation is composed of highly erodable lithology and is considered here to be the primary source of fine-grained sediments seen downstream in Wadi Sana.

Field observations of upstream sediment supply were compared to lithologic-structure geologic maps provided to the RASA project by Nexen, Inc. The Rus and Jeza Formations described above and summarized from Beydoun 1964 are located upstream of the studied reach and separated from the lower drainage system by a series of normal faults. Structural features coupled with climate change are interpreted in this research to control sediment production, availability and downstream transport. Figures 17 and 18 present a conceptual model as a working hypothesis to explain sediment production, transport, and availability. The upper drainage basin located upstream of the series of normal faults (Figure 3) contains the lithology and location necessary to suggest a potential source for wadi silt sediments. The cross section shown in Figure 4 shows that the normal faulting creates accommodation space for sediment aggradation within the sedimentary basin surrounding Ghayl bin Yumain. This system is partially isolated from the downstream studied reach by faulting, allowing the thick sediments to accumulate within the basin. The mechanisms and timing of sediment transport downstream are discussed later.

3.3 GPS-Based Survey Data and Fluvial Hydrology Results

GPS-based survey and grain size measurements of actively incising channels throughout the study reach provide data necessary to estimate stream velocity and discharge as proxies for overall flow strength of the system. GPS-based survey results provided reliable x and y coordinate data for stream width measurements. However, the elevation, z, coordinate plane is unreliable for analysis of geotransects and calculation of their hydraulic geometry. This is due to the sporadic availability of satellites and the technique employed. However, the GPS-based survey technique provided a streamlined approach for rapid assessment of channel geometry when coupled with other techniques.

ACG median grain size (d50) values were measured in the field and sampling is shown on Figure 14. The d50 value for the measured ACG flow surface is 6.8 cm. The friction slope (Sf) for the ACG flow surface study reach is 0.003 and was calculated from GPS-based survey
Figure 17. Early Holocene conceptual model.
Figure 18. Late Holocene conceptual model.
<table>
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<th>Geotransect #</th>
<th>Stream Width(^a) (\text{m})</th>
<th>Stream Depth(^b) (\text{m})</th>
<th>Wetted Perimeter (\text{m})</th>
<th>Hydraulic Radius (\text{m})</th>
<th>Cross Section Area (\text{m}^2)</th>
<th>Stream Velocity(^c) (\text{m/s})</th>
<th>Stream Discharge(^d) (\text{m}^3/\text{s})</th>
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Mean of Values: 120.8 1.7 124.3 1.6 204.1 2.2 444.4

\(^a\) Stream width is a measured parameter taken using differential-corrected GPS.

\(^b\) Stream depth is calculated using shear stress analyses after Shield’s 1936.

\(^c\) Stream velocity is calculated using the Manning equation. Manning’s \(n\) was estimated to be 0.035.

\(^d\) Stream discharge is calculated as the product of cross section area and velocity.

\(^e\) Geotransect #26 is downstream of Wadi Himyari confluence and not included in the mean calculations.
data. Hydrologic parameters for the geotransect measurements are summarized in Table 4. Channel depth (taken from Shields 1936) is approximately 1.7 m. The mean of wetted perimeter (P) measurements is approximately 135 m. Cross sectional area (A) ranges from 112 m² (Geotransect #14) to 491 m² (Geotransect #26). Geotransect #26 is located downstream of the major Wadi Himyari tributary and was not included in the averaged calculations for the measured sections. The mean of cross sectional area for the measured sections is 204 m² and the mean for hydraulic radius (R) is 1.6 m.

Fluvial hydrology calculations to estimate present hydraulic conditions associated with ACG channels are summarized in Table 3. Geotransect #26 values are not included in hydraulic calculations for the study reach for reasons noted previously. Stream velocities (V) calculated from the Manning equation average 2.2 m/s. Manning’s n value used to calculate stream velocity is estimated to be 0.03. This value was estimated based on the comparison of Wadi Sana’s length, drainage basin pattern, climate, and median grain size to available USGS data for multiple streams throughout the southwestern United States. Discharge (Q) calculations for the ACG flow surface provide quantification of the currently incising geomorphic regime. The mean discharge for the measured ACG geotransects is 444 m³/s. Although early Holocene discharge information is not available, inspection of the wadi identified a drastic difference between the ACG channel and the expansive wadi silt deposits within the system. Comparison of the geographic distribution for the two geomorphic units indicates that deposition of the silts must have occurred under hydrologic regimes very different than the present flows occupying the ACG flow surface. We suggest that the channels depositing the early Holocene wadi silts would have a greater cross sectional area, larger flow volumes, and decreased velocities.

Estimation of stream depths, velocities, and discharges quantify values necessary to incise the current system. These are minimum values required to transport the sediments currently being incised within the ACG streambed. The assumption is made in this research that dominant discharge is the middle frequency and magnitude flooding event which is responsible for shaping geomorphology of the fluvial system. Constraints and limitations associated with the remote nature of the study location require the estimation and assumption of certain hydrologic parameters involved in the computational analysis of the study reach. The assumption that the
same stream depth at each geotransect station can be estimated to be the height of the fluid column solved for in Shield’s 1936 equation is necessary for quantifying cross sectional area. Although this assumption is not ideal, the equation solves for the critical depth necessary for sediment entrainment and movement. Figure 19 shows an eroded notch within a terrace profile and shows the relative scale for stream depth. The approximate height of the notch is very close to the estimated value of 1.7 meters and provides confidence for the Shield’s approach to calculated fluid column height necessary to mobilize wadi gravels. Certainly, the depths at geotransect stations vary, but a minimum critical value provided by the calculated depth (H) is necessary when actual flow measurements are not available.

Figure 19. Hydrological measurements. Figure 19-A shows grain size measurements of the ACG flow surface and Figure 19-B shows an erosional notch above the ACG flow surface (Photos Oches 2004).
4. Discussion
4.1 Late Quaternary Geochronology, Stratigraphy, and Climate

A general agreement between the geochronological reconstruction of fluvial sediment profiles described in this research and the paleoclimatic history of the region provide the basis for our overarching hypothesis that climate change is the cause of channel adjustment along Wadi Sana. The evolution of late Quaternary paleoclimate throughout southern Arabia is summarized here in accordance with Wadi Sana fluvial stratigraphy.

Documented drier conditions during the late Pleistocene are correlative with the age of the gravel terrace unit. The upper extent of the gravel terrace unit is exposed through the lower Wadi Sana sub-basin by the incising ACG flow surface. Ages from sand lenses within the unit suggest their deposition during the drier late Pleistocene. The poor sorting of the gravel terrace unit suggests deposition and/or reworking of sediments under a high-energy hydrological regime. The sharp contact observed between the gravel terrace unit and lower wadi silt unit is correlative with the climatic transition to moisture conditions during the early Holocene and is continuous across the length of the lower Wadi Sana sub-basin. The timing of the climate shift on a regional scale is documented to be abrupt and caused by initial monsoonal enhancement (Kutzbach et al. 1996, Naqvi & Fairbanks 1996). Recent research by Fleitmann et. al 2007 on stalagmites in southern Oman, suggests the precipitation increase occurred between ~10.6 ky and 9.7 ky BP. The abrupt nature of the contact and climate shift is hypothesized here to represent a coeval relationship.

The early to middle Holocene throughout southern Arabia is documented to be much wetter than current conditions (Burns et al. 1998, 2001, Neff et al. 2001, Fleitmann et al. 2003, 2007). Numerous (>10) weak paleosols observed throughout exposed lower to middle wadi silt profiles suggest that the aggradation occurred in episodic flooding events separated by periods of stabilization. The ages of the topographically highest upper wadi silt units, preserved
in erosional notches and caves, imply that accumulation of these fine-grained sediments continued to the middle Holocene. Another agreement between the climatic and stratigraphic record is observed during the middle Holocene where a shift toward a drier precipitation regime and ages of the upper wadi silt unit are coeval. The geochronological record and stratigraphic profiles terminate at ~ 5,000 yr BP throughout the studied reach. Paleoclimate proxy data illustrated in Figure 13 documents a gradual shift beginning ~8,000 yr BP toward more arid conditions in the middle Holocene around ~5,000 yr BP (Fleitmann 2003, 2007). The timeframe depicted by a gradual decline in precipitation brackets the ages for middle to upper wadi silt deposits suggesting a terrestrial response to climate change throughout Wadi Sana.

4.2 Impact of External Controls on Geomorphic Processes

We suggest here a hypothesized response by Wadi Sana to climate change and structural control. The temporal correlation of late Quaternary fluvial units in Wadi Sana suggests that widespread, synchronous aggradation and incision reflect a response to external control. The middle Holocene transition from sediment aggradation to incision is explainable by a change in external control on the fluvial system. Tectonism and climate change elicit responses that can be similar in the evolution of fluvial systems. Sea level position would be gradually rising over the warming Holocene interval and cannot be considered as base level control because a rise in sea level would raise the base level for Wadi Hadramout and Wadi Sana. A rise in base level would not cause incision. Active tectonism must be considered here as a cause for incision by lowering base level. A decrease in base level elevation and increase in gradient would cause a perturbation in equilibrium resulting in channel incision. Wadi Sana is located on north dipping units of the Southern Jol and Hadramout syncline. These units demonstrate abundant faulting as seen on Figure 4; however, the absence of Holocene tectonic features in the region makes faulting a less plausible control. Continental uplift and subsidence information for highland Southern Yemen is limited and operates on a longer timescale than is relevant to our documented Holocene fluvial shifts.

On the basis of information presented to this point, climate change is proposed here to be the dominant control on fluvial geomorphology in Wadi Sana throughout the late Quaternary.
Hydrological response to climate change and the effect on channel processes is discussed here in terms of precipitation, stream flow, vegetation, and sediment supply. Research in the semiarid southwestern United States generally proposes that channel incision is triggered by increased precipitation and runoff from bedrock dominated uplands, and that channel aggradation occurs when a decrease in precipitation occurs (Bailing and Wells 1990). However, other research hypothesizes that aggradation is triggered by transitions to moister climates as a result of higher groundwater levels, higher sediment supply from uplands, stable valley margin slopes, and wider valley floor aggradation associated with unentrenched and more perennial channels (Karlstrom et al., 1974; Karlstrom, 1983; Karlstrom and Karlstrom, 1986). In consideration of those contrasting hypotheses, McFadden and McCauliffe, 1997, offer the explanation that differing responses to climate change can be a function of regional diversity in and areal exposure of bedrock type, vegetation changes, the nature of the climate change, and many other possible factors. Structural control, bedrock lithology, and vegetation change are suggested here as factors influencing the response of Wadi Sana fluvial geomorphology to late Quaternary climate change.

Precipitation analyses for the Hadramout Province identified several trends for rainfall distribution over a 22-year period from 1981-2002. General conclusions derived from these data are as follows: The presently arid precipitation regime receives the most rainfall in spring and late summer; Spring rainfall is less frequent but consists of higher magnitude events, whereas late summer rainfall is more moderate in magnitude with a more consistent frequency. These data are applied to fluvial geomorphologic and hydrologic observations in Wadi Sana to establish hypothesized relationships between precipitation variation and system response. If the broad assumption is made that this precipitation pattern is representative of late Holocene drier conditions in the study area, then comparisons can be made to a moister early Holocene.

Data shown in Figure 11 suggests that monthly precipitation totals ranging from 0.1 mm to 5 mm are the most frequent events occurring in the basin. However, geomorphic responses to those events are considered here to be insignificant because of their minute magnitudes. Monthly precipitation ranging from 5 mm to 45 mm occurs relatively frequently and is interpreted here to represent lower to moderate flow events in the wadi causing small scale
geomorphic change. During a drier climate regime, infiltration and interception of the precipitation would be minimized and the accumulation of runoff would likely lead to fluvial incision. A wetter regime would have an overall increased frequency for these smaller events, resulting in greater soil moisture and vegetation cover. Precipitation ranging from 45 mm to 75 mm occurs even less frequently, according to the data set, and would produce a comparatively higher flow response in the wadi. During presently drier climate conditions with limited vegetation cover to resist sediment erosion, these events are likely to cause relatively large incision events. Estimates of stream discharge and velocity shown in Table 4 are based on present geomorphology and hypothesized to occur under these moderate frequency-magnitude precipitation events. During a wetter climate, these events would occur more frequently and would likely maintain higher groundwater table elevations, increase overall soil moisture, and contribute to vegetation growth. Aggradation of fluvial sediments during the early Holocene in Wadi Sana is proposed here to be a response to this range of flow events.

The highest precipitation events occur very infrequently according to the Seiyun data. One event occurred during the 22-year record exceeding 100 mm. Stream flow events resulting from precipitation of the highest magnitudes would have a very large effect on a semi-arid or arid landscape because arid climate flooding usually produces high sediment yields, largely explained by relatively sparse vegetation cover and runoff (Langbein and Schumm, 1958). Stream power and velocity would be comparatively high with short hydrograph periods due to the lack of opportunities for interception and infiltration, coupled with smoother channel roughness. During the drier middle to late Holocene, these events are proposed to cause massive sediment incision along the wadi. Overall, it could be deduced that the early to middle Holocene wetter climate would dampen the effect of a single large event because greater vegetation cover and moister soil conditions decrease stream velocity and erosivity due to increases in stream roughness, soil infiltration, and interception. Aggradation of wadi silts is greatly enhanced during the early Holocene due to these factors.

The bedrock lithology and fluvial geomorphologic character of the upper and lower sub-basins in the Wadi Sana drainage basin are markedly different due to normal faulting explained earlier. In the upper part of the basin, the highly erodible upland Rus formation
supplies sediments to an expansive sub-basin created in accommodation space created by the
series of normal faults. Further work by Sander (2006) described the area just upstream of the
fault zone as a paleolake that existed during the early Holocene wet phase. This description is
based on radiocarbon dating of marsh-type sediments and spring tufa deposits. Structural
control imposed by faulting appears to have created a damming effect of the paleolake at the
relatively narrow stream channel separating the upper and lower parts of Wadi Sana. The
sediments accumulating within the paleolake are hypothesized as the source for the wadi silt unit
found in massive stranded terraces downstream. The paleolake is hypothesized to act as a
regulator of flow and sediment between the upper and lower sub-basins responding to the
varying precipitation regimes occurring throughout the Holocene.

4.3 Hypothesized Conceptual Model

Climate change and structural faulting are proposed here as controls on the
geomorphology of Wadi Sana. A conceptual model describing the hypothesized evolution of
Wadi Sana throughout the early Holocene wet phase and late Holocene dry phase is shown on
Figures 17 and 18, respectively. The basis of this model is that the upper and lower sub-basins
operate somewhat independently in dry climatic phases due to structural restriction and then
become connected in moister conditions when a critical threshold in precipitation is exceeded.
A model for the early Holocene wet phase is discussed, followed by a model for the later
Holocene dry phase.

The early to middle Holocene throughout southern Arabia is documented to be much
wetter than current conditions. Increased stream flow throughout the structurally controlled
upper drainage sub-basin would increase sediment production and transport. The structural
restriction created by normal faulting causes internal drainage and aggradation of sediments into
a faulted basin located at the terminus of the upper sub-basin during wetter and drier phases of
precipitation. Increased precipitation, sufficient to cross a critical threshold, could cause a
breach of the sediments damming the restriction between the upper and lower sub-basins,
resulting in an episodic connection of upper and lower Wadi Sana. Subsequent transport of
massive volumes of fine-grained sediments would be transported downstream through the
narrow canyon section and onward to areas where the present silt terraces are observed. The narrow canyon system at the normal faults would initially receive the large flood discharges with high sediment yield and relatively high velocities. With increased velocities throughout the canyon sections, little to no sediment deposition occurred until the cross sectional areas increased further downstream. Areas where the Wadi Sana drainage network is wide and velocities decrease resulted in the deposition of the fine-grained material. The Wadi Sana-Wadi Shumlya confluence at the Khuzma is very wide and is a good example of areas where deposition of sediment would occur over multiple threshold breaches caused by large flood events (Figure 11). Numerous (>10) weak paleosols observed throughout exposed WS profiles suggest that the aggradation occurred in numerous flooding events interrupted by periods of stabilization.

The geochronological record and stratigraphic profiles terminate at approximately 4,500 yr BP. Paleoclimate proxy data illustrated on Figure 13 documents a gradual shift beginning ~8,000 yr BP toward current arid conditions in the middle Holocene (Fleitmann 2003, 2007). A shift in hydrological regime toward drier conditions would eliminate the ability of the fluvial system to surpass a critical precipitation threshold necessary to move large volumes of fine-grained material downstream. Vegetation cover would also decrease across the entire basin leading to greater erosivity of the fluvial sediments previously deposited downstream. Decreased flow would lower rates of sediment production and transport in the upper sub-basin. The decrease in stream roughness due to a loss in vegetation and drier soils would allow incision to occur during flow events and massive incision during low frequency high magnitude flood events. These drier regime flow events are hypothesized to produce the incised geomorphology presently observed throughout the lower Wadi Sana sub-basin.
5. Conclusion

The initial hypothesis of this research states that climate change was the cause of channel adjustment from aggradation to incision. Support for this hypothesis was documented through further geochronological reconstruction of the system, demonstrating that the coarse lower Gravel Terrace stratigraphic unit was deposited during the latest Pleistocene. Dating of the overlying wadi silts suggests that they were deposited throughout the early to middle Holocene and ceased around 4,500 yr BP. Inspection of the system for stratigraphically higher sediments documented no fluvial sediments above the PSI level of mid-Holocene deposition. Hydrologic estimates for the present climatic regime provide baseline data for what types of flow are shaping the incised wadi system. The remote location of the study area and lack of ground-truth data for actual flow events hinders the ability to understand the massive amounts of incision seen throughout Wadi Sana. Structural components of the system and hypothesized damming of a paleolake identified during research activities provide a mechanism for the timing and transport of wadi sediments. Combined, the climatic and structural controls operating on Wadi Sana’s fluvial geomorphology dictate sediment availability and timing of transport. These structural and climatic controls on Wadi Sana hydrologically connect the upper and lower sub-basins during periods of wetter climate and disconnect them during periods of arid climate. Flow regime change for the Holocene is counterintuitive when comparing increased flow strength with deposition of sediment and vice versa. The presence of structural controls operating within the system presents a mechanism to explain the details of the Holocene fluvial evolution of Wadi Sana.
6. References


