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LANDSCAPE RESPONSE TO LATE
QUATERNARY CLIMATIC CHANGE ON THE
SOUTHERN HIGH PLAINS, USA

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St. John's College

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ABSTRACT

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Long-term palaeo-climatic conditions have primarily been interpreted from ocean marine sediments and ice cores. Few middle and low latitude continental records exist that provide insight into continental response to climate change over time. This research offers new chronologies on a variety of low latitude continental deposits from the Southern High Plains, and demonstrates their importance as palaeo-environmental archives. These chronologies extend the existing Southern High Plains palaeo-environmental record from the historic period to the late-middle Pleistocene, and provide an important basis from which to examine landscape response to late Quaternary climate change.

This study demonstrates the applicability of optical dating procedures to well-bleached sedimentary features, such as lunettes, lacustrine material, tufa, and coversands. The precision and accuracy of the technique permits the detection of historic depositional events, whilst the range of the dating technique extended the chronology to the middle-late Pleistocene. The physical isolation of the Southern High Plains from its surrounding areas for the last 1.6 Ma has preserved a record of past climatic fluctuations within the aeolian and fluvio-lacustrine sediments. This research has demonstrated that the Southern High Plains landscape is sensitive to periods of less effective moisture, causing reactivation during historic drought periods (e.g. 1930s "Dust Bowl" event). Coversands and small playa lunettes were active during glacial and interglacials. This suggests that these features are sensitive to smaller scale climatic fluctuations that result in reduced effective moisture for the region during both glacial and interglacial periods. Large lake lunettes were inactive during the Wisconsin glacial. During this same period, active lacustrine and tufa deposition occurred; this offers evidence of greater effective moisture for the Southern High Plains, which resulted in regional recharge.

The record of climate change preserved in the lunettes, lacustrine material, tufa, and coversands has provided insight into the response of this dynamic landscape to climatic fluctuations and has been employed for the reconstruction of the palaeo-environmental history of the Southern High Plains. An understanding of landscape response is important in light of the future of the Southern High Plains environment as global temperatures increase, and is critical to a complete evaluation of continental response to climatic change.

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DEDICATION

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To see a world in a grain of sand
And a heaven in a wild flower,
Hold infinity in the palm of your hand
And eternity in an hour.

William Blake (1757-1827)
Auguries of Innocence
(excerpt)

Chapter 1

INTRODUCTION

Chapter overview

Chapter 1 introduces the aim and objectives of this research. It begins by outlining the regional importance of the Southern High Plains (SHP) to our understanding of late Quaternary climate change. The value of applying optical dating techniques to samples from a range of depositional environments is then explained. This is followed by a discussion of each of the four depositional features that form the subject of this research; these include lunette, lacustrine material, tufa deposits, and coversands. The specific research objectives are then presented in detail. This chapter concludes with an overview of the thesis structure and subsequent chapter content.

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INTRODUCTION

The Southern High Plains (SHP) of northwest Texas and eastern New Mexico is a culturally and geologically important area that has been the focus of inter-disciplinary research for many decades. This area contains some of North America's most significant archaeological sites and sediment records, which can provide insight into climatic conditions throughout time. The aim of this research is to investigate landscape response to late Quaternary climate change in order to reconstruct the environmental history of the Southern High Plains.

1.1 Regional importance

The Southern High Plains is an isolated plateau that has been classified as one of the flattest places on earth (Holliday, 1995c). Interrupting this flat plain and providing slight topographic relief are lunettes, lake basins and playas (with lacustrine and tufa deposits), and coversands. These features contain an important late Quaternary stratigraphic record that can provide insight into the palaeo-environment of this region, and form the subject of this research.

The regional importance of the Southern High Plains in terms of understanding low latitude continental response to late Quaternary climate change is due to four main factors. First, several of the most significant archaeological sites in North America are located on the Southern High Plains. The discovery of the earliest known Palaeo-Indian site at Clovis, New Mexico on the eastern edge of the Southern High Plains has created a strong on-going interest in the area. Subsequent important finds, including the unearthing of human remains, have established the archaeological pre-eminence of the Southern High Plains in North America. The existence of these important palaeo-Indian cultural sequences has generated an interest in deciphering climatic fluctuations on the Southern High Plains in order to better understand the human/environment interaction.

Second, the Southern High Plains has been physically isolated from its surrounding regions for the last 1.6 Ma. Streams from the Rocky Mountains that once flowed across the surface of the plateau are no longer active, or have by-passed it altogether. Thus, precipitation has been the only source for water on the Southern High Plains, supplying the aquifer, draws (dry river valleys), the small ephemeral playas, and the large saline lake basins since the Pleistocene. This absence of permanent streams on the Southern High Plains may be advantageous in palaeo-climatic studies, because fluctuations in the water table or surface water are a direct result of climatic events on the Southern High Plains, and not of recharge or flow reaching the plateau from a more humid region. Hence, lunettes, lacustrine material, tufa deposits, and coversands would have recorded previous environmental conditions, and can be used to interpret the landscape response to climatic fluctuations.

Third, Pleistocene/Holocene-aged fossil and plant remains on the plateau are markers of pre-existent climates. Temperature and/or precipitation fluctuations are reflected through time in the changing fauna and flora that are adapted to particular climatic conditions. Previous research by others that have investigated these palaeo-environmental markers will be used to support research concerning landscape response to climate change on the Southern High Plains.

Fourth, the Southern High Plains region has previously demonstrated its susceptibility to drought conditions and the response of its landscape to reduced precipitation. For example, the famous “Dust Bowl” of the 1930’s, resulted from a contraction in effective moisture for the North American Great Plains region. This event devastated croplands, stripped away topsoil and created "black blizzard" dust storms (Figure 1-1), which buried homes and farm equipment (Figure 1-2). Presently, the majority of the aeolian features (lunettes and coversands) on the Southern High Plains are vegetated and stable. According to Muhs and Maat (1993), the dunes of this region may reactivate with temperature increases and precipitation reductions. If optical dating can be used to correctly establish the chronology of the known 1930s drought conditions, then it is possible to infer, by dating older sequences, past dune accumulation.

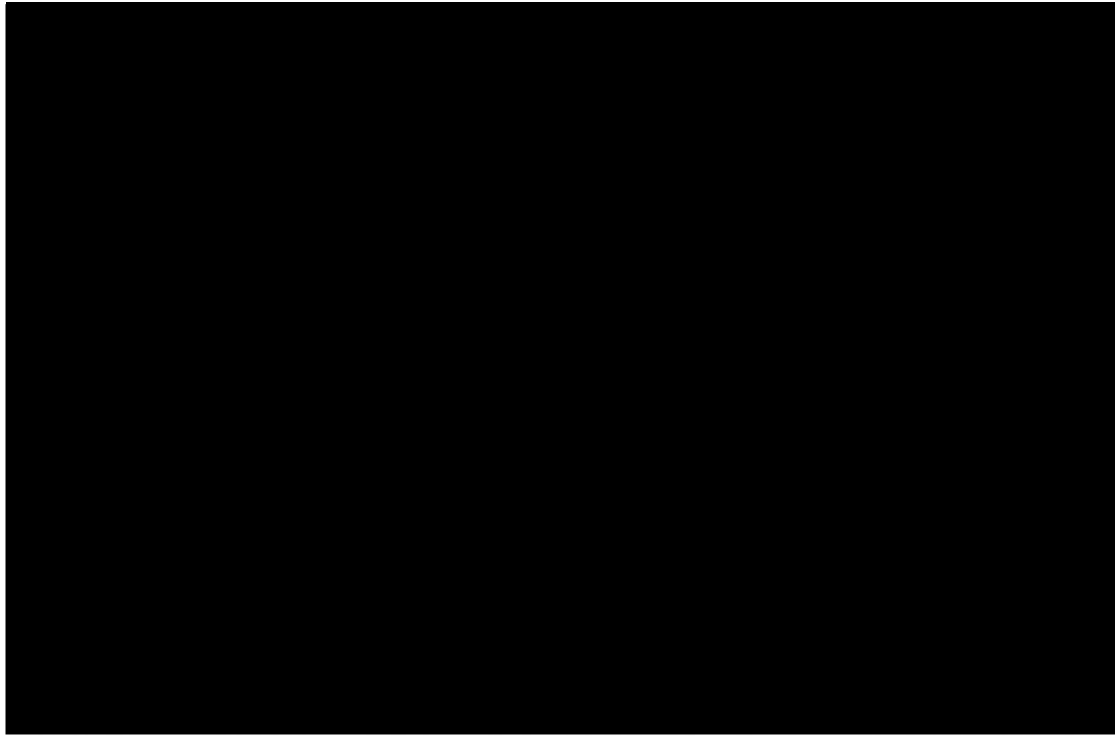


Figure 1-1. Black Sunday dust storm (image from Paul Bonnifield).

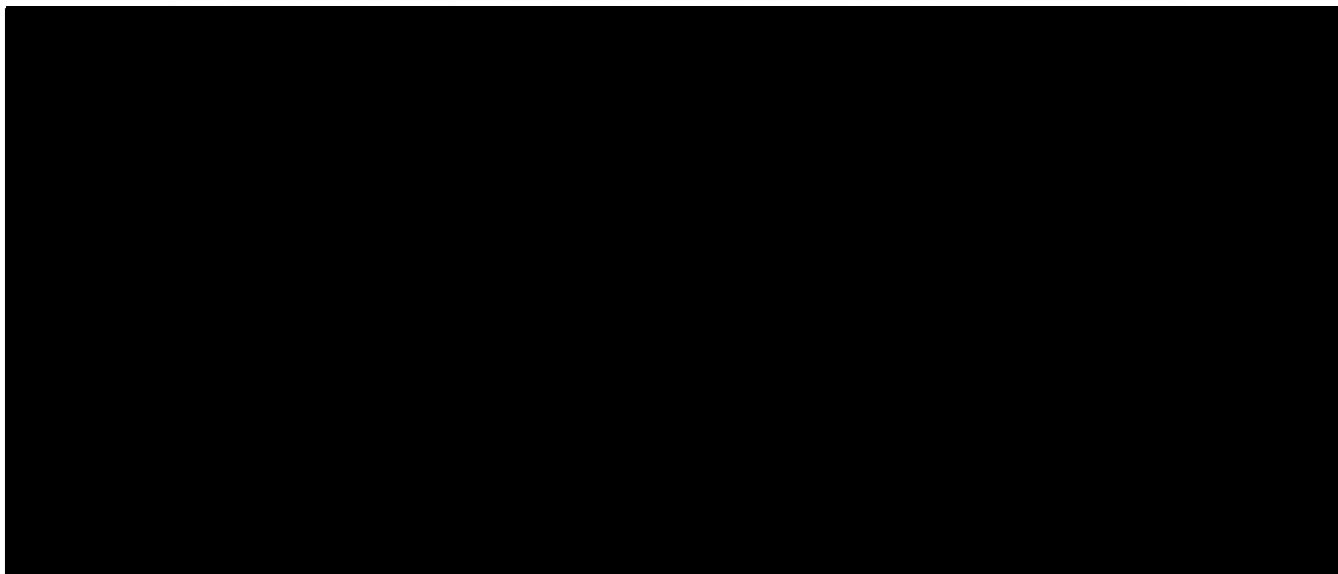


Figure 1-2. Aeolian deposition resulting from the 1930's Dust Bowl "Black Blizzards" (image from Paul Bonnifield).

1.2 Key depositional features investigated

The following subsections on lunettes, lacustrine material, tufa deposits, and coversands address each of these key depositional features and provide the justification for their selection as research subjects.

1.2.1 Lunettes

Southern High Plains lunette dunes were chosen as research subjects because evidence of past climatic oscillations can be preserved in their strata. This is due to the fact that when the water table drops during arid periods their adjacent lake basin

desiccates and provides a source of sediment for dune construction (Bowler, 1983; Frederick, 1998; Holliday, 1997a). Alternatively, a wet phase causes the water table to rise, filling the basin and terminating deflation. The adjacent lunette would then be stabilised, allowing the initiation of soil-forming processes (Bowler, 1983). The Southern High Plains is an isolated plateau, so lunette sediments can provide proxy evidence of fluctuating groundwater levels that result from changes in effective moisture.

This study evaluates previous research on the Southern High Plains lunettes and greatly expands the number of sites investigated. The timing of lunette accretion is compared with other aeolian and fluvial activity on the Southern High Plains, thus providing a broader understanding of how climatic fluctuations can influence aeolian and fluvio-lacustrine environments.

1.2.2 Lacustrine material

Lacustrine material in the Southern High Plains lake basins accumulated during intervals of greater effective moisture. Establishing the timing of deposition for the lacustrine material provides further insight into when the Southern High Plains experienced raised water tables. This chronology on lacustrine deposition can then be compared with lunette accretion intervals that correspond to lower water table levels, in order to identify wet and dry intervals across the Southern High Plains.

1.2.3 Tufa

A relict tufa deposit located at Double Lakes (on the Southern High Plains) is positioned several metres above the present lake bed. According to Pedley *et al.* (1996) and Viles and Goudie (1990), tufas occurring in spring vent locations within arid environments can provide evidence of former increased moisture and artesian surface water flow. Critical to the interpretation of tufa archives is a firm dating framework. Unfortunately these deposits have proven problematic to age-date. This study evaluates the potential of optically dating tufa deposits using entrained quartz grains.

1.2.4 Coversands

Coversands blanket nearly one eighth of the Southern High Plains surface, and provide a substantial proxy record of aeolian activity throughout the Pleistocene and Holocene, encompassing both glacial and interglacial periods. Their response to changing environmental and climatic conditions is important to further understanding the dynamics of dune reactivation. Additionally, the re-evaluation, refinement, and extension of their geochronology will permit a regional cross-comparison with accretionary periods for lunettes and other adjacent coversands.

1.3 Justification for using optical dating

The Southern High Plains has been investigated for over 100 years owing to its archaeological preeminence and the record of late Quaternary history preserved at these locations. Ongoing palaeo-environmental research on the Southern High Plains over the past five decades has provided a rich database of information that subsequent investigations have been able to build upon (e.g., Haas *et al.*, 1986; Haynes, 1995; Haynes and Mead, 1987; Holliday, 1989b; 1994; 2000b; 2001; Holliday and Meltzer, 1996; Reeves, 1965a; Reeves and Parry, 1965). A drawback of these investigations is that age control for sediments was by indirect means such as the location of vertebrate fauna remains (Huffington and Albritton, 1941) or archaeological artifacts within sediments (Wendorf *et al.*, 1955; Wendorf and Krieger, 1959). Later research based age control on radiocarbon dating of plant remains and interbedded palaeosols (e.g., Hall, 1990b; 1994; Holliday, 1988a; 1990; 1997a; 2000b; 2001; Holliday and Meltzer, 1996; Johnson and Holliday, 1989). This has limited the establishment of a robust chronology for this region due to the paucity of material on the Southern High Plains which can be reliably dated using radiocarbon methods. Other restrictions for this technique are the age range limits. The maximum age limit of ~40 ka (Aitken, 1998) confines environmental reconstruction to the later Pleistocene, while its minimum age (~1700 AD) (Wagner, 1998), prohibits detection of recent depositional and/or climatic events such as the pivotal North American 'Dust Bowl'.

Critical to palaeo-environmental research on the Southern High Plains is a firm dating framework that can provide absolute age control. During the past decade optical dating has provided an approach for the development of late Quaternary

chronologies (Aitken, 1998). When applied to aeolian sediments such as lunettes and coversands, robust age estimates can be obtained (e.g., Stokes et al., 1997; Stokes and Swinehart, 1997; Twidale *et al.*, 2001; Wilson *et al.*, 2001), while this method has also proven to be applicable to lacustrine materials (English et al., 2001; Shulmeister et al., 2001). Tufa deposits, on the other hand, have been difficult to date as both uranium series dating and radiocarbon methods suffer from their open system behaviour. An alternative approach would be the optical dating of entrained sand grains in the calcareous material.

1.4 Research aim and objectives

The aim of this research is to investigate landscape response to late Quaternary climate change in order to reconstruct the environmental history of the Southern High Plains. To accomplish this aim, the objectives of this research are to:

- 1) Test a combination of multiple and single aliquot optical dating results on selected Southern High Plains sediments (aeolian and fluvio-lacustrine), in order to determine which approach will provide the most robust chronology.
- 2) Utilise optical dating methods to refine and extend existing chronologies for lunette, lacustrine material, tufa deposits, and coversands. Both aeolian and water lain sediments were chosen to provide insight on wet and dry climatic conditions.
- 3) Investigate the possibility of using optical dating to determine age estimates on a tufa deposit adjacent to Double Lakes. This proxy record provides insight into the timing for intervals of greater effective moisture, which assists in our understanding of palaeo-climates on the Southern High Plains.
- 4) Determine if optical dating can correctly establish the chronology of the known 1930s North American drought conditions. If it is possible to date recent dune activity resulting from drought conditions, then we may be able to infer that older dune sequences may also have corresponded with earlier drought intervals.

- 5) Employ the proxy record preserved in the lunette, lacustrine material, tufa deposits, and coversands to assist in interpreting and reconstructing the region's palaeo-environmental history.
- 6) Compare the results from previous research on the Southern High Plains and surrounding regions (e.g., the Great Plains) to the suite of absolute age estimates derived from this study. A review of the overall results will assist in the interpretation of the regional extent of climatic fluctuations.

1.5 Thesis structure

The thesis will be structured to meet the requirements set forth in the 2003 University of Oxford Examination Decrees and Regulations (University of Oxford, 2003) that states:

"...a D.Phil. thesis may be accepted for examination if comprised of a minimum of four scientific papers submitted for publication if not yet accepted or published. Such a body of work shall be deemed acceptable provided it represents a coherent and focused body of research. It should include an Introduction, a Survey of Literature [general background], and a Conclusion" (paragraph 50, page 834).

Each required section is designated as a chapter, with two additional chapters added that cover field sampling and related optical dating experiments. Having introduced the Southern High Plains and outlined its importance, plus listed the key features, and the dating technique employed, the remainder of the thesis will proceed as follows:

- **Chapter 2 - General background:** Chapter 2 provides a description of the physical environment, climate, and vegetation of the Southern High Plains. This is followed by a detailed overview of the geology, geomorphology, and the specific features to be investigated in this study (lunettes, lacustrine material, tufa deposits, and coversands). Also included in this chapter is a review of key

literature regarding archaeological investigations on the Southern High Plains. The final section of this chapter is dedicated to luminescence dating.

- **Chapter 3 - Sample collection and preparation:** This chapter discusses the sample collection programme on the Southern High Plains and is subdivided into sections that explain the sampling and preparation techniques used for lunettes, lacustrine material, tufa, and coversands. Each section includes a map of the sample site plus a cross-section of the strata showing sediment characteristics and sample depth.
- **Chapter 4 - Some tests relevant to the optical dating procedures:** This chapter contains information on experiments, which were carried out on selected Southern High Plains samples that relate to the optical dating procedure, namely pre-heat plateaus, test-dose variance and recycling ratios, in order to test the robustness of the dating approach.
- **Chapter 5 - Accepted papers and manuscripts prepared for submission:** This chapter is comprised of FOUR papers that have been accepted for publication and TWO manuscripts that have been prepared for submission to journals. Each paper builds on the information of the previous papers and addresses the objectives of this research. The final manuscript, Paper 6 is a culmination of the empirical research presented in this thesis.
- **Chapter 6 - Conclusions:** This final chapter presents a synthesis of the findings and ideas presented in this thesis. Chapter 6 begins with an outline of the aim and objectives of this research, and demonstrates how they were accomplished. This is followed by a section that details the specific conclusions drawn from each of the key depositional features on the Southern High Plains; namely lunettes, lacustrine material, tufas and coversands. The chapter ends with a brief summary, which draws together all of the research and provides a history of depositional events across the Southern High Plains. This is then followed by suggestions for further research.

1.6 Additional Notes

- 1) The interval of time discussed throughout the thesis is the middle-late Pleistocene to Historic, which spans the following glacial and interglacial periods (as described by Richmond and Fullerton, 1985). The following North American terminology is used to describe the various divisions within the glacial periods :
 - Early Illinoian (OIS 8) *c.* 302-252 ka
 - Illinoian (OIS 7) *c.* 252-198 ka
 - Late Illinoian (OIS 6) *c.* 198-132 ka
 - Sangamon (OIS 5e) *c.* 132-122 ka
 - Eowisconsin (OIS 5d-a) *c.* 122-79 ka
 - Early Wisconsin (OIS 4) *c.* 79-65 ka
 - Middle Wisconsin (OIS 3) *c.* 65-35 ka
 - Late Wisconsin (OIS 2) *c.* 35-10 ka
(including last glacial maximum *c.* 21-17 ka)
 - Holocene (OIS 1) *c.* 10 ka-present
- 2) To ease comparison with optical ages, Radiocarbon (^{14}C) ages have been calendar corrected, and are presented with one sigma error range (based on Stuiver and Reimer, 1993).
- 3) The table of contents, list of figures, list of tables, and appendices given at the beginning of this document are for the thesis only and do not include the contents, figures, tables, or appendices of the papers found in Chapter 5.
- 4) The references at the end of the thesis are for the thesis only. The references for each of the papers in Chapter 5 are found at the end of each manuscript.

Chapter 2

GENERAL BACKGROUND

Chapter overview

Chapter 2 is divided into two sections. The first section introduces the physiographic characteristics of the Southern High Plains and lists some of the key investigations for this area. An overview of the present climate and vegetation is also given. The chapter then moves on to describe the geology and geomorphic background of the Southern High Plains. This is followed by a more detailed discussion on the physical features that are the focus of this research, namely lunettes, large lake and small playa basins lacustrine material, tufa deposits, and coversands. At the end of the first section is a literature review of archaeological investigations on the Southern High Plains, which concentrates on studies that reconstructed the past climatic history for the area. The second section discusses the approach used for the dating these features. This section begins by laying out the physical basis of luminescence dating, discusses the measurement of luminescence, and the determination of equivalent dose using single aliquot regeneration methods. Together, these sections provide a context for the basis of this study.

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GENERAL BACKGROUND

2.1 Physical environment

The Southern High Plains is a southerly extension of the American Great Plains located in north-western Texas and eastern New Mexico (Figure 2-1) and covers an area of about $\sim 81,000 \text{ km}^2$, and though extremely flat, grades gently from north-west to south-east (Reeves, 1976; Wendorf and Hester, 1975). The Southern High Plains was originally known as the “Llano Estacado”. Some debate exists on the origin of this name; some believe that Spanish explorers crossing the region supposedly placed stakes “Estacado” in the ground in order to find their back trail on this relatively featureless plain “Llano”. Deeply entrenched in Texas mythology is the story of the “Staked Plains”, but the name “Llano Estacado” may also have been derived from the stockaded appearance of the plains’ escarpment as viewed from a distance by early explorers (Spearing, 1998). The term ‘High Plains’ is used because the Llano is elevated above the surrounding area, varying from 1463 m in the north-west near Clovis, New Mexico, to 822 m in the south-east near Midland, Texas (inclined approximately 1.8 m/km). This plateau is well defined physiographically from the surrounding region by a 50 to 200 m escarpment (Holliday, 1995c). The eastward flowing Canadian River, with its headwater in the Rockies, effectively divides the Southern High Plains from the adjacent Great Plains to the north. Additionally, the incision of the south flowing Pecos River defines its western limit, and headward erosion of intermittent rivers flowing off the eastern side of the plateau has created a prominent escarpment (Gustavson, 1987). An exception to this is the plateau’s southern boundary, as it ‘gently’ merges with the Edwards Plateau (Figure 2-1).

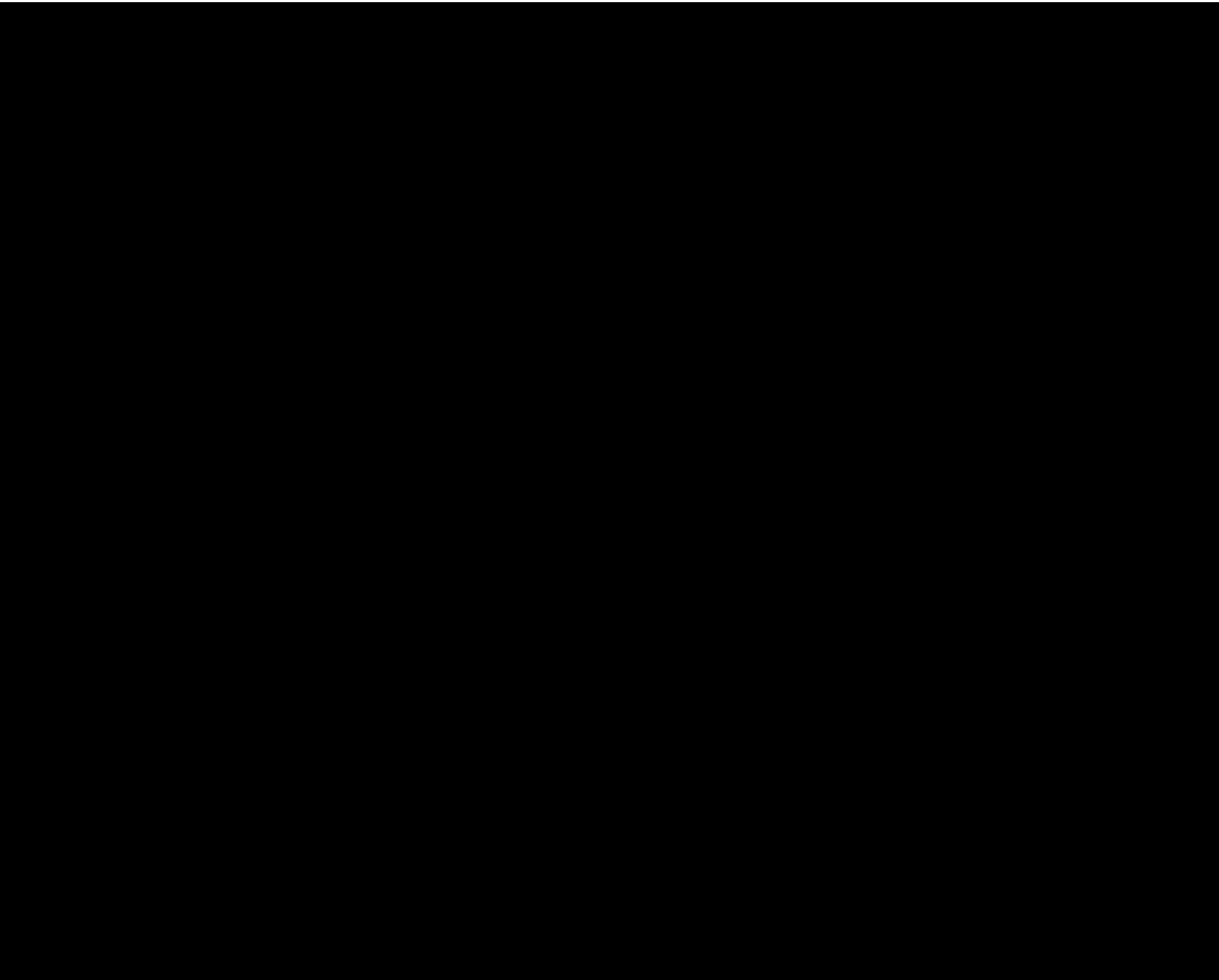


Figure 2-1. (a) Southern High Plains location map. (b) The physical landscape including coversands (or sand sheets). (c) Principal basin sites discussed in this study.

The surface of the Southern High Plains is interrupted by the occasional shallow valley (draw), playa lake depression, or dune. At present, there are no permanent streams crossing the Southern High Plains but aeolian scouring and deposition plus ground water continue to alter the surface to some degree.

The Southern High Plains has been the subject of research for over 100 years (Table 2-1). Early investigations were made by government explorers passing through this region while surveying the American west. Later, scientists were drawn to the Southern High Plains to study its widely scattered archaeological sites, of which Clovis and Lubbock Lake are two of the better known, due to the record of late Quaternary history preserved at these locations. In the late 1950's and early 1960's a landmark interdisciplinary 'High Plains Paleoecology Project' was conducted which

brought together scientists from various disciplines whose aim was to discern the late Pleistocene environment and address certain aspects of late Quaternary history including archaeology, geochronology, palaeobotany, and paleontology (Holliday, 1995c).

2.2 Climate

The climate of the Southern High Plains is continental semiarid and classified as BScDW (steppe with dry winters) (Larkin and Bomar, 1983). Average temperatures decrease with latitudinal position during winter, from 7.2° C in the south to 2.7° C in the north. Summers are long and hot with mean annual temperatures varying longitudinally, from 23.8°C to 26.6°C west to east across the plain (Wendorf, 1975).

The climate is transitional in character due to its south-central location on the North American continent where three differing air masses converge. These air masses arrive as warm moist air from the Gulf of Mexico in almost all seasons; as cold dry air from the Canadian Arctic principally in winter; and on occasion, as relatively dry air from the Pacific coast during various times of the year (Bryson and Hare, 1974) (Figure 2-2). Winds on the Southern High Plains are variable with a strong southerly component as shown from wind roses at Amarillo, Lubbock, and Midland, Texas (Larkin and Bomar, 1983) (Figure 2-3). During the winter season, the dominant wind direction for the Southern High Plains plateau is a south, south-easterly flow, while during the summer period the region is at the focal point of air flowing from three directions, the south, south west and north (Figure 2-3). Wind blows almost constantly across the flat open landscape throughout the year, with average wind speeds ranging from 16 to 24 kph, however speeds up to >80 kph are common (NOAA , 2002).

Subject	Key investigations
Aeolian deposits	(Gilbert, 1895; Melton, 1938; Huffington and Albritton, 1939; Melton, 1940; Huffington and Albritton, 1941; Reeves, 1965b; Carlisle and Marrs, 1982; Holliday, 1989a; Stokes, 1992; Holliday, 1995b; Holliday, 2001; Muhs and Holliday, 2001)
Archaeology	(Oldfield and Schoenwetter, 1964; Hester, 1975; Stafford, 1981; Holliday, 1985a; Johnson and Holliday, 1989; Meltzer, 1991; Holliday, 1994; Holliday, 1997b; Wood <i>et al.</i> , 2002)
Climate	(Reeves, 1973; Holliday, 1982; Holliday <i>et al.</i> , 1983; Holliday, 1985c; Johnson, 1987; Holliday, 1989b; Nativ and Riggio, 1990; Holliday, 2000a; Holliday, 2000b)
Fauna	(Ho, 1965; Johnson, 1986)
General characteristics	(Ballance and Titus, 1967; Wendorf and Hester, 1975; Reeves and Temple, 1986)
Geology	(Reeves, 1976; Holliday and Gustavson, 1988)
Hydrology	(Theis, 1937; Cronin, 1964; Frye and Leonard, 1964; Cronin, 1969; Reeves, 1970; Nativ and Smith, 1987)
Lakes	(Osterkamp and Wood, 1987; Wood and Osterkamp, 1987; Reeves, 1990; Sanford and Wood, 1995; Wood and Jones, 1990; Wood <i>et al.</i> , 1992)
Playas	(Judson, 1950; Bell and Sechrist, 1972; Reeves and Parry, 1969; Gustavson <i>et al.</i> , 1995; Sabin and Holliday, 1995)
Pollen analysis	(Hafsten, 1961; Hafsten, 1964; Oldfield, 1975; Bryant and Schoenwetter, 1987; Holliday, 1987)
Stratigraphy	(Sidwell, 1943; Frye <i>et al.</i> , 1947; Stormer, 1972; Harbor, 1975; Haynes, 1975; Holliday, 1985b; Holliday, 1990; Holliday, 1995a; Holliday, 1995c)

Table 2-1. Key investigations on the Southern High Plains.

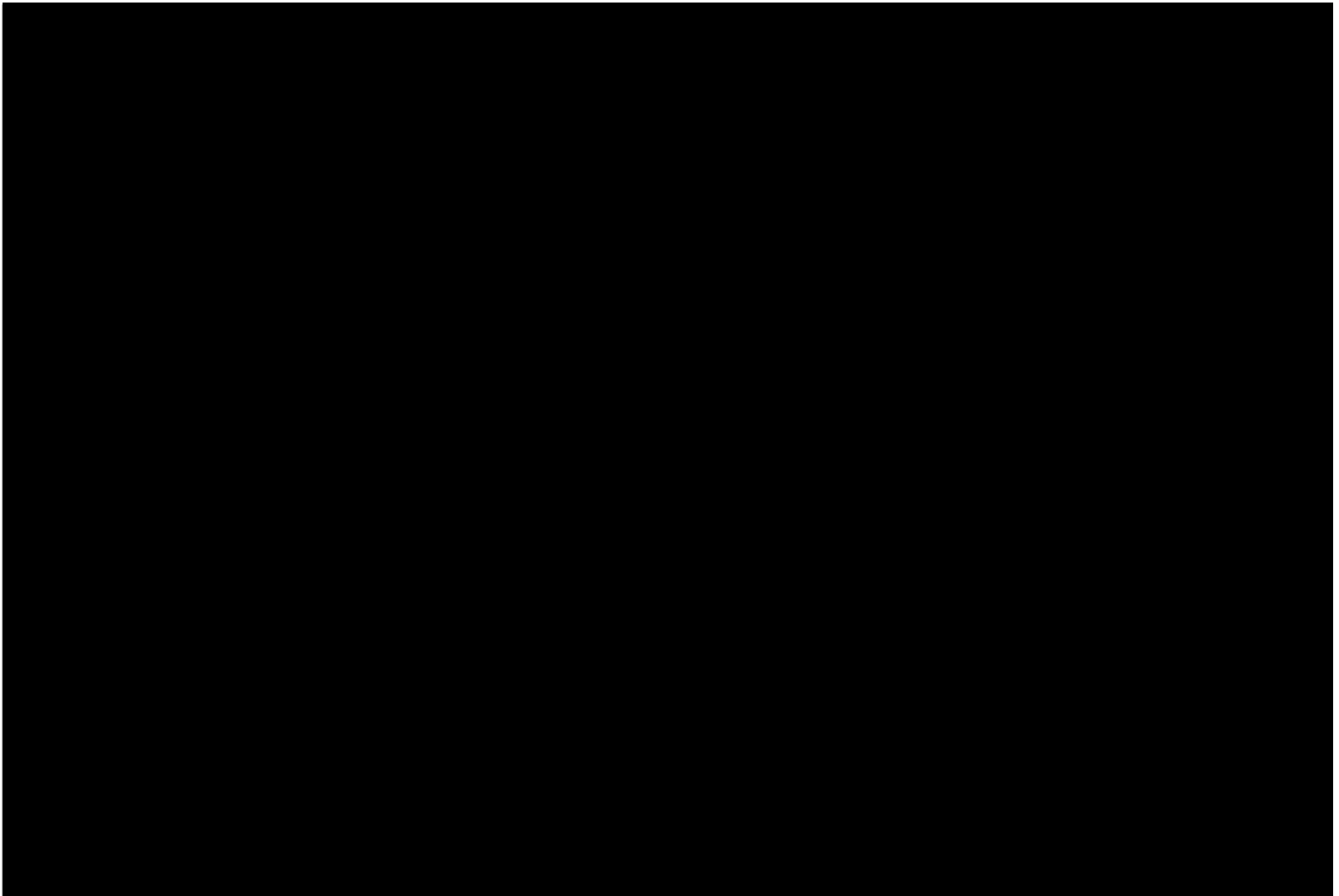


Figure 2-2. Schematic diagram illustrating seasonal wind surface flow for the Southern High Plains. During the winter season (a) the dominant wind direction for the plateau is south-easterly. During the summer season (b) the SHP is at the focal point of air flowing from three directions, the south, south-west, and north (adapted from Bryson and Hare, 1974).

The wind regime and its impact on Southern High Plains dunes and coversands can be characterised by its sand moving capability. A method developed by Fryberger and Dean (1979) to determine the potential for sand movement was used by Muhs and Holliday (2001) to determine annual resultant drift potentials (RDP), and resultant drift directions (RDD) for northern Texas and New Mexico. They determined that the RDD for the Southern High Plains is generally southwest to northeast, with RDP values ranging from 47-318 (mean = 155) (Muhs and Holliday, 2001) (Figure 2-4).

As is typical of a semiarid continental climate, the annual precipitation varies considerably from year to year. Lubbock county, for instance the highest total annual rainfall on record occurred in 1941 with 103 cm, while the lowest recorded average was in 1917 with 22 cm (Blackstock, 1979). Generally, the total amount of precipitation that falls on the plateau decreases from 56 cm on the eastern scarp to 33 cm on the western scarp. Precipitation maxima occur during the summer months when the

westerlies contract, move north and the tropical air from the Gulf of Mexico advects into the south-central region of the North American continent and collides with cooler drier air from Canada or the Pacific Ocean (Bryson and Hare, 1974). Due to the high summer temperatures existing during the period of highest rainfall the effective moisture is negative (Wendorf, 1975). Winter precipitation is relatively low because the westerlies, which bring air from the Pacific, have relatively reduced moisture content resulting from orographic lifting over the southern Rocky Mountain cordillera system and crossing the Sonoran Desert of Mexico (Bryson and Hare, 1974). Open pan evaporation potential is greater, in all seasons, than the average precipitation (Wendorf, 1975). Annual potential evaporation averages ~193 cm, and ranges from 183 cm in the north, while increasing to 203 cm towards the south (Larkin and Bomar, 1983; Wendorf, 1975) (Figure 2-5).

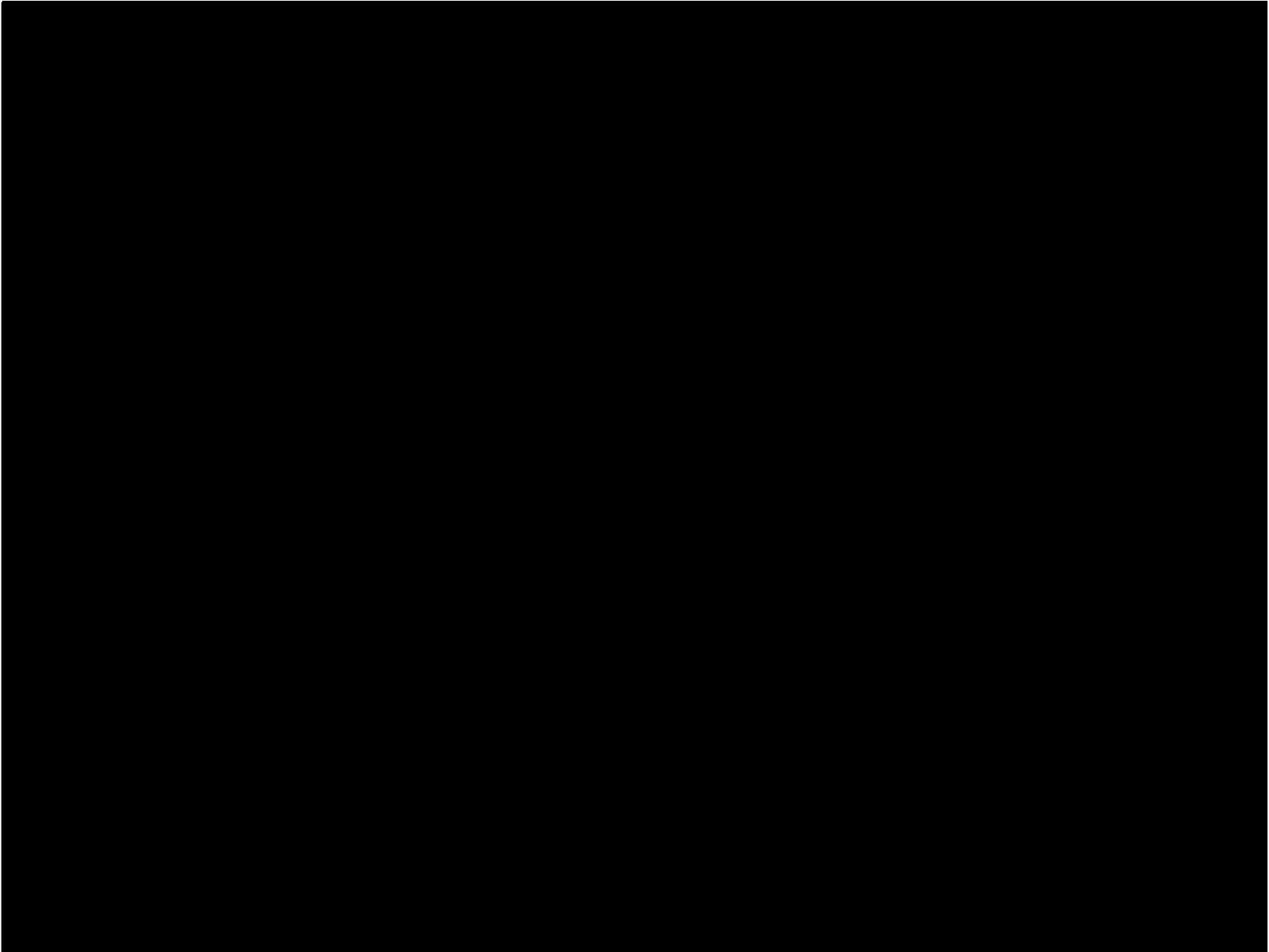


Figure 2-3. Seasonal wind roses at Amarillo, Lubbock, and Midland, Texas (Data from Larkin and Bomar, 1983).

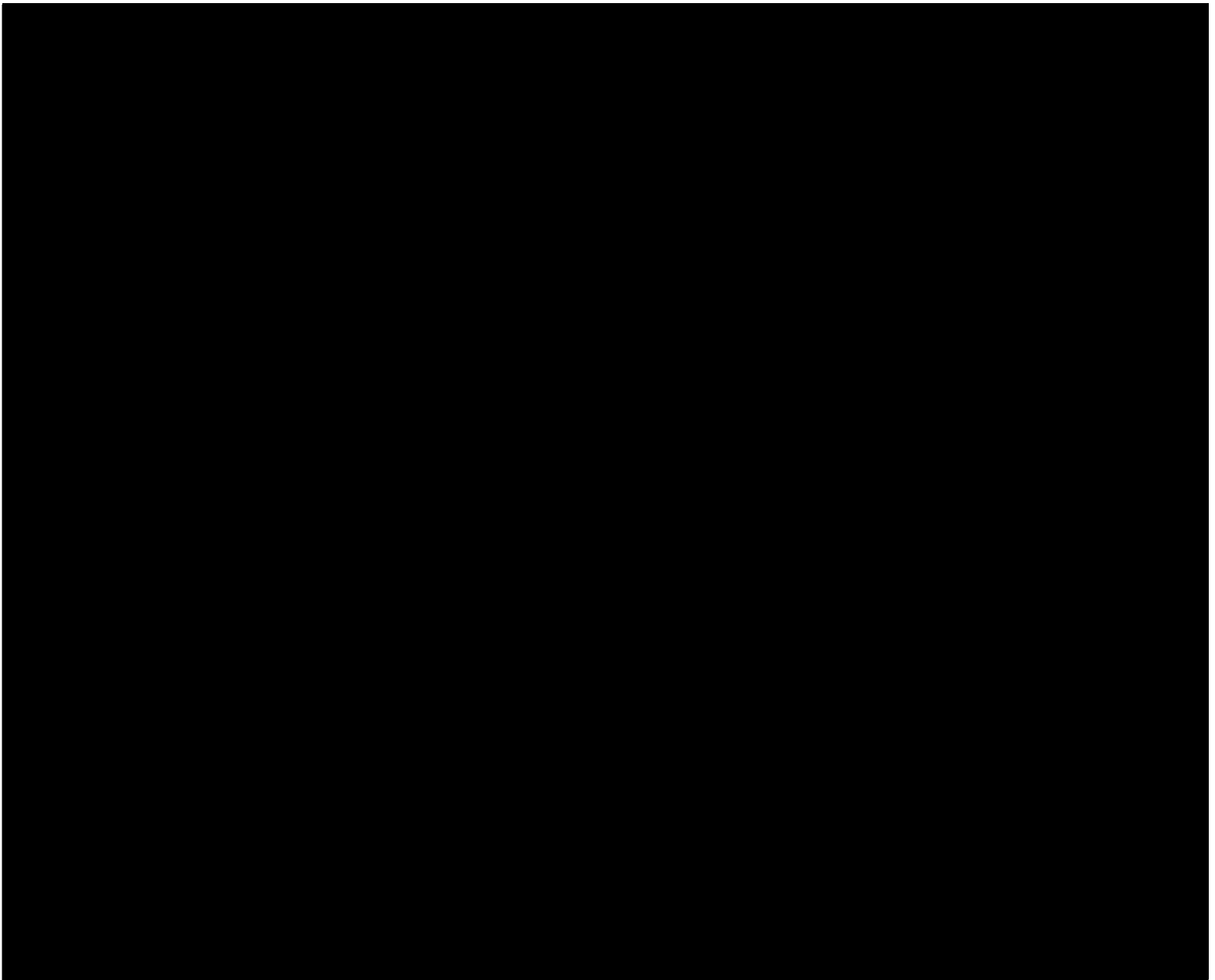


Figure 2-4. Dune fields of Southern High Plains and adjacent regions. Map arrows are resultant drift directions (RDD) showing potential direction for net sand migration. Resultant drift potential (RDP) given by length of arrow (from Muhs and Holliday, 1995; Muhs and Holliday, 2001).

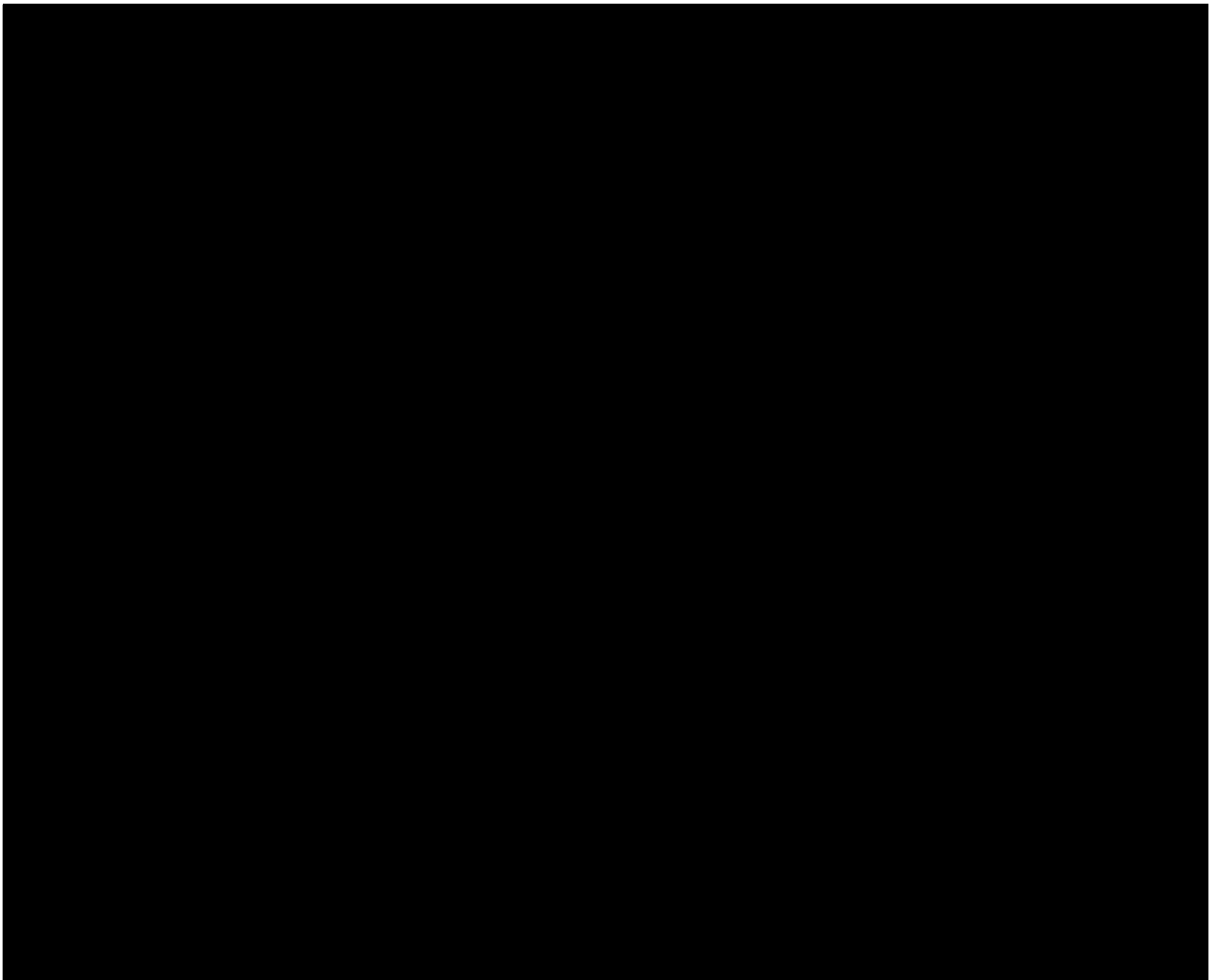


Figure 2-5. Average annual precipitation and potential evapotranspiration values for the Southern High Plains. Monthly rainfall totals for Lubbock, Texas (in upper right diagram) (adapted from Wood *et al.*, 2002, Appendix H).

2.3 Vegetation

The natural vegetation of the Southern High Plains is mixed-prairie grassland with dominant native plants of gramma (*Bouteloua* sp.) and buffalo grass (*Buchloe dactyloides*) (Holliday, 1995c; Lotspeich and Everhart, 1962). Naturally occurring trees are mostly absent across the plateau but can be found along the Southern High Plains escarpment and in re-entrant canyons. The composition of the natural flora varies from north to south, but today occurs in relatively few areas because much of this region is under cultivation.

2.4 Geologic and geomorphic background

The Palo Duro basin, that underlies much of the Southern High Plains, is bounded by the Amarillo Uplift-Ouachita Mountains to the northeast and the Matador Arch to the south (Figure 2-6) (Gustavson, 1987). These latter structures resulted from faulting and uplifting during the Paleozoic era (*c.* 570-245 ma) (Gustavson, 1987; Wendorf, 1961a; Wendorf and Hester, 1975). Sedimentation into the Palo Duro Basin, during the later Pennsylvanian and Permian periods (*c.* 320-245 ma), resulted from erosion of the tectonically active Amarillo Uplift and Matador Arch (Gustavson, 1990; Reeves, 1976).

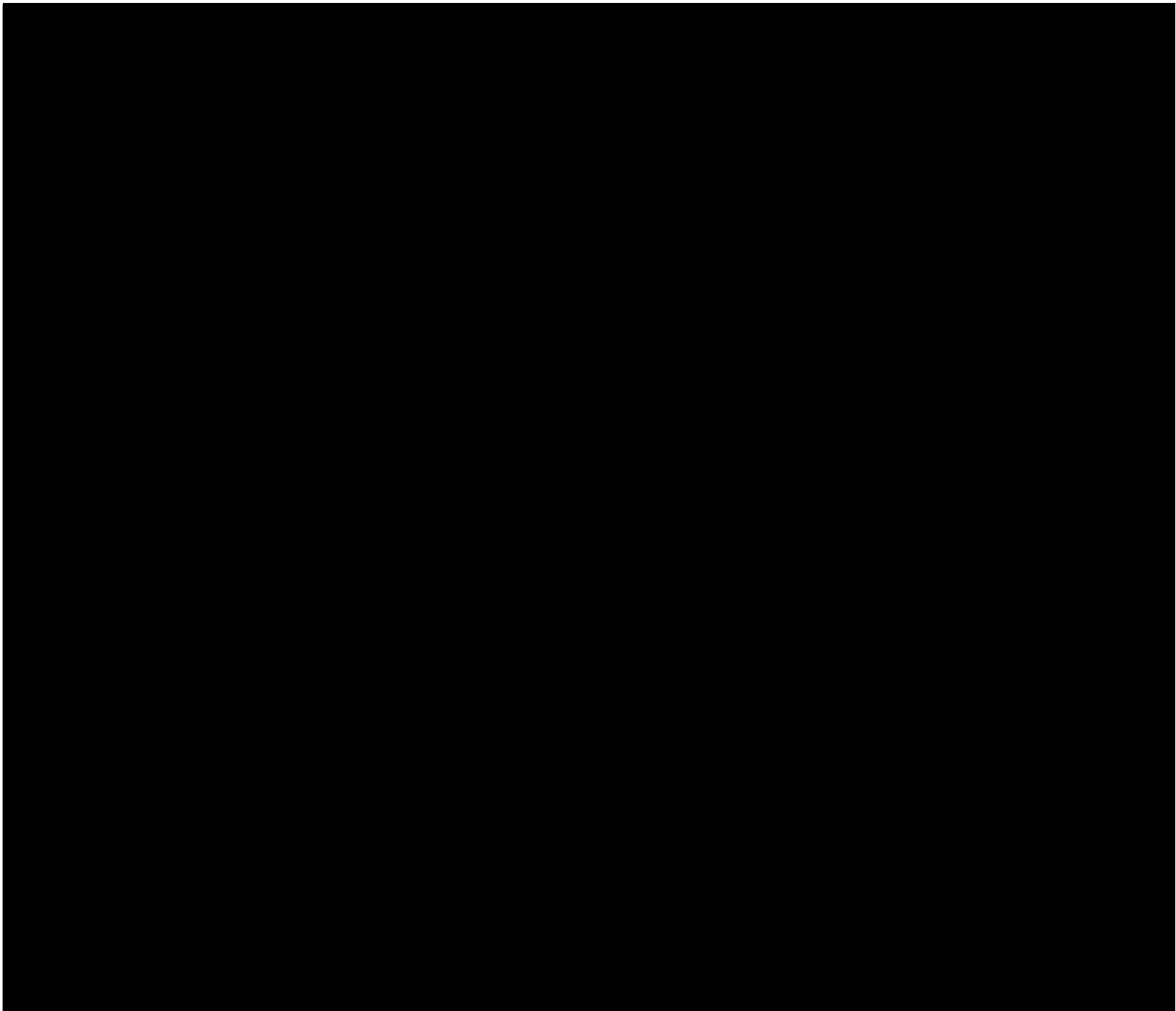


Figure 2-6. The Palo Duro Basin underlying much of the Southern High Plains with the regions of uplift that occurred during the Paleozoic era (570-245 ma) (adapted from Wendorf and Hester, 1975).

Evaporation flats located in the pan handle of Texas were the depositional site of bright red shales known as Permian 'Red Beds' (Wendorf, 1961a; Wendorf and Hester, 1975). This strata is widely exposed beyond the eastern edge of the Southern High Plains scarp and in the canyons of the Canadian and Red Rivers. These Red Beds have been eroded into rolling hill country that extends eastward from the Southern High Plains for over 200 km across the north central region of Texas (Reeves, 1976). Evaporites, such as salt and gypsum, were also deposited during the Permian (Wood and Sanford, 1990). Layers of salt, interbedded in the strata, later produced regional subsidence when they were removed by solution during the Triassic period (245-208 ma) (Reeves, 1976). Subsequent uplifting during the Triassic period resulted in gradation and subsequent deposition of lacustrine sediments known as the Dockum Group (Gustavson, 1990) that are exposed along much of the eastern and northern scarp of the Southern High Plains.

During the Jurassic period (208-144 ma), the North American continent experienced a period of uplift known as the Rocky Mountain orogeny (Spearing, 1998) (Figure 2-7). This was followed by the Cretaceous period (144-66 ma), when an ancient seaway covered the entire central Texas region depositing thick layers of limestone. This limestone strata was uplifted over 900 m during the Tertiary period (66-2 ma) forming the Edwards Plateau (Gustavson, 1990). Limestone exposures along the northern margins of the Edwards Plateau and the Southern High Plains south-western flank are partially covered by Quaternary-aged sand dunes (Machenberg, 1984; Spearing, 1998). These limestone deposits make up the principal base rock of the Edwards Plateau and thin northward under the Southern High Plains, where erosion eventually removed them completely (Gustavson, 1990). Edwards chert, the most popular source of stone for Palaeo-Indian tool making is found as nodules within this Cretaceous limestone (Holliday and Welty, 1981).

During the late Tertiary, approximately 12 to 2 ma, the Rocky Mountains underwent a renewed period of uplift and erosion (Spearing, 1998). Miocene- and Pliocene-aged materials were eroded from the Rockies and carried eastward by a series of intermittent high-energy braided streams of variable water and sediment discharge. Eroded sands, gravels, and clays were deposited as a series of alluvial

fans, forming an apron of sediments along the eastern slope of the Rockies (Gustavson and Winkler, 1988). These fluvial materials, known today as the Ogallala Formation, were laid over an undulating, maturely eroded surface of Permian, Mesozoic, and Tertiary stratigraphy that covered much of the Great Plains (Gustavson, 1987) (Figure 2-7).

During the later Tertiary period, fluvial sedimentation across the Southern High Plains from eastward flowing rivers ceased, because the Pecos River captured these rivers and diverted their drainage southward (Gustavson, 1990). The end of deposition for the Southern High Plains Ogallala Formation was marked by the development of a caprock. The caprock was formed by the translocation and accumulation of carbonates within the fluvial sediments, which fostered the development of caliche or calcrete on top of the Ogallala Formation (Gustavson, 1987; Gustavson, 1990). This pedogenic process of calcrete formation on the Southern High Plains may have required an extended period of landscape stability of several hundred thousand years within a semiarid climate to produce the present amount of concretion (Gustavson, 1990) (Figure 2-7).

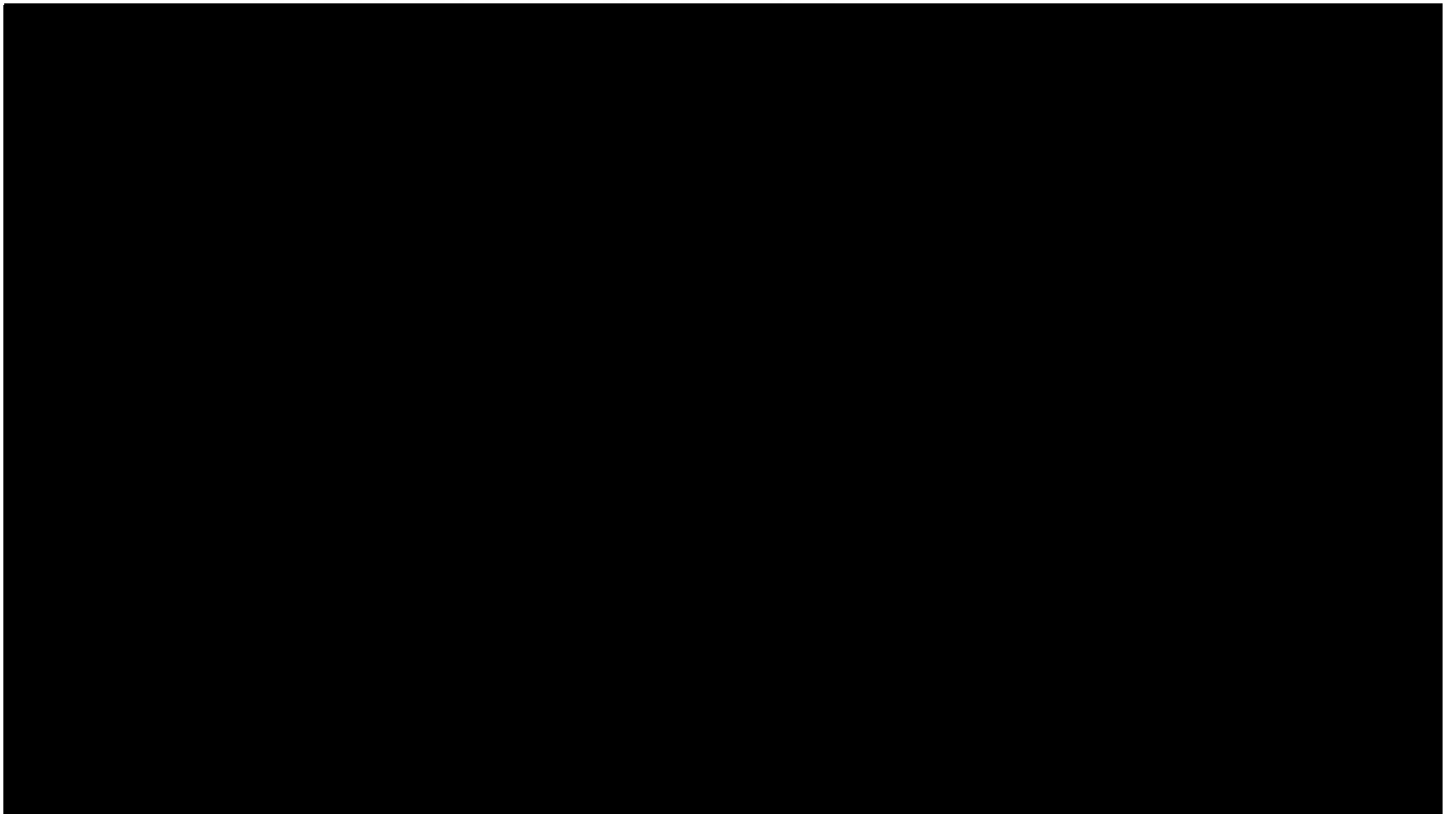


Figure 2-7. Generalised geologic cross-section of the Southern High Plains (adapted from Gustavson, 1987).

During the later Pliocene, local lacustrine deposits of the Blanco Formation and the Cita Canyon Lake beds were deposited over the Ogallala Formation (Holliday, 1988b). The Blanco strata contain mostly very fine sand and minor amounts of sheet wash gravel (Gustavson, 1987). With the onset of the Pleistocene, the climate changed to one having a more effective moisture regime, reactivating formerly desiccated streams (Holliday, 1995c). Some of these streams carved shallow valleys across the Southern High Plains while others emerged from the eastern escarpment as springs supplied by ground water from the Ogallala aquifer (Spearing, 1998). These eastward flowing streams began cutting downward, laterally, and upstream, directing erosion toward their headwaters on or near the Southern High Plains. In the process the eastern edge of the Southern High Plains scarp was eroded westward over 200 km to its present location during the late Pliocene and Pleistocene (Harrell, 1993).

The principal surficial deposit on the Southern High Plains is the Backwater Draw formation (Figure 2-7), first studied by Frye and Leonard in 1957, who used the informal term 'coversands' to denote the mantle of aeolian materials covering the Ogallala. (Reeves, 1976) proposed the replacement of the term 'coversands' with the formal designation 'Blackwater Draw Formation' and identified a "thin cover of loess" overlying the formation in the northeast (Gustavson, 1990). Other research found the Blackwater Draw Formation to be primarily quartz and feldspar in its coarse fraction with clay-sized minerals being predominantly smectite and illite, fining from southwest to northeast supporting the hypothesis that the material was aeolian and had its origin in the Pecos Valley (Seitlheko, 1975). This further demonstrated that these silty and clayey sediments are the result of downwind fining and not a separate 'loess cover' as Reeves (1976) proposed. Age control on the Blackwater Draw Formation is limited. Recognition of a geomagnetic polarity reversal within the deposits (Patterson *et al.*, 1987; Patterson *et al.*, 1988), coupled with identification of the Guaje (1.4 Ma) and Lava Creek (0.6 Ma) ash layers (Izett and Wilcox, 1982; Izett *et al.*, 1972) in the sequence demonstrate that its accumulation occurred during most of the Quaternary period.

Other late Quaternary-aged sediments comprising the stratigraphic record of the Southern High Plains are found in the lake basins and their associated lunettes, plus the coversands, and spring-vent tufa deposits (Figure 2-7). The numerous (~25,000) small playas (<5 km²) (Sabin and Holliday, 1995) (Figure 2-8) and the 40-50 large lake basins (>15 km²) (Osterkamp and Wood, 1987; Wood *et al.*, 2002) (Figure 2-9) are collapsed or cut into the Blackwater Draw Formation or older units (Harbor, 1975; Holliday, 1995a; Holliday, 1995c; Reeves, 1972). The lunettes and coversands of the Southern High Plains rest on top of this formation and contain Pleistocene- and Holocene-aged sediments (Figure 2-7). The aforementioned surficial features are the subject of this thesis and are discussed in further detail below.

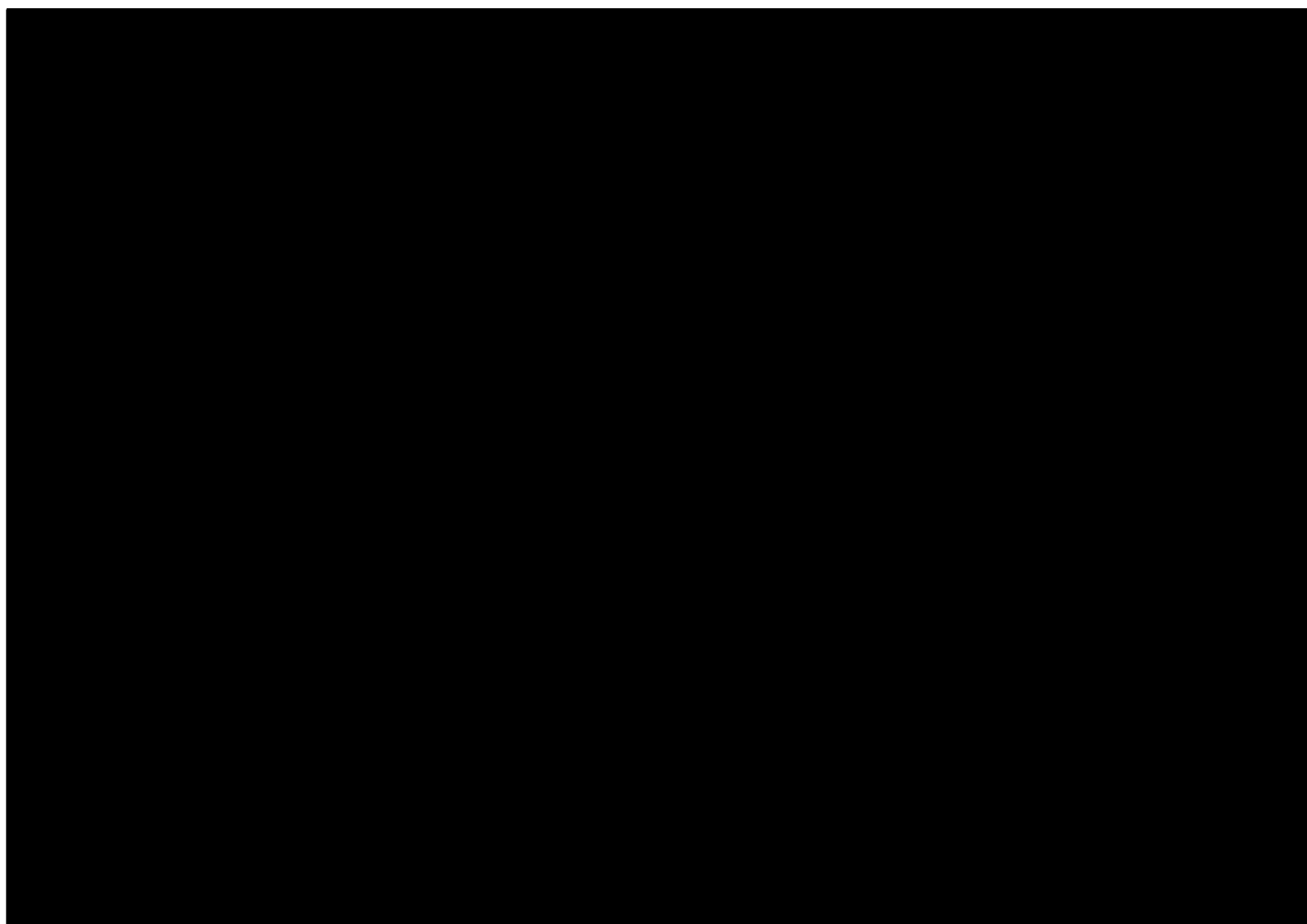


Figure 2-8. Small playa basins of the Southern High Plains. Locally known as “Silver Dollar Lakes” (photo supplied by W.W. Wood) .

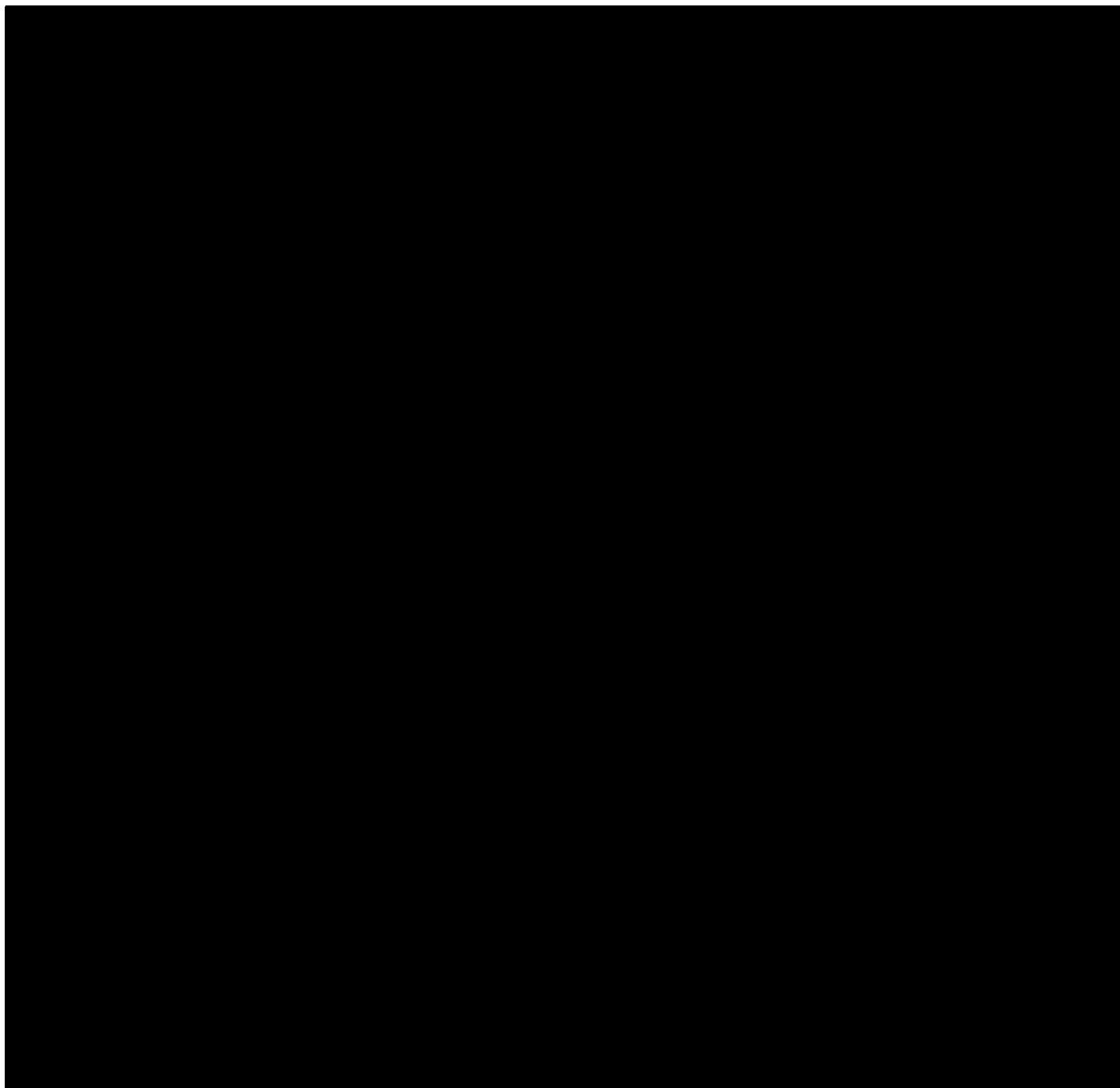


Figure 2-9. High altitude photograph of Double Lakes on the Southern High Plains (lower right-hand corner). Small playa basins can be seen northwest of the large lake basin (image supplied by W.W. Wood).

2.5 Lunettes

Lunettes were chosen as research subjects because evidence of past climatic oscillation can be preserved in their strata. The term 'lunette' was first used by E.S. Hills (1940) to describe arcuate-shaped dune deposits that were fixed along the leeward side of playa basins in southeastern Australia. They do not migrate with the wind but remain close to their sediment source (Bowler, 1973), which creates a relatively permanent archive of sediment.

Lunettes are semi-arid geomorphologic features associated with regions of mean annual precipitation of less than 700 mm (Bowler, 1973). They occur in Australia (Bowler, 1973), Argentina (Dangavs, 1979), Tunisia (Coque, 1962), Algeria (Boulaine, 1956), Texas (Holliday, 1997a; Huffman and Price, 1949; Stokes, 1994), South Africa and Botswana (Lancaster, 1978), Mauritania and Senegal (Tricart, 1954).

The size of a lunette is related to the areal extent of their associated lake or playa, the larger basin the higher the dune. A clay dune in western New South Wales, Australia exceeds 30 m in height while a lunette at Sabkha el Kelbia in Tunisia is 145 m high (Goudie and Thomas, 1984). However, the average height of lunettes rarely exceeds 20 m with most lying between 5 and 15 m (Bowler, 1973).

The earliest known writing concerning lunettes is from the diary of Major T. L. Mitchell dated 24 July 1836, while he was conducting an exploratory journey along the rivers of southeastern Australia (Mitchell, 1839). He noted that the area contained shallow saline lakes, each of which was bordered by a narrow beach of soft mud or clay on the margin of which were ridges with a curved shape concentric with the lake on its east or northeast shore. Half a century later, these saline lakes with their adjacent lunettes caught the attention of G.K. Gilbert on the High Plains of the Western United States (Gilbert, 1895). Coffey (1909) was one of the first to describe the process of wind dislodging clay aggregates from dry mud flats on the margin of hyper-saline lagoons in the barrier island system off the Texas gulf coast. These clay pellets were then deposited along the margin of the lagoon creating a lee-side dune.

The first systematic lunette observations were made by Harris (1939) and Hills (1939; 1940); the former described loam ridges on the shore of Lake Cooper, Australia, while the latter investigated lunettes in the Kerang region of this same country.

Following these initial observations into lunette dynamics, the mechanics of their formation has been the object of an ongoing debate. In general, the debate has centered on the role of water and salt in the formation of the lunettes. This has generated two main questions: (1) does wave action on the basin margin supply the necessary building material as proposed by Hills (1939), or (2) does the dune experience growth due to deflation in the absence of water in the adjacent lake/playa as set forth by Harris (1939). Hills (1939) noted that each successive ridge-building phase was inside the perimeter of the previous lunette and on the margin of successively lower lake levels, establishing a relationship between lunette occurrence and water level. Thus, he proposed a mechanism of downwind flocculation of fines by salt spray, producing a concentration of clay-sized sediments.

Stephens and Crocker (1946) revived Harris' lake floor deflation theory, which they said provided a satisfactory explanation for textural variation within the lunette, a view that was supported by Bettenay (1962). They saw no need to associate lunette development with the presence of water as proposed by Hills (1939, 1940) but that a lunette's composition was governed by the nature of the material on the dry lake floor hence they were evidence of aridity.

Bowler and Harford (1966) postulated a much more complex theory of lunette development when they proposed a high water level origin for coarse textured sand lunettes due to the discovery of *Coxiella* shells in the dunes of western Victoria. It was later proposed by Bowler (1973) that there were two distinct types of lunettes: (1) high quartz sand content lunettes that developed by deflation from active lakeshore beaches, and (2) high clay content dunes deflated from exposed lake floors during periods of low water, as had been proposed by Huffman and Price (1949) based on Texas lunettes. Wells (1992) suggested that there could be variations of the two mechanisms in the same dune complex with seasonal changes in precipitation or long periods of drought producing alternating layers of sand or clay dominated sediments.

A hypothesis was put forward by Wood *et al.* (2002), which stated that lunette construction on the Southern High Plains was controlled by water table elevation and that the two were in dynamic equilibrium. For instance, during arid phases reduced effective moisture may result in a drop in the water table, which exposes accumulated

basin sediments. Aeolian processes deflate the basin material, and accrete the sediments on the lee-side of the lake. Alternatively, humid conditions can elevate the water table, moistening the lake bed and effectively locking the sediments in place, thus terminating excavation of the basin (Wood *et al.*, 2002; see Appendix G). The lunette dune surface would then experience a period of non-accretion and stability. During these periods of greater effective moisture, fluvial sediments are carried into the lake basin while pedogenesis may be occurring on the adjacent lunette. An ensuing arid phase, which lowers the water table again will repeat the cycle of basin deflation and renew lunette accretion, thus preserving within the lunette stratigraphy changes in lake basin hydrogeological processes.

Southern High Plains lunettes, including other aeolian features, provide the limited topography on this relatively flat plateau. The number and size of lunettes varies depending on whether the dune is associated with one of the 40-50 large lake basins ($>15 \text{ km}^2$) on the plateau (Wood *et al.*, 1992) (Figure 2-10). These lakes generally have concentric lunette dunes (2 or more) with elevations up to 30 m high (Stokes, 1994). Of the 25,000 small playas ($<5 \text{ km}^2$) only ~4% have lunettes flanking their leeward side with typical elevations being 5-6 m high (Curtis and Beierman, 1980; Sabin and Holliday, 1995).

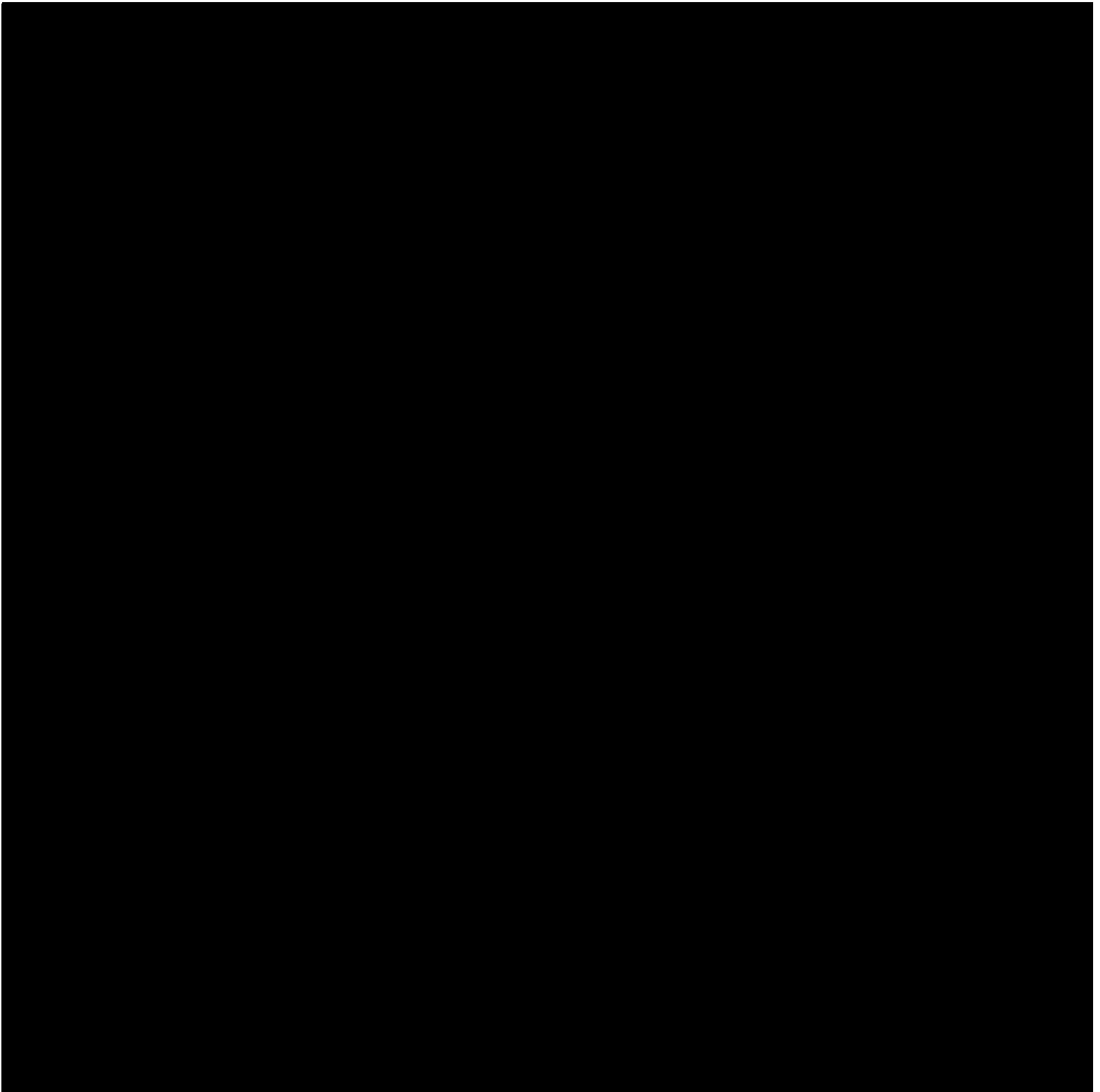


Figure 2-10. (a) Location map. (b) Lake basin and playa site map.

Investigations into the timing of lunette deposition and environmental reconstruction on the Southern High Plains has been conducted for three decades (e.g., Buchanan, 1973; Frederick, 1998; Harbor, 1975; Holliday, 1989b; Holliday, 1997a; Reeves and Parry, 1965). Their emplacement was initially estimated using a number of different approaches, including their position relative to radiocarbon dated lacustrine basin material, the presence of Palaeo-Indian artifacts within the dune sediments, plus the use of grain size analysis (Barnes *et al.*, 1976; Buchanan, 1973; Green, 1961; Harbor, 1975; Reeves and Parry, 1965; Wells, 1992) (Table 2-2) .

Two lacustrine deposits commonly known as ‘Double Lakes Formation’, which was estimated to have been emplaced 79-65 ka, and the ‘Tahoka Formation’, deposited roughly between ~35-13.5 ka, provided relative base ages for overlying lunette deposits (Evans and Meade, 1945; Harbor, 1975; Reeves, 1976). Lacustrine sediments comprising these two formations were deposited during a time of greater effective moisture on the Southern High Plains.

Research by Reeves and Parry (1965) on three nested Mound Lake lunettes estimated that the inner dune, composed of excavated Tahoka Formation sediments, was formed <13.5 ka, with younger upper sediments deposited during Holocene. They stated that the middle lunette accreted from 21 to 18 ka while the outer lunette was formed prior to the Double Lakes Formation, due to the absence of these sediments in the dune material.

Buchanan (1973) observed that the innermost lunette associated with Double Lakes, rested on approximately 9 m of Tahoka Formation sediments, and placed the timing of dune deposition after ~13.5 ka. He further stated that the middle and outer lunettes were formed prior to the deposition of the Double Lakes Formation (>79 ka).

Harbor (1975) unearthed artifacts from Coyote Lake inner lunette ridge, which belonged to the Plains Indian culture placing the timing of deposition for upper dune sediments during the late Holocene. He noted that the outer lunette held Archaic artifacts, which suggests that dune accretion was occurring during the middle Holocene.

Four distinct lunette dunes are associated with Shafter Lake basin. A large outermost and inner dune are separated by two smaller lunettes. The outermost lunette of this series lies on Tahoka Formation lacustrine sediments (Barnes *et al.*, 1976) placing the timing of its deposition <13.5 ka.

Crane Lake basin has five nested lunettes. The outermost and inner lunette are substantial in size, with three subtle intermediate dunes that are difficult to detect on the surface. The outermost lunette was emplaced prior to the deposition of the Tahoka Formation lacustrine unit (Green, 1961).

A lunette located adjacent to Lubbock Lake was investigated by Holliday (1989b), who proposed that two layers of sediment were deflated from the basin during

the early Holocene between about 8800 and 7000 yr BP (9800 and 7800 cal yr BP). He further indicated that these were overlain by an aeolian unit deposited in the middle Holocene between 6000 and 4500 yr BP (6800 and 5100 cal yr BP).

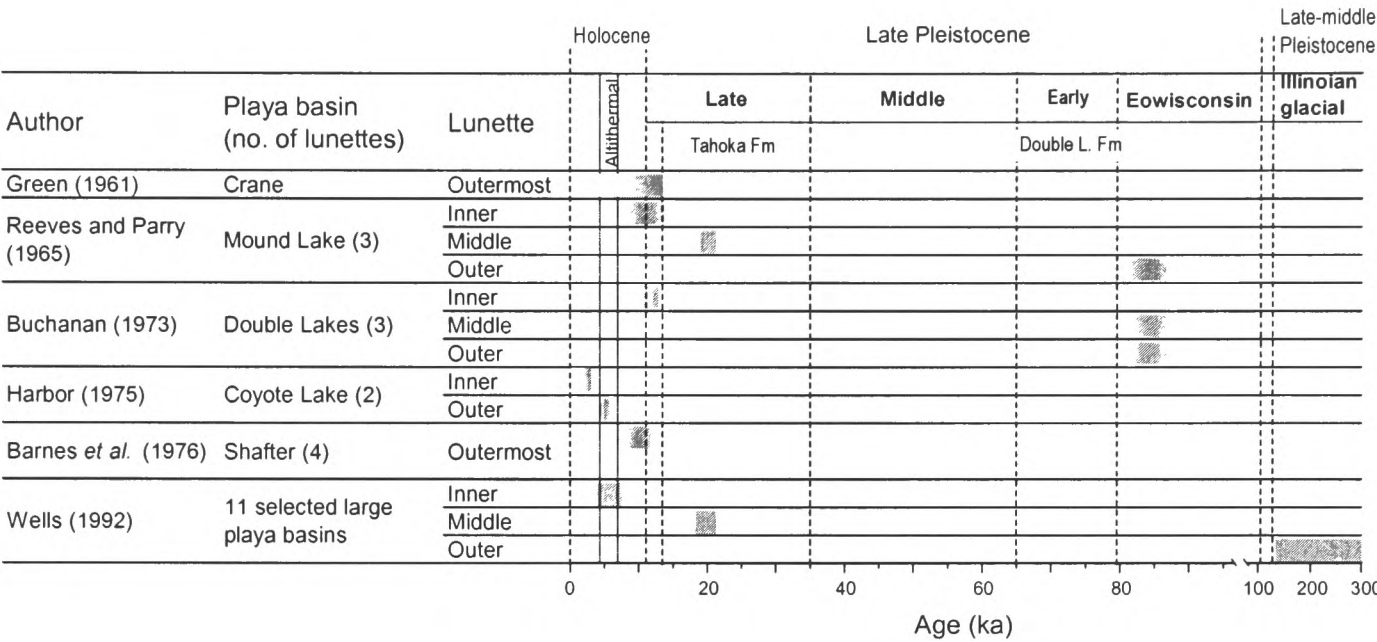


Table 2-2. Earlier research on the timing of lunette deposition (based on indirect dating approaches).

Grain size analysis of dune sediments from 11 large lake lunettes was conducted by Wells (1992). Recovery of material from the outermost and middle lunettes indicates their deposition during two distinct paleo-environments when compared to the inner lunette. The oldest or outer lunette contains a substantially greater proportion of sand-sized particles, possibly derived from the deflation of aeolian coversands. In contrast, the middle and inner lunettes incorporate a greater fraction of silt- and clay-sized particles derived by the removal of lacustrine and playa sediments deposited in the basin. He concluded that there may have been three periods of lunette formation on the Southern High Plains. The first episode occurred when the large pan basins were created, but lunettes from this period have not been precisely dated. The final episode of lunette deposition occurred during the Holocene. This is confirmed by the presence of modern bison remains and artifacts of middle Holocene Archaic culture within the innermost lunettes of several basins, suggesting a date during the Altithermal, 7.5 to 4.5 ka (Wells, 1992).

Using optical dating for age control, Stokes (1994) identified phases of lunette development at Rich, Mound, and Double Lakes, which transpired between 13.4 and

4.4 ka, with late Holocene activity based on ages of $2.7 \pm 1/-1.5$ ka and 680 ± 90 years. These optical ages were generated using a multiple aliquot additive dose (MAAD) technique.

Eleven small playa basin lunettes from across the Southern High Plains were researched by Holliday (1997a), the research of which is outlined below. He presented 33 radiocarbon ages determined on organic carbon in the upper 5 cm of buried soil A-horizons within the dune. Assays provided an age estimate for the palaeosol as well as the maximum age for termination of aeolian deposition. The oldest radiocarbon date of $33,750 \pm 3600$, from the Lubbock Lake lunette, was based on a weakly developed palaeosol. This led him to state that all of the lunettes on the Southern High Plains began forming in the late Pleistocene and therefore, all associated playas are at least as old. It was further concluded that the interval of 15,000-8,000 yr BP (17,900-8,800 cal yr BP) was identified as a time of episodic lunette accumulation with brief intervals of soil formation, suggestive of relatively rapid fluctuation between dry and wet playa conditions. This was followed by deposition of non-bedded sands between 8000-5000 yr BP (~ 8800 -5700 cal yr BP), which was overlain by a weak soil horizon. He noted that there have been relatively few lunette deposits dated to <3000 yr BP (<3200 cal yr BP), and concluded most have been largely stable during the late Holocene.

Two small playa basin lunettes near the southern margin of the Southern High Plains in Pleistocene-aged Lomax Basin were investigated by Frederick (1998). He presented three ^{14}C ages from soil horizons within the Red Lake lunette (10 ± 2 cal ka, Beta-59874) located in Martin County, and Sulphur Springs Draw lunette (3.2 ± 0.9 cal ka, Beta-55750 and 0.9 ± 0.07 cal ka, Beta-55749) associated with Sulphur Draw Reservoir (Frederick, 1998). The Red Lake depositional event, post 10,000 yr BP (11,500 cal yr BP), broadly coincides with Holliday's (1997a) 15,000-8000 yr BP (17,900-8,800 cal yr BP) episodic lunette depositional events, while the ages from Sulphur Springs Draw lunette suggest deposition in the late Holocene, a time Holliday (1997a) stated was relatively stable.

Overall, previous research on the timing of Southern High Plains large lake lunette deposition has provided a generalized chronology, which infers that deposition was occurring at least prior to the Double Lakes Formation event (>79 ka) with

minimal dune activity during the later Pleistocene from 79-20 ka. Throughout the Holocene lunette deposition was episodic. Chronology for the small playa basin lunettes indicates initial emplacement during the later Pleistocene with accretion also occurring at the beginning of the Holocene with subsequent intervals corresponding with the Altithermal, and relatively little deposition after 3200 cal yr BP.

2.6 Large lake and small playa basins (including lacustrine material)

In order to investigate the Southern High Plains landscape response to late Quaternary climate change, a review of the large lake and small playa basins literature was completed. This will provide insight into their formation, and provide information on when lacustrine sediments were deposited. Age estimates derived from optically dated lacustrine samples in this thesis will be compared to periods of deposition found in the literature.

Research on the Southern High Plains 40-50 large lake basins and their formation has been ongoing since 1895. In his paper on the origin of lake basins, G.K. Gilbert (1895) postulated that aeolian deflation created the large playas. During the early 20th century, challengers questioned Gilbert's hypothesis. Baker (1915) and Meigs *et al.* (1922) were aware that underlying areas of the Southern High Plains were deposits of Permian salt beds; hence, they proposed that evaporite dissolution at depth, with the subsequent collapse of the overlying materials, as an alternative explanation for the origin of large lake basins. Several decades later, detailed stratigraphy put into question this hypothesis when studies showed no evidence of sediment collapse, or sufficient subsurface evaporite removal to account for the present basin volume (Reeves and Temple, 1986).

Using aerial photographs and topographic maps, Wells (1992) proposed that the Southern High Plains large lake basins formed in NW-SE drainage channels that conforms to subsurface Cretaceous topographic lows. This drainage pattern had been inherited by the overlying Ogallala Formation and the subsequent aeolian coversands which blanket the Southern High Plains surface. Wells (1992) concluded that during

the later Pleistocene northwest winds deflated certain channel segments creating the basins.

More recently Wood *et al.*, (1992) argued that the previous salt-dissolution hypothesis (Baker, 1915; Meigs *et al.* 1922) had appeal but studies at several basins had shown no evidence of collapse or sufficient salt removal to account for the observed basin volume. In addition, Wood and Jones (1990) had shown that evaporite minerals in the playa basins were not derived from the dissolution of underlying salt. They further debated that the deflation hypothesis, put forth by Reeves and Temple (1986), which was consistent with the formation of lunettes, could not explain the problem of how wind could possibly remove the deflation-resistant 'caprock' to create a lake basin. Wood *et al.*, (1992) proposed a modification of the deflation hypothesis by eliminating the principal objection to it, the hard caliche caprock. The Wood *et al.*, (1992) theory, which builds upon work initiated by Reeves (1970) and Reeves and Parry (1969), states that the creation of large lake basins appears to result from their near universal association with subsurface bedrock highs. Their model suggests the caprock never formed in those areas where a bedrock high existed, because groundwater would flow over it reaching near, or to the surface; thus, preventing its formation. The absence of the protective calcrete would permit the playa basins to form by deflation during periods of a drier climate and lowered water table with the scoured material accreted onto their shores, forming lunettes.

Some of the first age estimates for large lake basin genesis were by Reeves and Parry (1965) on lacustrine sediments named the Tahoka Formation, who published 18 (12 reliable) representative dates from two major groups of lakes. The largest number of radiocarbon dates were for the lakes located south of Lubbock, Texas, including Rich Lake (6 dates), Mound Lake (2 dates), T-Bar Lake (now called Double Lakes) (2 dates), and Guthrie Lake (4 dates) (Figure 2-10). In the second grouping of lakes located north west of Lubbock there were only four radiocarbon dates among the seven large playas in that region. These included White Lake (2 dates) and Goose Lake (1 date) in the Muleshoe Basin, and Silver Lake (1 date) (Figure 2-10). The radiocarbon dates ranged from $\sim 17,400 \pm 600$ yr BP ($21,000 \pm 800$ cal yr BP) to more than 37,000 yr BP ($\sim 43,000$ cal yr BP). The age estimates for the samples tend to occur in four major groupings: 18,000 yr BP ($\sim 21,500$ cal yr BP), 27,000 yr BP ($\sim 30,500$ cal yr BP), and

30,000 yr BP (33,500 cal yr BP), with the oldest lacustrine sample estimated to over 37,000 yr BP (43,000 cal yr BP) (Reeves and Parry, 1965). The occurrence of carbon datable lacustrine carbonates led them to conclude that the formation of the lake basins predated the glacial maximum (~21 ka). Further evidence of widespread pluvial conditions during this time is found at Arch Lake, where fossiliferous lacustrine deposits produced a radiocarbon age of $14,300 \pm 230$ yr BP ($17,000 \pm 500$ cal yr BP) (Glass *et al.*, 1973). These sediments, which are similar to the Tahoka Formation material at other large lake basins, mark the final depositional phase for this deposit at *c.* 14,000 to 12,500 yr BP (~16,700 to 13,600 cal yr BP) (Hawley *et al.*, 1976; Reeves, 1976).

Subsequent studies have led to the recognition of earlier episodes of basin formation. Reeves (1976) took an 8.5 m core from basin sediments at Double Lakes, which were thought to be early glacial in age (79-65 ka) and named these lacustrine deposits the 'Double Lakes Formation'. He noted that this same formation was also found in neighbouring Rich and Mound Lake basins.

The latest investigation into the timing of basin formation was carried out by Sanford and Wood (1995), who estimated the age of the Double Lakes basin to be >300 ka based on uranium-series dating of carbonate crystals, but <610 ka due to the absence of the Lava Creek B volcanic ash. This places the timing of Southern High Plains lake basin development in the middle Pleistocene; a time much earlier than previously estimated.

The debate over the origin of the approximately 25,000 small playa basins on the Southern High Plains has been ongoing for several decades (Baker, 1915; Evans and Meade, 1945; Osterkamp and Wood, 1987; Reeves, 1966). Since these ephemeral lakes occur above the zone of saturation or water table, deflation was a popular explanation for their creation. This mechanism was first suggested by Gilbert (1895), with subsequent elaboration by Evans and Meade (1945) and Reeves (1965a). Subsidence or collapse resulting from solution of subsurface carbonates or evaporites has been proposed for basin formation (e.g., Baker, 1915; Price, 1940). Piping was also suggested as a process that initiated the development of small playa basins (Reeves, 1965a). Surface excavation by herds of buffalo who made "buffalo wallow"

depressions in the High Plains of Texas was cited by Darton (1905) as the possible genesis of their origin. It was demonstrated conclusively by Ostercamp and Wood (1987) that small playa basins developed by carbonate dissolution and eluviation of clastic and organic material. Their model was based primarily on hydrologic data, which was later supported by Reeves (1990) and Gustavson *et al.* (1995). The timing of formation for the small playa basins was suggested by Holliday (1997a) to have occurred approximately 34,000 years ago based on indirect evidence from an adjacent lunette.

2.7 Tufa

This section provides a brief description of tufa and presents information on attempts at dating these precipitated carbonates. A further discussion follows, which outlines previous investigations on Southern High Plains tufas. Precipitated carbonates commonly termed “tufas” or “travertines” can broadly be defined as variably formed carbonate-rich sedimentary deposits (Pedley, 1990). Ford and Pedley (1996) outlined differences between “tufas” and “travertines” based on their precipitation environment. They defined travertines as hard, crystalline precipitates that are deposited under hydrothermal conditions, whereas tufas are distinguished from travertines as having been precipitated in an environment with near ambient temperature and freshwater conditions. Precipitated carbonate deposition on the Southern High Plains has primarily been in the form of tufas (personal communication with Warren W. Wood). The genesis of tufas begins with meteoric water passing through the soil, with biogenic processes elevating the carbon dioxide (CO₂) levels of the water (Pentecost, 1981). Subsequent subsurface contact the water may have with limestone, or zones of calcium carbonate (CaCO₃), will result in dissolution of the material and its removal in solution (Pedley, 1990). Tufa deposition will occur given the availability of enough dissolved CaCO₃, the degassing of CO₂ from supersaturated waters on resurgence to the surface, and the presence of substrates on which the precipitation can occur (Ford and Pedley, 1996; Goudie *et al.*, 1993).

Tufas have been described on every continent except Antarctica, making this deposit an important global archive of climate change and may be of considerable utility for palaeoenvironmental reconstruction (Ford and Pedley, 1996). Goudie *et al.*

(1993) and Pedley (1996) noted that active tufa precipitation is limited by low temperatures which restrict the soil respiration and limestone dissolution, which may indicate that regimes with higher rainfall and temperatures could encourage formation. Thus, relict tufas within arid environments can provide evidence of former increased moisture and artesian surface water flow (Ford and Pedley, 1996; Pedley, 1990; Pedley *et al.*, 1996; Viles and Goudie, 1990).

The potential for using tufas in palaeoclimatic reconstruction is commonly limited by difficulties associated with their absolute age control. Many spring tufas have been dated using uranium series methods (Grün *et al.*, 1988). Unfortunately, tufas have proven problematic to date as both uranium series and radiocarbon methods suffer from their open system behaviour and contamination effects (Ford and Pedley, 1996; Giegengack and Ralph, 1973; Szabo *et al.*, 1995; Viles and Goudie, 1990). With uranium series dating of tufa, the analysis must be on the primary growth where no recrystallisation has occurred. Many tufas with pore spaces allow for the formation of secondary calcite to be deposited, which can alter the resulting uranium series date (Ford and Pedley, 1996; Giegengack and Ralph, 1973; Szabo *et al.*, 1995). With radiocarbon dating, the ages estimated on the organic matter depend upon direct contact with atmospheric ^{14}C (Ford and Pedley, 1996). Spring waters may have a blend of isotopic ratios from both the atmosphere and from water held underground for long periods where it may have reacted with ancient limestone; thus, producing unreliable ^{14}C dates (Pedley, 1990).

Very little exists in the literature regarding tufas on the Southern High Plains due to the difficulties associated with their absolute age control; thus, most research has concentrated on other surficial features or deposits where age control is more reliable. Primarily, information on Southern High Plains tufas comes from Wendorf (1975), Wendorf and Hester (1975), Wood *et al.* (2002). Wendorf (1975) notes a fresh water limestone deposit at Rich Lake. Samples were taken from this material for radiocarbon dating (Wendorf and Hester, 1975) but subsequent information regarding the results was unavailable. Wood *et al.* (2002) in their research on water supply for indigenous Americans during Holocene aridity discusses various spring sites on the Southern High Plains. They noted a relict spring deposit at Double Lakes. This

inactive spring vent site is elevated from the current lake basin and is presumed to correspond to a phase of enhanced surface water resources associated with artesian flow and perennial palaeolakes on the Southern High Plains.

2.8 Coversands

This section provides background information on the Southern High Plains coversands in order to lay a foundation on their origin and timing of deposition. The Southern High Plains coversands comprise more than 10,000 km² (~10%) of the plain's surface area (Holliday, 2001; Muhs and Holliday, 2001). These aeolian deposits are concentrated in two locations: (1) along the western escarpment, and (2) in re-entrant valleys along the western escarpment of the plateau. The western escarpment deposits are comprised of two major sand sheets known locally as the Monahans and Mescalero Dunes (Muhs and Holliday, 2001). Two west-east trending dune fields named Muleshoe and Lea-Yoakum, have accumulated in the Portales and Seminola valleys, respectively (Figure 2-11). The Andrews Dunes is an easterly extension of the Monahans Dunes into the Winkler Valley. These aeolian deposits have been considered important environmental archives for over 60 years (e.g., Gile, 1979; Gile, 1981; Haynes, 1975; Haynes, 1995; Holliday, 1995b; Holliday, 2001; Huffington and Albritton, 1939; Huffington and Albritton, 1941; Melton, 1940; Muhs and Holliday, 2001; Reeves, 1965a; Wells, 1992).

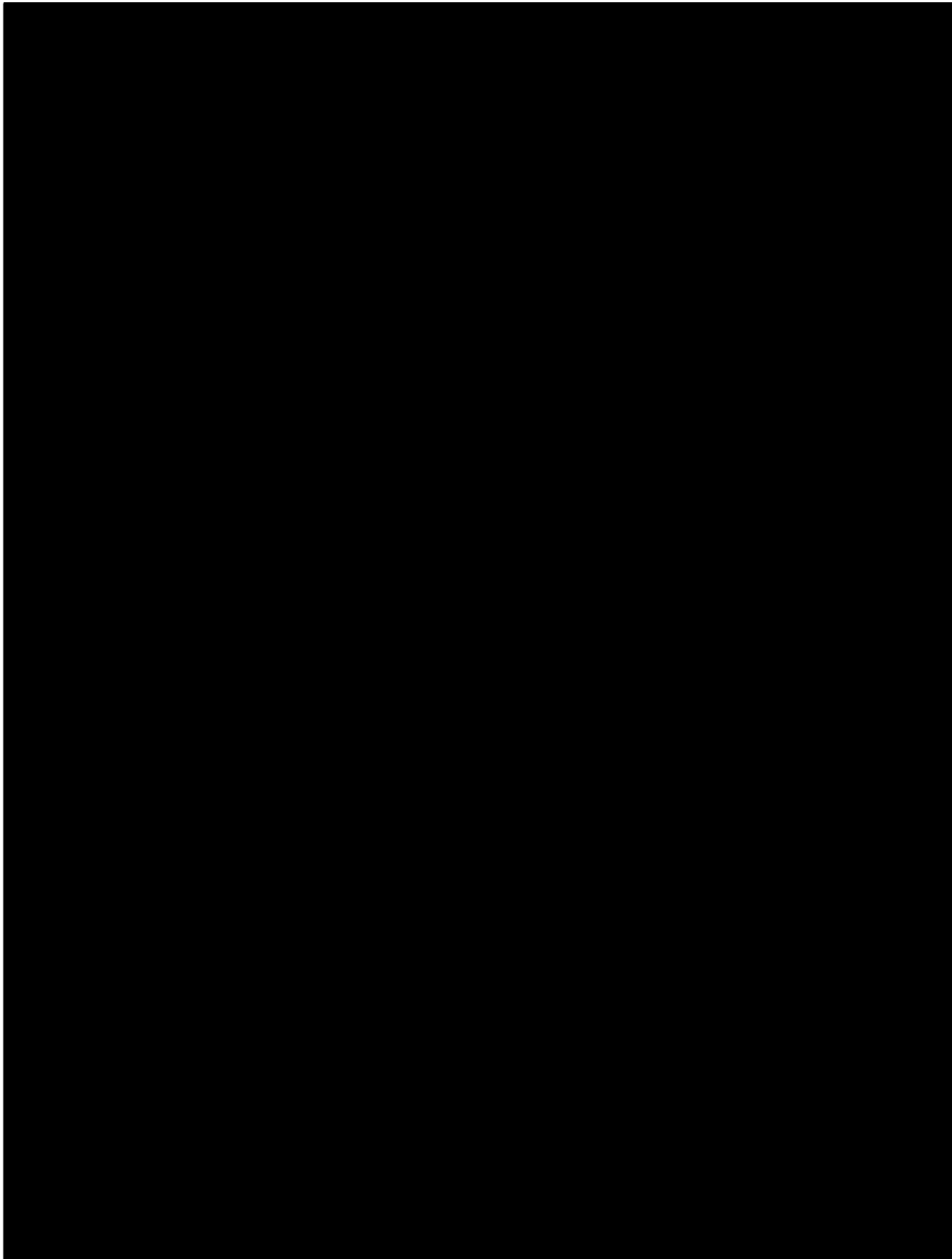


Figure 2-11. Coversand location map.

The study of aeolian coversand features on the Southern High Plains began in 1928, when the first aerial photographs of a portion of the region made by Fairchild Aerial Surveys revealed a type of dune (the windrift) never previously described in interior U.S. (Melton, 1940). This fostered an interest in the sediment supply source for the coversands that has continued for several decades. Hefley and Sidwell (1945) proposed that the sands of the Muleshoe Dunes originated in the underlying Pleistocene sands, later identified as the Blackwater Draw Formation (Reeves, 1976). Work done

by Luginbuhl (1968) postulated that the main source region for sand across the entire Great Plains was the Pliocene-Miocene Ogallala Formation, which underlies the Blackwater Draw Formation.

Huffington and Albritton (1941), Green (1961), Hawley *et al.* (1976) and Carlisle and Marrs (1982), suggested that the dune fields owe their origins to sediments blown from the adjacent Pecos River valley. They postulated that sediments were funnelled onto the Southern High Plains through re-entrant valleys in the escarpment.

Recent research by Muhs and Holliday (2001) proposed that the most likely sediment source for the coversands is not the Pecos River valley, but the Pleistocene Blackwater Draw Formation that underlies most of the sand sheets and dunes. Their study presents extensive mineralogical and geochemical analysis of late Holocene aeolian sand that indicates a composition more similar to the Blackwater Draw Formation than to Pecos River sediments. They concluded these Blackwater Draw sediments had been reworked over a long period, creating the most mineralogically mature aeolian sands on the Great Plains. Their observations support the premise that the Southern High Plains aeolian features comprise a sediment-availability-limited system that could reactivate with a modest (10%-15%) decrease in precipitation or increase in evapotranspiration.

The timing of coversand formation was first investigated over 60 years ago by Melton (1940), who recognized three phases of dune movement, in the Muleshoe Dunes. He proposed a tentative classification of sand dunes based upon changing wind direction reflected in the dunes and established a chronological series (I-III) of their formation dates: I (<5,000), II (5 to 15,000), and III (>15,000). He observed a change in prevailing wind in the last 15,000 years (estimated) from NW to SW as revealed by the relative position of blowout and windrift dunes (Melton, 1940). His work also states that from 1920 to 1930 there was an insignificant number of active dunes (Figure 2-12).

Huffington and Albritton's (1941) work on the Quaternary sands of the Southern High Plains, concentrated on the Monahans Dune Field. Using Melton's (1940) classification they differentiated the chronology and physical characteristics of the Judkins (III) and Monahans (I) formations. They recognised the Judkins had a

greater clay and silt content than the Monahans plus subtle colour and hardness differences and thought the latter to be reworked Judkins sands (Figure 2-12). Green (1961) divided the stratigraphy of the Monahans Dunes into 9 Units beginning with the Judkins formation at 19.2 ± 0.5 ka (radiocarbon assay upon snail shells). The most recent dune formations (Unit 1) were dated at less than 1 ka (Figure 2-12).

Haynes (1975) studied both Pleistocene and recent stratigraphy of the Clovis archeological site at Blackwater Draw Location # 1. Because parts of the study area lay beneath the Muleshoe Dune some attention was given to the overlying coversands, which occupy the region. He discussed a tan aeolian sand, which was designated Unit G but gave no estimated or ^{14}C age. It was stated that the sand had to have been derived from the reworking of underlying strata (Figure 2-12).

A detailed evaluation of the soils and stratigraphy of coversands along a segment of Farm Road 1731, Bailey County, Texas, in the Muleshoe Dunes was undertaken by Gile (1979; 1981). This seminal work on the coversand mantle and dune sands has contributed to development of a late Pleistocene and Holocene chronology of aeolian deposition in the region and is summarised as follows. Ten stratigraphic units in the coversands were recognised and categorised, these include: Fairview that was deposited approximately 100 yr BP to present, Muleshoe 100-4,000 yr BP (~100-4,400 cal yr BP), Longview 4,000-7,000 yr BP (~4,400-7,800 cal yr BP), Birdwell II 7,000-11,500 yr BP (~7,800-13,400 cal yr BP), Birdwell I 11,000-13,000 yr BP (13,400-15,400 cal yr BP), Roosevelt 15,000-25,000 yr BP (15,400-25,000 cal yr BP), Hale and Curry (Late-Pleistocene) and Bailey II and I (Mid Pleistocene) (Gile, 1979; 1981). Multiple phases of Holocene aeolian activity were inferred, punctuated by periods of soil development. It was stated that the origin of the Muleshoe sand sheet had its source in the alluvium that was deposited during the Pleistocene by the ancestral Pecos River that once flowed through the Portales Valley (Figure 2-12).

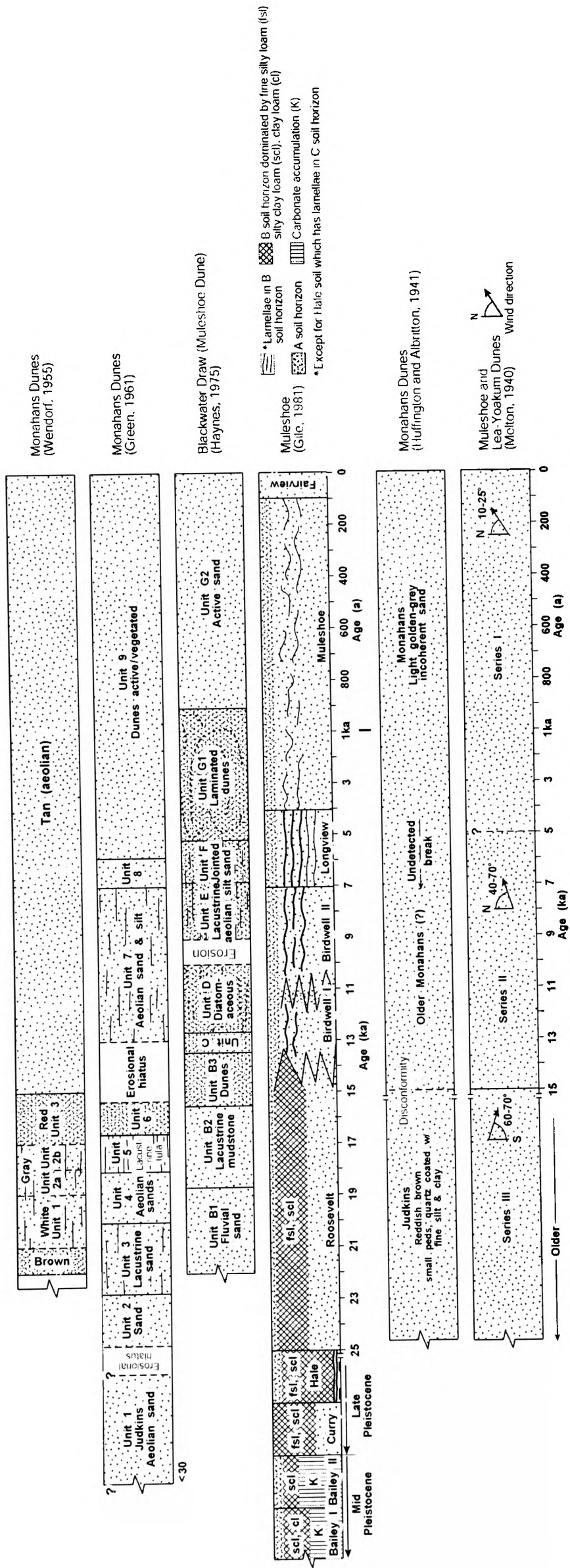


Figure 2-12. Chronology for discovery of key archaeological sites discussed in this text.

Holliday (1989b) discussed the results of radiocarbon dated materials either proximal or within Southern High Plains coversand depositional units. Conclusions drawn from the data indicate that in the southern region of the plateau aeolian sediments overlie a marsh marl deposited about 6,500 yr BP (7,400 cal yr BP). These same aeolian sediments reside beneath a palaeosol unit that began forming ~5,000 yr BP (5,700 cal yr BP), which was overlain by aeolian sediments from a second episode of deposition around 2,000 yr BP (1,900 cal yr BP). It was estimated that aeolian deposition at the Lubbock Lake archaeological site began in the early Holocene about 9,000 yr BP (10,000 cal yr BP) with two main depositional events concentrated around 6,500 to 5,000 yr BP (7,400 to 5,700 cal yr BP) and 5,000 to 4,500 yr BP (5,700 to 5,100 cal yr BP) (Holliday, 1985a).

North of Lubbock along Blackwater Draw, aeolian sediments cover a marsh deposit with an age of $8,130 \pm 500$ yr BP ($8,700 \pm 500$ cal yr BP) with the upper dune material deposited approximately 5,700 cal yr BP, based on a radiocarbon date of $5,130 \pm 100$ yr BP on sand containing organic materials (Holliday, 1989a). He further described the timing of a coversand section at Marks Beach, which consisted of middle Holocene-aged deposits that were emplaced approximately 5,000 yr BP (5,700 cal yr BP) and 1,000 yr BP (930 cal yr BP). At the Plainview archaeological site, located in a draw (dry river valley), aeolian sediments overly Palaeo-Indian artifacts of the culture that inhabited the region approximately 11.5 ka (Holliday, 1985a; Sellards *et al.*, 1947). Holliday (1989b) suggested sedimentation continued at these sites until 6,800 yr BP (7,500 cal yr BP) and was followed by a depositional hiatus and soil formation. Two metres of aeolian deposits were emplaced, which he suggested occurred after 3230 ± 600 yr BP ($3,450 \pm 600$ cal yr BP) based on a radiocarbon date from underlying lacustrine carbonates (Holliday, 1985a) (see Figure 2-13 for site locations).

An investigation of the Muleshoe Dunes completed by Wells (1992) produced three thermoluminescence (TL) age estimates in exposures of the Blackwater Draw Formation. One sample collected northeast of Portales, New Mexico, from below the floor of an active blowout yielded an age of 17.8 ± 1.8 ka. A second sample taken from the blowout exposure had an age estimate of 11.1 ± 1.1 ka. The third TL date of 17.28 ± 1.7 ka, was based on sediments from a road cut through a ridge of coversands in Bailey County, Texas, northwest of Coyote Lake. It was deduced from these dates that

the last significant period of regional coversand deposition may have concluded as recently as 17 ka (Wells, 1992).

The nature and age of coversands on the Southern High Plains was investigated by Stokes (1994). Optical luminescence dates for a number of coversand samples demonstrated a range in ages from 34 to <1 ka, with deposition occurring during four main periods approximately 13-15, 8-9, 4-6 and <1 ka (Stokes, 1994). Stokes (1994) also commented on how sand colour was a good indicator of age with Pleistocene-aged sediments exhibiting strong 5 and 2.5 YR hues, and Holocene-aged material typically having hues of 10 or 7.5 YR.

Holliday's (2001) study on the stratigraphy and geochronology of upper Quaternary aeolian sand on the Southern High Plains, found most of the dune fields and sand sheets to be Holocene in age. Overall he estimated that the earliest phase of deposition began between 11,000 and 8,000 ^{14}C yr BP (~12,900 and 8,800 cal yr BP), with rare deposits between 8,000 and 3,000 ^{14}C yr BP (~8,800 and 3,200 cal yr BP). Many deposits were dated to the late Holocene, which were mostly emplaced before 1,500 ^{14}C yr BP (1,350 cal yr BP). Muleshoe, Lea-Yoakum, and Seminole coversands underwent eastward expansion in late Holocene accumulating in several stages probably in response to drought (Holliday, 2001). Holliday (2001) states that the climatic fluctuations responsible for mobilizing the dunes were probably relatively minor, yet landscape impacts were substantial, which resulted in widespread wind erosion and dune construction.

Overall, these later studies suggest broad trends of coversand deposition on the Southern High Plains. Periods of accretion were generally recognized during the later glacial period, at the beginning of the Holocene, during the Altithermal, plus near the later Holocene time.

2.9 Archaeological investigations

This section provides a general overview of the key archaeological investigations that have been conducted on the Southern High Plains. As stated earlier, several significant archaeological sites in North America are located on this plain, and has been the focus of much interdisciplinary research. Some of the studies have provided evidence into climatic conditions during the later Pleistocene and Holocene,

which will be compared to the palaeo-environmental information interpreted from the aeolian record and the lacustrine/tufa materials from this thesis.

One of North America's earliest accepted Paleo-Indian sites was discovered in 1933 by E.B. Howard at Clovis, New Mexico (near the eastern edge of the Southern High Plains) (Bolderian and Cotter, 1999) (Figure 2-13). Subsequent important finds

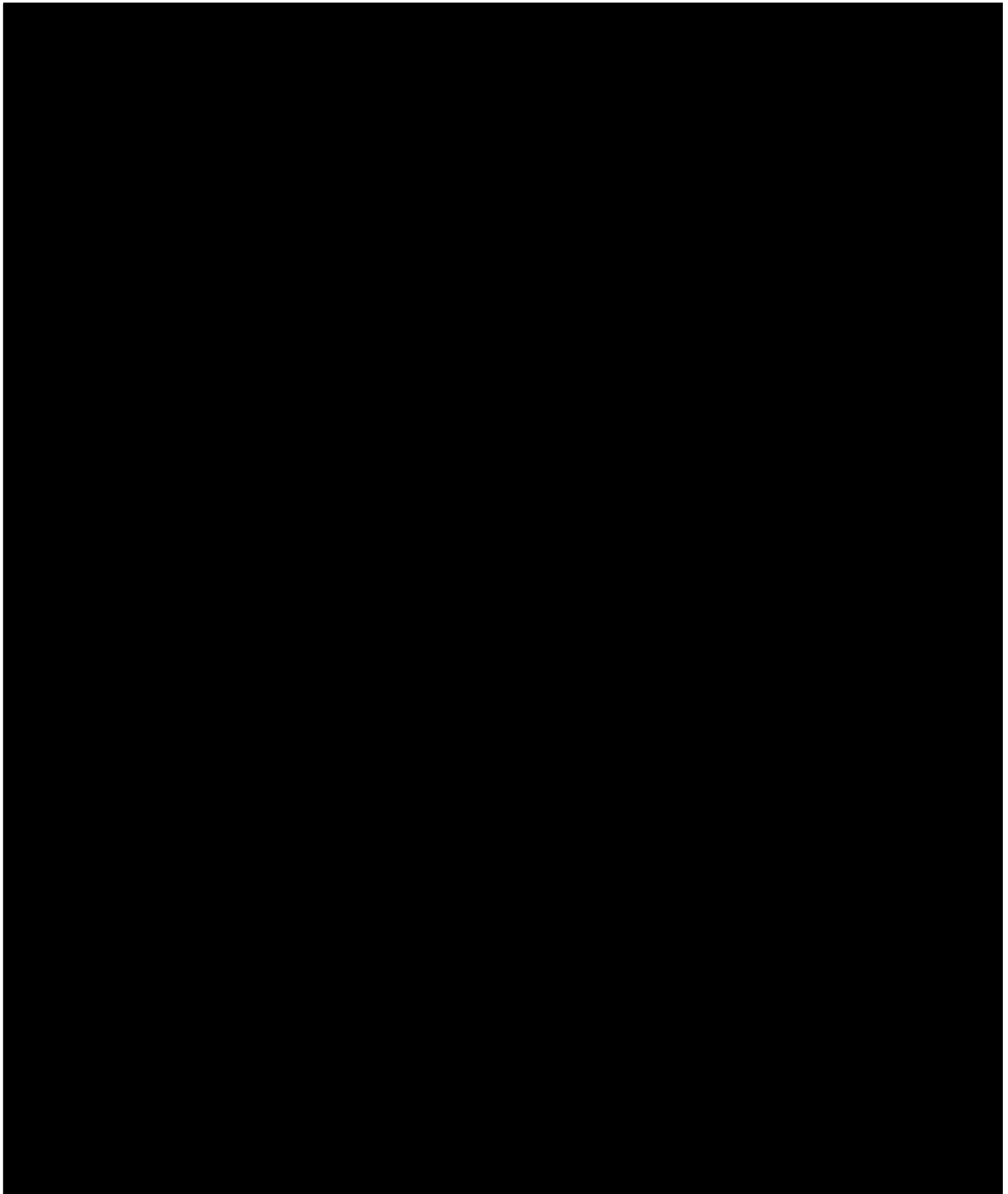


Figure 2-13. Selected Southern High Plains archaeological sites discussed in this study.

were in 1942 at Miami, and at Lubbock Lake beginning in 1948. Palaeo-Indian skeletal remains were unearthed near the south-eastern scarp of the plateau at Midland, Texas in 1953 (Holliday, 1995c). In addition to these four major sites there have also been a number of smaller finds at other localities (e.g., Plainview, Milnesand, Marks Beach, and Mustang Springs) that have established the archaeological pre-eminence of the Southern High Plains in North America (Figure 2-13). Evidence of this region's important cultural sequence has helped create a strong incentive to better understand climatic fluctuations and the human/environmental interaction on Southern High Plains (for example Appendix G and I).

Palaeo-Indians utilised the Southern High Plains resources, making flint-tipped hunting tools from several different types of stone found on or near the Southern High Plains (Holliday and Welty, 1981). Quarry was usually hunted at or near permanent sources of water, which were used by the animals as well as the Palaeo-Indians (Mandel, 2000). Evidence of Pleistocene and Holocene animal fossils on the Southern High Plains had been known since the late 1800's, when they were first discovered by early settlers who had come to the region (Cummins, 1892; Wendorf and Hester, 1975).

Investigations into the fauna fossil remains and Palaeo-Indian existence on the Southern High Plains came several decades later (Figure 2-14). In 1926 G. McJunkin, found Bison bones protruding from a newly eroded gully near Folsom, New Mexico and news of this find was sent to J. D. Figgins, the Director of the Colorado Museum of Natural History (Preston, 1997). Following up on this information, Figgins visited New Mexico and Texas, where a spear point between Bison skeleton ribs was discovered (Figgins, 1927). This earliest confirmed archaeological proof of Palaeo-Indians in the Americas established the baseline known as "Folsom Man" (Figure 2-14).

The discovery at Folsom intensified the search by archaeologists to be the first to discover skeletal remains of Palaeo-Indians in North America. Bolderian and Cotter (1999) gave a detailed description of E. B. Howard's "Southwest Early Man Project", which brought him to New Mexico in the early 1930's where he explored caves for a season, without success. In 1932, Howard moved from the caves to pit

digging on the Southern High Plains after fluted projectile points were found by R. Whiteman in the Blackwater Draw near Clovis, New Mexico (Mandel, 2000).

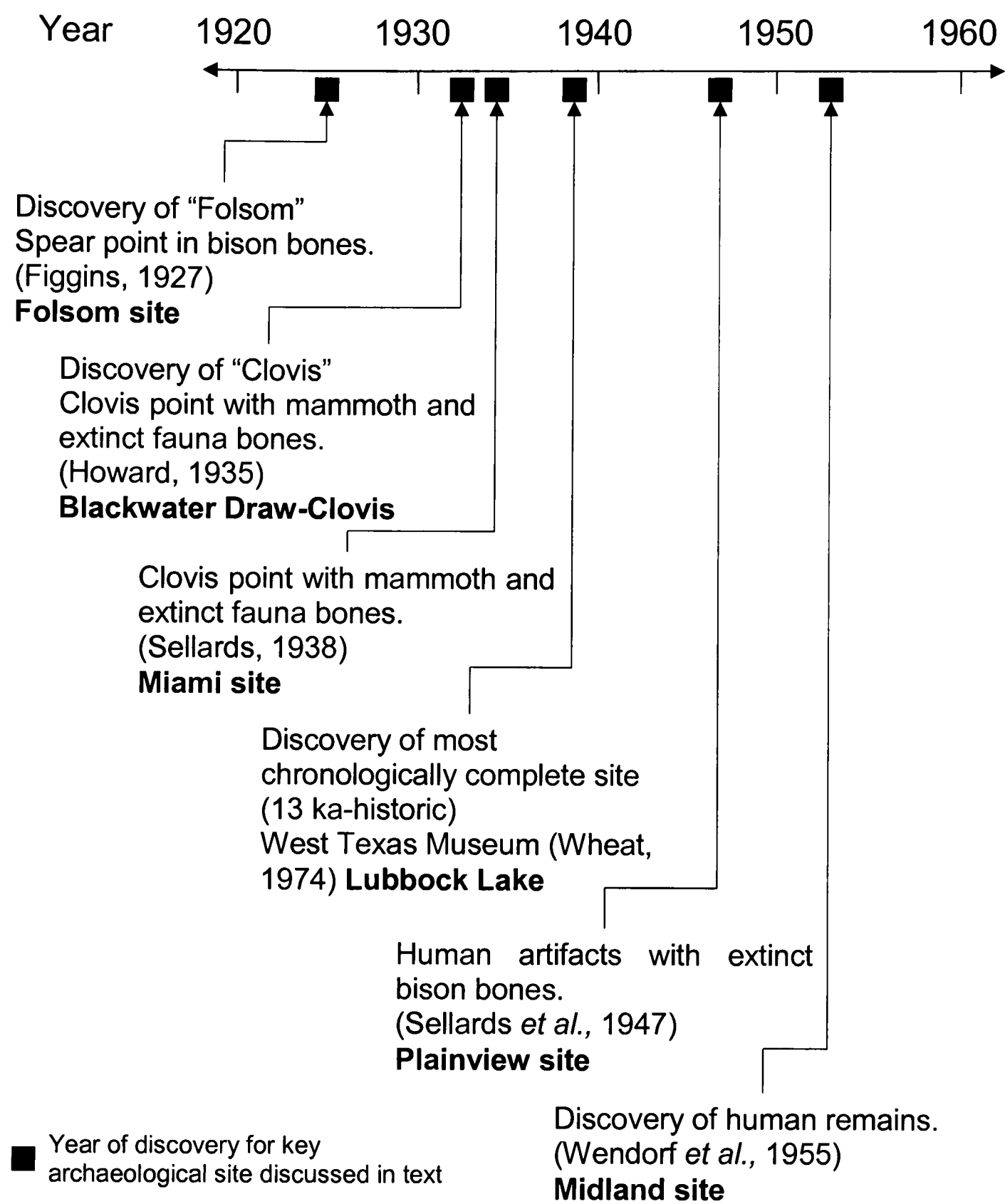


Figure 2-14. Chronology for discovery of key Southern High Plains archaeological sites discussed in this text.

Howard and Whiteman began searching the Blackwater Draw in 1933, and discovered fluted spear points among the bones of mammoth and bison in a shallow

basin along with other extinct Pleistocene fauna (Holliday, 1997b; Mandel, 2000). This confirmed the presence of mammoth hunters in the New World during the terminal Pleistocene (Holliday, 1997b). The find also established the fact that the site at Folsom was a more recent event making Clovis the oldest known human artifact find on the North American continent (Bolderian and Cotter, 1999). The projectile points at Clovis were found to have a unique design and workmanship, which has resulted in their serving as a benchmark for discoveries of similar points located at other more distant sites across North America (Mandel, 2000)

Clovis projectile points are unique to North America and have no similar form in Europe or Asia, but are related to finds discovered as far away as Florida and the Yukon (Parfit, 2000). The Clovis point poses a problem for those who support early migration of humans to North America via the Bearing land bridge (Dixon, 2001). This is because Clovis points found in the Yukon, British Columbia, and Mexico are all younger than those found nearer to Clovis. The same is also true for most Clovis points discovered in the Eastern U.S. and Mexico; the discoveries generally get older in age the closer they are to the Southern High Plains (Parfit, 2000).

Other sites of Palaeo-Indian activities on the Southern High Plains were subsequently found soon after the Blackwater Draw (Clovis) discovery. In 1935, E.N. Sellards and G. L. Evans began excavation near Miami, Texas on the northeastern edge of the plateau (Sellards, 1938). This site contained mammoth remains and fluted points in the sediments of a small playa basin (Wendorf and Hester, 1975). The West Texas Museum began work in 1939 on a more chronologically complete site at Lubbock Lake in the Yellowhouse draw on the outskirts of Lubbock, Texas, which work has continued intermittently to the present (Holliday, 1995c). Following their initial research at Miami and Lubbock Lake, Sellards and Evans, along with G. E. Meade, began excavating a site in the Running Water Draw near Plainview, Texas, which yielded human artifacts associated with extinct bison (Sellards *et al.*, 1947). Another major discovery was made in 1953 when fossil human remains were unearthed in a small deflation basin near Midland, Texas by Wendorf, Kreiger, and Albritton (1955). These finds demonstrated that the Southern High Plains had a unique concentration of archaeological sites dating to the Late Pleistocene and Holocene which promoted further investigation. In 1957, Wendorf formed the Fort Burgwin Research Center,

which undertook a multidisciplinary study conducted from 1961-62 (Holliday, 1997b). The results of the study were eventually published in 1975 (Wendorf and Hester, 1975) and was a culmination of methodologies and data from a variety of disciplines in an attempt to focus on Southern High Plains environmental change during the late Pleistocene and Holocene.

The Lubbock Lake site, which is now a National Historic and State Archaeological Landmark, has yielded a large amount of information about the Late Pleistocene and Holocene and the activities of earlier cultures and their environments (e.g., Bryant and Schoenwetter, 1987; Haas *et al.*, 1986; Holliday, 1985a, 1985b, 1985c, 1997b; Holliday *et al.*, 1983; Johnson and Holliday, 1989; Kreutzer, 1988; Stafford, 1981). This site has a virtually complete geological and cultural record that spans from Clovis to the 1880's and the summary that follows is based on the research of Holliday (1985a) and Johnson and Holliday (1989). The strata is divided into five units or strata based on archaeological finds in the sediments. Strata 1 (pre-10,500 yr BP; pre-12,300 cal yr BP), which include the remains of mammoth, and other extinct fauna along with a Clovis point and pounding stones (Figure 2-15). They state that climatic conditions during this early period may have been both wetter and cooler than those found today on the Southern High Plains.

Strata 2 encompassed the Folsom, Plainview, and Firstview Palaeo-Indian periods spanning 10,500 to 8,500 yr BP (~12,300 to 9,500 cal yr BP) that included several bison kill sites found around the perimeter of ponds. These finds were associated with stone tools and probably existed in a cyclic lacustrine and marsh environment, which began to dry due to warmer climatic conditions around 8,500 yr BP (~9,500 cal yr BP), as evidenced by a decrease in vegetative cover and an increase in aeolian deposition. The end of Strata 2 is characterized by stable conditions, which resulted in the formation of Firstview Soil.

Strata 3 estimated at approximately 8,500 to 5,000 yr BP (9,500 to 5,700 cal yr BP) contained Archaic cultural remains in an environment, which up to approximately 6,400 yr BP (7,200 cal yr BP) exhibited signs of increased aeolian deposition, and aridity with decreasing water for fauna, which resulted in diminished bison kills. During the latter half of the Strata 3 period between 6,400 and 5,000 yr BP (7,200 and

5,700 cal yr BP) the formation of soil occurred under marshy, high water table conditions, indicating a possible climatic change to one with more effective precipitation.

Strata 4 encompassed the middle to late Archaic period approximately 5,000 to 2,000 yr BP (5,700 to 1,900 cal yr BP), the beginning of which experienced a dryer and warmer climate, corresponding with the Altithermal (Antevs, 1955; Holliday, 1989b; Johnson, 1986; Johnson, 1987). Around 4,500 yr BP (5,100 cal yr BP) the climate may have become cooler and moister with a stable vegetation cover and little aeolian sedimentation.

Lubbock Lake Strata 5 includes the Ceramic period to present (approximately 2,000 yr BP to present; 1,900 cal yr BP to present), which was represented by camping areas and scattered stone tools in association with modern bison, pronghorn antelope, coyote, and wolf. The climate for Strata 5 is inferred to be similar to that of today; one having fairly effective moisture patterns, but with minor departures toward aridity and increased temperature.

Subsequent research by Holliday (2001), which re-iterates and expands on much of his earlier studies and research by others (e.g., Holliday, 1985a; 1988a; 1994; 1997b; Holliday *et al.*, 1983; Holliday and Meltzer, 1996; Sellards, 1938), and has provided additional interpretation of climatic conditions during the Palaeo-Indian occupation of the Southern High Plains and later cultures. Using information gathered principally from palaeosols, pollen data, and fossil remains, Holliday (1995c) suggests that the pre-Clovis period (Pre 11,200 ^{14}C BP; Pre13,500 cal yr BP) was likely a cool and dry savanna dominated by grassland, which differed from modern prairies and may have no modern analogue (Hall and Valastro, 1995).

Holliday (2001) inferred that during Clovis occupation (11,200 - 10,900 yr ^{14}C BP; 13,500 -12,700 cal. BP) the environment was the most equable of any time during which humans occupied the Southern High Plains. There was an abundance of water in through-flowing, perennial streams that were fed by run-off and discharge from artesian springs (Holliday, 1997b). He suggested that it was during the latter part of Clovis occupation (11,000 ^{14}C yr BP; 13,000 cal yr BP) that episodic aeolian deposition began on the Southern High Plains and continued into the early Holocene (~9,000 cal yr BP)

(Holliday, 2001). His evidence for this aridity was found in archeological data and the upland sand sheets, which were formed between 11,000 to 10,000 ^{14}C yr BP (13,000 to 11,500 cal yr BP) due to episodic drought (Holliday, 2001). By the end of the Clovis period various types of Pleistocene mega-fauna became extinct (Mandel, 2000). Haynes (1991) proposed that by 11,000 yr BP (12,900 cal yr BP) the Southern High Plains region as well as other parts of the American Southwest experienced drought conditions that resulted in the collapse of the Clovis culture and Pleistocene extinctions. Evidence for this drought has been postulated from only a few archaeological sites and to some represents too restricted a data set (Holliday, 1997b). Despite their differing views, Haynes (1991) and Holliday (2001) both recognise that by 10,900 ^{14}C yr BP (12,700 cal yr BP) there was a marked lowering of the regional water table, reduced spring activity, and more wind-deflated surfaces and deposition. Late Clovis-age wells discovered on the Southern High Plains are evidence of the first attempts by early cultures in North America to reach water supplies during periods of episodic drought (Haynes *et al.*, 1999; Meltzer, 1991; Meltzer, 1999).

According to Holliday (2000b), the Folsom period (10,900-10,200 ^{14}C yr BP; 12,700-12,000 cal yr BP) began with an abrupt change towards reduced volume in all water bodies, reflecting periods of episodic drought, which continued during Folsom through later Palaeo-Indian time. Folsom-age strata in Blackwater Location no. 1 and other lake basins contain an abundance of diatomaceous clays indicating the existence of ponds and marshes, the result of a reduced water supply. This period may have been the warmest in Palaeo-Indian times and was the earliest episode of regional wind erosion and aeolian deposition. The Folsom period was suggested to be marked by an accumulation of sheet sands on uplands and the beginning of the earliest phase of regional dune field construction (Holliday, 1995c; 2000b).

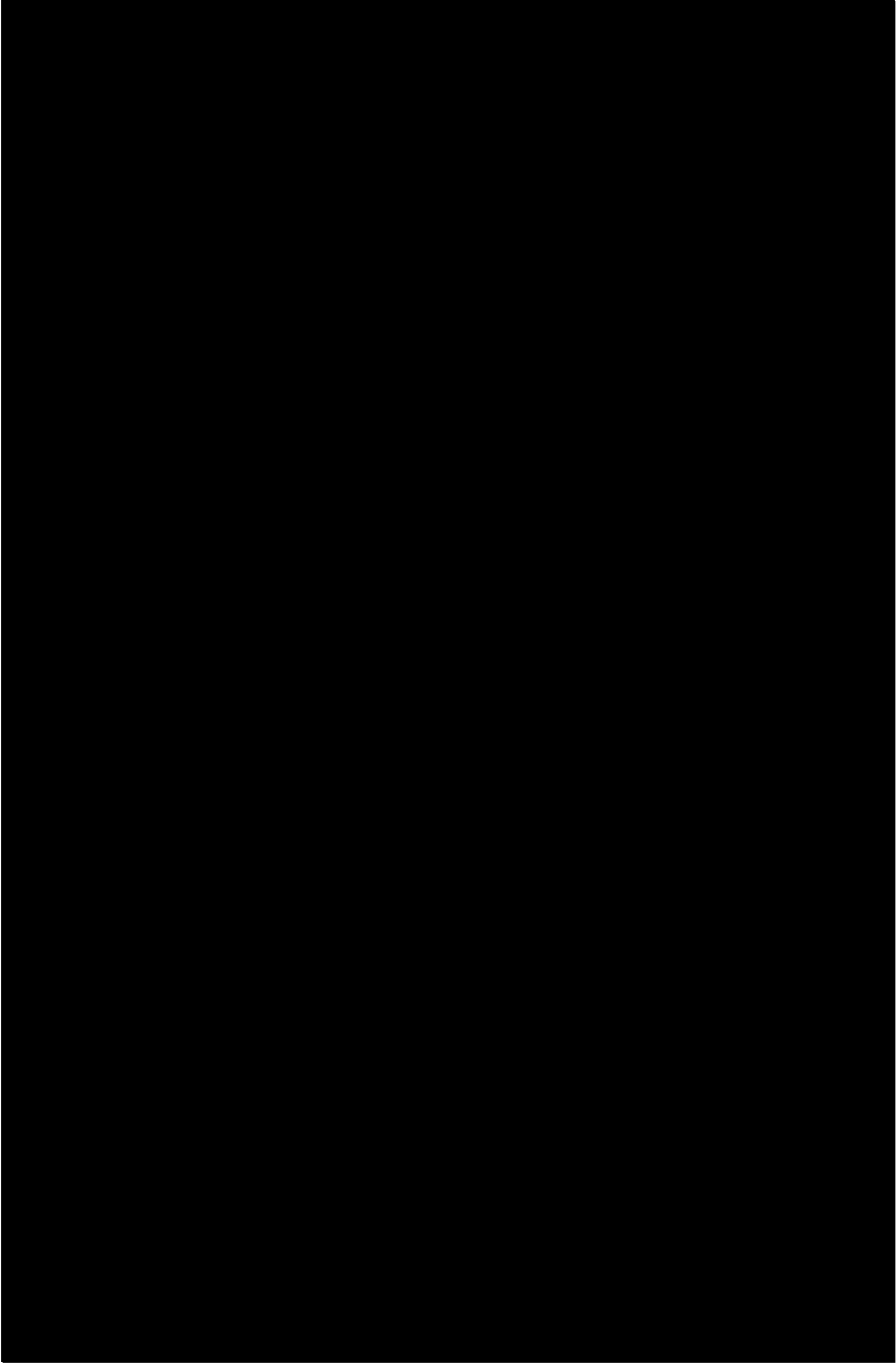


Figure 2-15. Summary of SHP cultures, environments, and inferred climatic history (adapted from Johnson and Holliday, 1989 and Holliday, 2001).

The late Palaeo-Indian period (10,200-8,000 ^{14}C yr BP; 12,000-8,900 cal yr BP) was a relatively cooler climate that fluctuated between wetter and drier conditions (Holliday, 2001). The overall trend was toward drying that resulted in enlargement of the dune fields and culminated in the warm, dry Altithermal, as defined by Holliday, occurring 8,000 ^{14}C yr BP (8,800 cal yr BP) (Holliday, 2000b). Paleoenvironmental conditions during the middle Holocene (7,500-4,500 ^{14}C yr BP; 8,200-5,100 cal yr BP) and during the early to middle Archaic period is characterised by either erosion or local stability indicating that aeolian deposits throughout the region were subject to reactivation during this time (Holliday, 2001) suggesting alternating wet and dry conditions.

Holliday (1995c) stated that around 5,000 cal yr BP, aeolian deposition in the draws (dry river valleys) ended. Holliday (1997b; 2001) also recognised an absence of substantial amounts of dunes or coversands dating to the period 5,000-1,500 cal yr BP, which led him to suggest that much of the Southern High Plains from the late Archaic to the Ceramic period was stable with little erosion or deposition. Post 5,000 cal yr BP, climatic conditions were possibly moister and cooler than previous, having conditions somewhat similar to those of today on the Southern High Plains, with episodic departures toward aridity after 3,300 cal yr BP becoming increasingly common (Holliday, 1995c).

According to Holliday (2001), the largest component of the coversands, dates to the late Holocene, which deposition began after 1,500 cal yr BP and includes substantial sedimentation during historic times. He states that this accretion occurred in a punctuated manner as indicated by the existence of multiple palaeosols, and may be due episodic departures toward aridity.

Resources required by the early inhabitants on the Southern High Plains were relatively limited with water being the most important. During the late Pleistocene and early Holocene this region evolved from an alluvial environment to lacustrine and palustrine conditions, interfacing with an aggrading aeolian environment (Holliday, 1995c). Alternating wet and dry conditions throughout the Holocene made lakes, playas, and springs that existed under the drier climate regimes a vital part of human existence on the Southern High Plains (Wood *et al.*, 2002). Whatever subsistence activities Clovis and later inhabitants engaged in, they were usually near shallow, and

often seasonally available water (Holliday, 1997b). The importance of water to the Palaeo-Indians can be seen at almost every kill or camp site, which is located in close proximity to a lake or playa, which had been filled during a seasonal or a lengthier period of rain (Holliday, 1997b). Additionally, the Clovis site contains a hand dug pit which is now believed by archaeologists to be the first known man-made well in the New World; an attempt by the occupants to adjust to changing environmental conditions (Haynes *et al.*, 1999). The important connection between the early inhabitants of the Southern High Plains, their prey, and water may help to narrow the field of investigation for archaeological sites that might contain artifacts belonging to Palaeo-Indians or later cultural groups, and may further lead to the discovery of subsequent skeletal remains. Sites such as Lubbock Lake and Clovis are good examples of typical Palaeo-Indian camping locations, in proximity to water, which have been overlain by over 10,000 years of Holocene aeolian deposition (Bolderian and Cotter, 1999).

2.10 Luminescence dating

2.10.1 Physical basis of luminescence dating

Luminescence dating measures light emission from crystals, mainly quartz and feldspar, which is due to accrued nuclear radiation in the burial environment. Quartz and feldspar exhibit solid state physical properties that allow them to ‘record’ and ‘erase’ their exposure to ionizing radiation. For a given type of crystal in a given type of burial environment more light is emitted the longer the crystal has been buried. The crystals do not store “light”, but store energy which can be released by heating the sample (thermally stimulated luminescence-TL) or by exposing the sample to light (optically stimulated luminescence-OSL) (Aitken, 1985; 1998). The luminescence age is therefore a record of elapsed time since the last exposure of the material to sunlight before burial or heat (Figure 2-16).

Luminescence requires the existence of crystal lattice defects, which interrupt the regular order of the crystal, some of which were acquired during mineral formation. There are three categories of crystal lattice defects that can be identified (1) vacancies, which are unoccupied lattice positions; (2) impurities, classified as chemicals that may either substitute or occupy interstitial lattice locations; and (3) the Schottky-Frenkel type of defect, referring to a defect pair consisting of a vacancy and a corresponding

interstitial atom (Wagner, 1998). These defects are commonly characterised by positive or negative charge deficits, which trap free charges diffusing around the crystal lattice (Aitken, 1998).

In a sediment matrix, crystals are exposed to ionising radiation resulting from the decay of naturally occurring radioisotopes ^{40}K , ^{232}Th , and ^{238}U and the emission of alpha (α) and beta (β) particles as well as gamma (γ) and cosmic radiation, which interact with the atoms of a solid. The interaction of this radiation with the mineral grains frees electrons (e^-) from the atoms and results in positively charged 'holes' (Figure 2-17) (Wagner, 1998). These free charges move through the crystal lattice while the holes are trapped in lattice defects. Electrons migrate through the crystal until a trapped hole is encountered and recombination occurs or they become trapped at 'electron traps' in lattice defects with a negative charge deficit. Lattice defects which are occupied by charges are called 'centres' (Aitken, 1985, 1998). Through exposure to heat or light (*stimulation*), the electrons may be released from the traps, diffuse through the conduction band, then recombine with the trapped hole, emitting stored energy in the form of luminescence (Aitken, 1998; Duller, 1996). The steps involved are illustrated by the energy-level model shown in Figure 2-18.

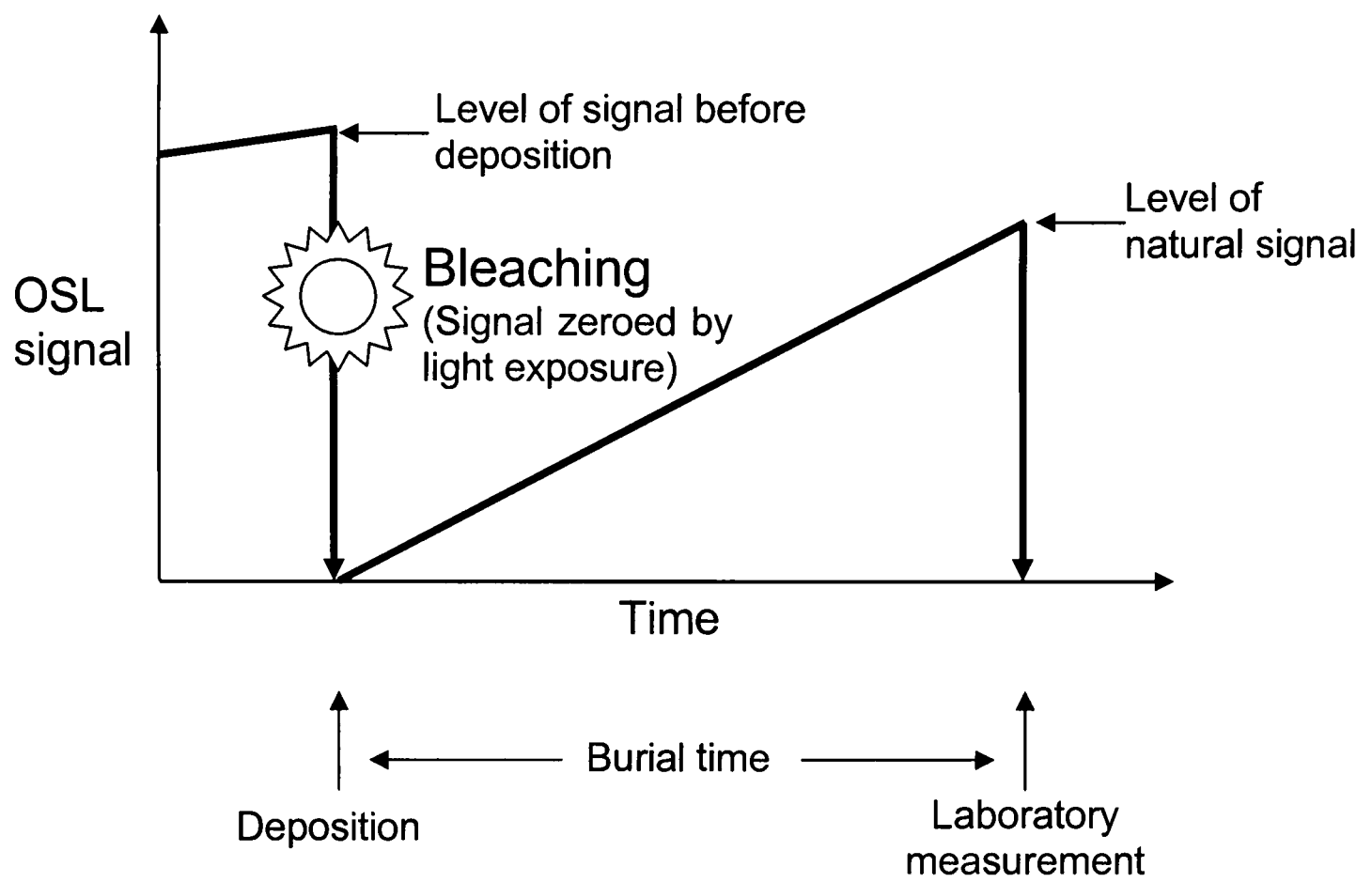


Figure 2-16. Resetting of the signal (trapped-electrons). This occurs when sediment is exposed to light ('bleaching') during erosion, transportation, and deposition.

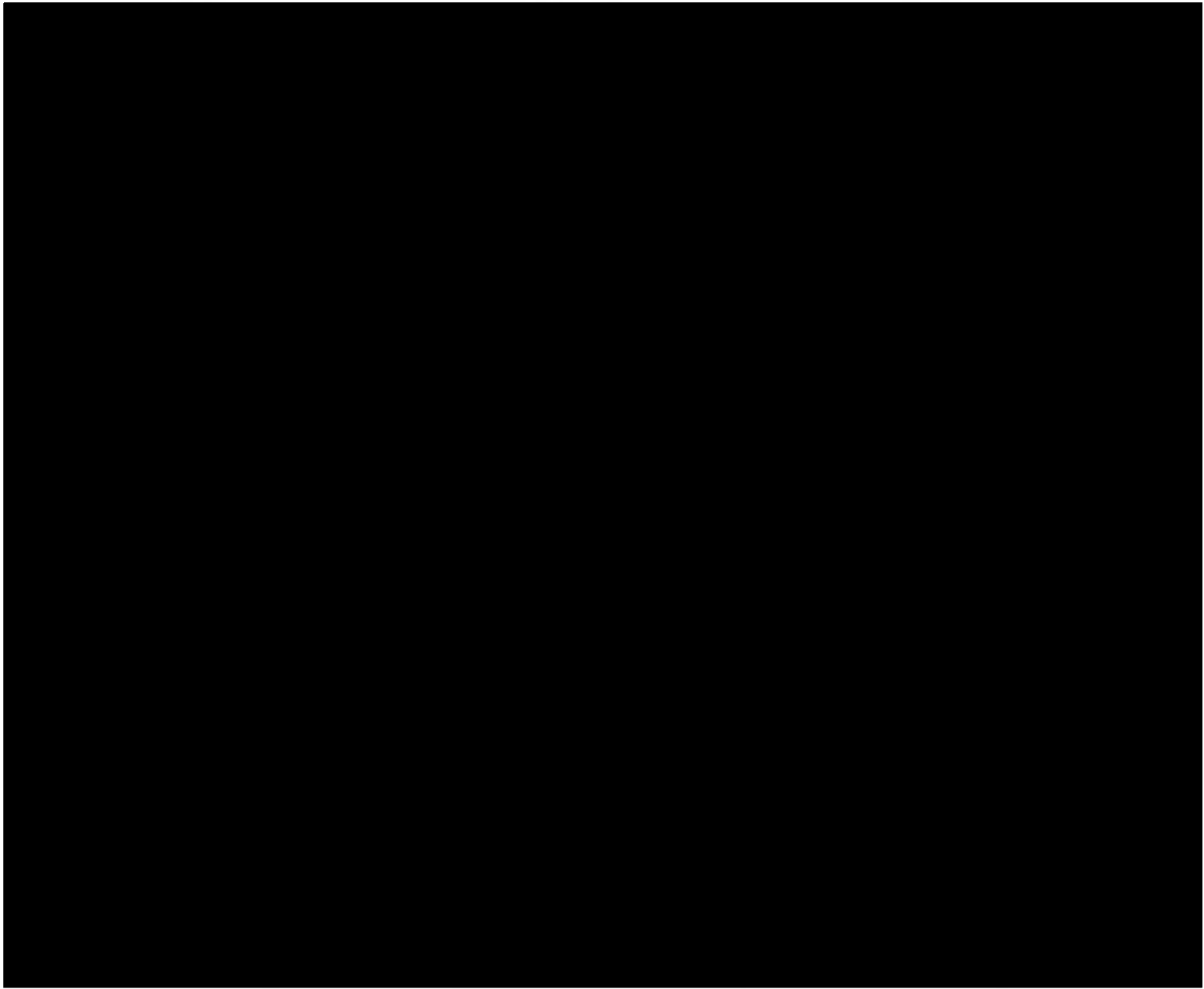


Figure 2-17. Schematic diagram of quartz structure. (a) Luminescence mechanism of quartz structure. (b) Defects in the crystal lattice are shown as an O^{2-} vacancy and an Al^{3+} in place of Si^{4+} . These are associated with charge defects that serve as traps for freed charges. (c) Ionization frees electrons (e^-) and electron holes which then wander through the lattice until the electron is trapped at the O^{2-} vacancy and the hole at the Al^{3+} defect. (d) The system becomes metastable during this excited stage. (e) Trapped electrons are released during stimulation (optical or thermal) and recombine with the Al^{3+} center emitting luminescence (adapted from Wagner, 1998).

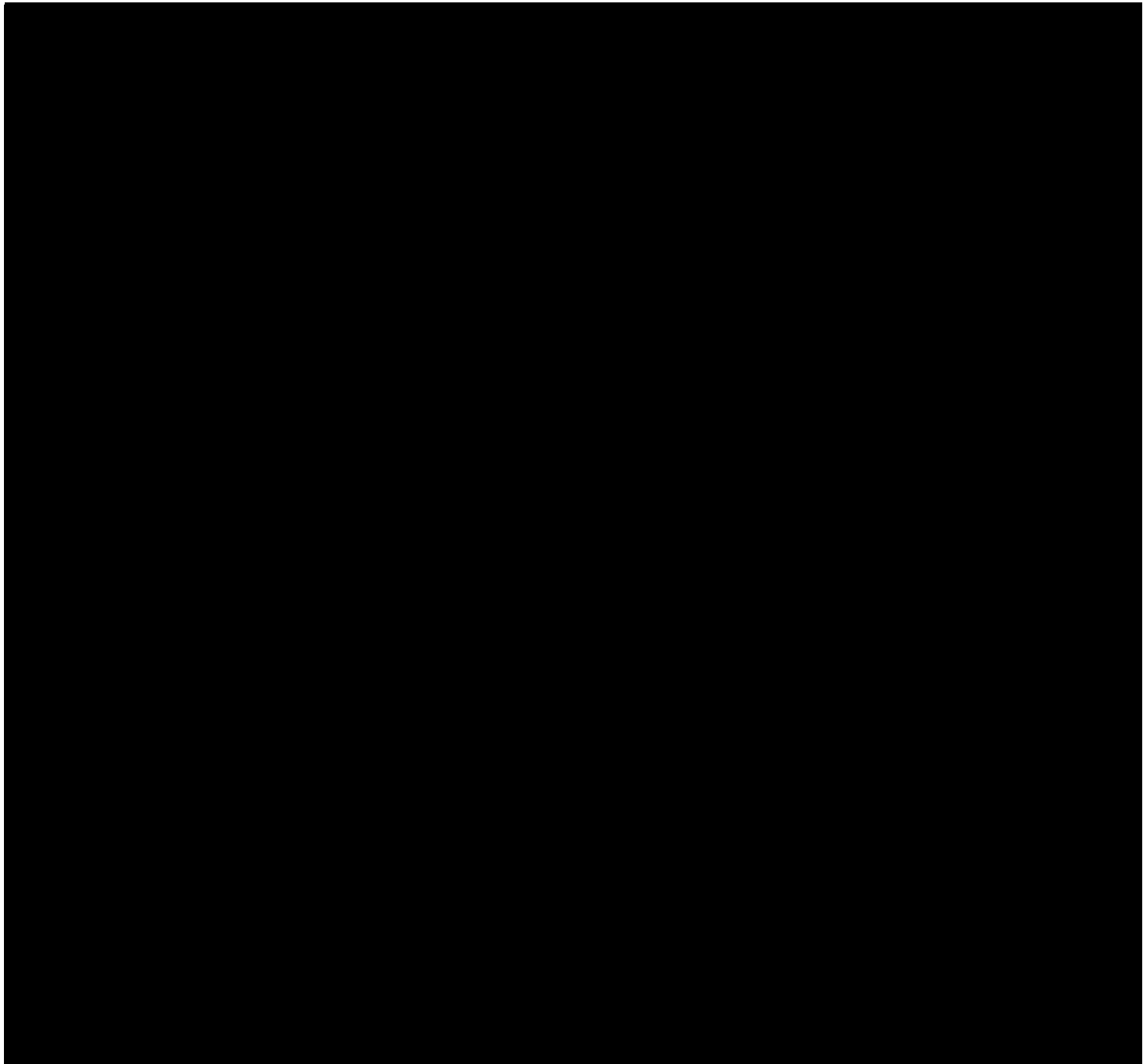


Figure 2-18. Energy-level model. (a) Normal circumstances with atoms residing in a low energy or ground state with empty charge traps. (b) Energy added to system through ionizing radiation results in the ejection of an electron from the valence band to the conduction band and into an electron trap, while the remaining positive charge (electron hole) is trapped at a hole trap. (c) Electron and hole in metastable state occupying charge traps within the forbidden gap. (d) At a later stage the electron is liberated from its trap by optical (or thermal) stimulation, this causes the electron to diffuse through the conduction band and recombine with the trapped hole causing stored energy to be emitted as a photon of light (adapted from Aitken, 1998 and Wagner, 1998).

2.10.2 Measurement of luminescence

According to Aitken (1998), “serious scientific studies of luminescence”, began in the mid-seventeenth century with Boyle in 1664, who investigated the emission of light (luminescence) from natural crystals. About 100 years ago, Wiedemann and Schimidt (1895) discovered that this luminescence is induced by ionising radiation. In the mid-20th century, Daniels *et al.* (1953) presented the idea of using minerals for age determination due to their capacity to act as natural thermoluminescence (TL) dosimeters.

Thermoluminescence (TL) was initially developed as a dating technique for establishing age estimates on archaeological samples, such as pottery and burnt stones, from hearths that had previously been fired, or heated, resetting their luminescence signal to zero. The basic approach to the measurement of TL involves the heating of laboratory-refined quartz or feldspar from ambient room temperature to between 400 and 700°C (Aitken, 1985). A luminescence signal is produced as the sample is heated. This results in a typical ‘glow curve’, with the magnitude of the signal plotted as a function of temperature (Figure 2-19). The equivalent dose (D_e) the quartz or feldspar has received in the field is based on thermally heating the sample. The individual peaks in the glow curve represent thermal activation temperatures for individual electron traps (Aitken, 1998).

In general, the higher the activation temperature the deeper the trap lies within the ‘forbidden gap’ (Aitken, 1998). This is important since some traps are not stable over a geological time period (Duller, 1996). For example, a 100°C peak will decay rapidly ($1/2$ hr) over time at room temperature. The glow curve shown in Figure 2-19 has a comparatively shallow trap at 100°C from which the unstable electrons may be released. Thus a luminescence signal with trapped charges at this site would be unsuitable for dating over a geologic time period (Duller, 1996). Traps of higher activation temperature and greater stability are therefore used for TL dating.

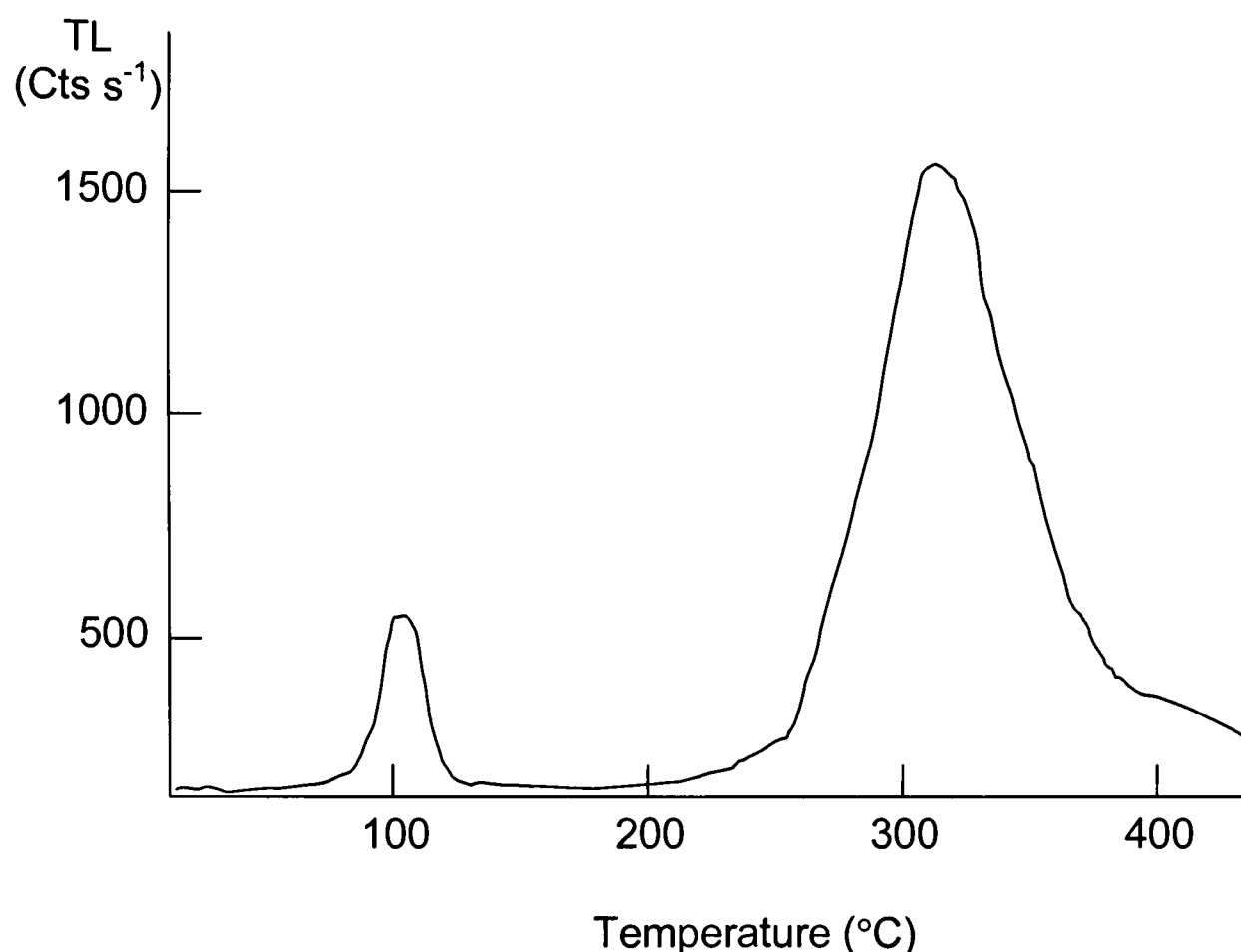


Figure 2-19. TL glow curve for a quartz sample from northeast Tasmania.

Since thermoluminescence dating covers an age range of 10^2 up to 10^5 years, which is beyond the limits for the ^{14}C method, this technique was well suited for archaeological investigations. Some of the first materials dated using TL were ceramics and bricks (Grogler *et al.*, 1958). The dating of ceramics was the dominant application of TL during the 1960s and 1970s (Wagner, 1998; Aitken, 1998). This was followed, in the 1980s, by investigations into using TL for the dating of sediments. Russian scientists were among the first to examine thermoluminescence intensities for unheated sediments with their research being examined in detail by Wintle and Huntley (1982). Initially, the application of TL dating of sediments from various environments appeared to be the only suitable method for Quaternary environments (e.g., Mejdahl, 1985; Singhvi *et al.*, 1982; Wintle, 1981; Wintle and Huntley, 1980) and specifically aeolian sequences (Stokes, 1994); however, its application to sedimentary environments was not without some difficulties (Debenham, 1985; Wintle *et al.*, 1993).

The main challenge TL practitioners confronted was that light exposure does not entirely remove pre-burial luminescence, with the TL in sediments containing both light-sensitive and light-insensitive components (Huntley *et al.*, 1985; Stokes, 1994; Wintle and Huntley, 1980). Other difficulties were encountered when applying TL methods to older (50 to >100 ka) loess deposits, feldspars, and polymineral grains (Debenham, 1985; Wintle, 1993). Since that time, a range of approaches have been developed to overcome these difficulties (e.g., Berger and Easterbrook, 1993; Berger and Eyles, 1994) and today one sees an increasing number of published TL sediment dates and applications (see proceedings of the 9th and 10th International Conference on Luminescence and Electron Spin Resonance Dating in Volumes 20 and 22 of Quaternary Science Reviews), which demonstrate the continued expansion of the thermoluminescence field.

In the mid-1980s Huntley *et al.* (1985) proposed a new technique known as optically stimulated luminescence (OSL). In this technique the D_e , or equivalent dose of quartz or feldspar is based on light-stimulated luminescence (OSL) rather than heat-stimulated luminescence (TL). Using an argon laser for light stimulation and a series of filters which detected peak transmission at 400 nm, Huntley *et al.* (1985) were able to detect OSL from feldspars. They were also able to demonstrate the possibility of measuring only the light-sensitive luminescence by selectively sampling the optically-sensitive traps and avoiding the challenges encountered in TL dating with regards to light-insensitive luminescence (Stokes, 1994). Other advantages of OSL over TL include, automated and rapid read-out of the luminescence signal (Liritzis, 2000), the measurement of OSL at room temperature, and avoidance of thermal quenching and blackbody radiation” (Stokes, 1994).

Following the discovery by Huntley *et al.* (1985) of optically stimulated luminescence, Hütt *et al.* (1988) later demonstrated the possibility of stimulating luminescence with infrared photons. Until the late 1990s, the majority of optical dates were based on infrared (IR) stimulation of feldspars (Aitken, 1998; Wintle, 1997). This was primarily due to poor aliquot to aliquot reproducibility for quartz, and insensitivity of this mineral to infrared stimulation (Murray and Olley, 2002). Over the last few years, the mineral and laboratory techniques that are used to measure OSL have changed. Initially, stimulation of the quartz grains required visible light that was

usually derived from expensive lasers (e.g., Ar, Kr) or a monochromatic beam from xenon spectrum (Huntley *et al.*, 1985; Rhodes, 1988; Smith *et al.*, 1986). The development of inexpensive green and blue light sources (Bøtter-Jensen and Duller, 1992) filtered from the broad-band emission of an incandescent source became available, which has since been superseded by light emitting diodes (Bøtter-Jensen, 2000).

Overall, the fundamental concept of luminescence dating is to use naturally occurring minerals such as quartz and feldspar as dosimeters to record the exposure to the weak flux of ionising radiation within the surrounding sediment matrix. Laboratory measurements are used to estimate the accumulated dose that the material or sample has absorbed. The resulting luminescence signal is dependant upon the equivalent dose (D_e) (expressed in SI units of Grays (Gy)), which is a measure of the radiation exposure during the burial period (Forman, 1989). The longer the exposure to radiation, the larger the resulting signal. Separate measurements are carried out in both the laboratory and on-site to assess the rate (dose-rate) (Gy/ka^{-1}) at which the energy is absorbed from the flux of nuclear radiation (Aitken, 1998). The luminescence age equals the accumulated absorbed dose (D_e) divided by the dose-rate, expressed as;

$$Age(ka) = \frac{D_e (Gy)}{D_{\alpha} + D_{\beta} + D_{\gamma} + D_{cosmic} (Gy ka^{-1})} \quad (1)$$

The D_e is the laboratory β or γ dose that produces the same luminescence intensity as the accumulated absorbed dose or ‘palaeodose’. The absorbed dose is the amount of exposure induced by α , β , and γ radiation, resulting from the decay of naturally occurring radioactive elements within the sediment matrix, including incoming cosmic rays.

The dose-rate is the rate at which the sample absorbs ionising radiation (the effective D_{α} , D_{β} , D_{γ} , and D_{cosmic}) from the surrounding sediment matrix, and is estimated either *in-situ* or by lab-based dosimetry (Aitken, 1998; Wagner, 1998). Various options are available for determining the U, Th, and K and consist of :

- 1) Portable 4-channel γ -Spectrometry (Liritzis and Galloway, 1980)
- 2) High Resolution γ -Spectrometry (HRGS) (Murray and Aitken, 1982; 1988; Saro and Pikna, 1987)

- 3) Neutron Activation Analysis (NAA) (Aitken, 1998; Stokes, 1994)
- 4) Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Aitken, 1998)
- 5) Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) (Aitken, 1998)
- 6) Thick Source α -Counting (TSAC) (Aitken, 1985; Huntley *et al.*, 1994; Liritzis and Galloway, 1982)
- 7) Thermoluminescence Dosimetry (TLD) (Liritzis and Galloway, 1980)
- 8) Flame Photometry (FP) (Potts, 1987; Stokes, 1994)

The cosmic dose-rate a sample receives depends on the amount of shielding the overlying sediments provide. According to Aitken (1998), the cosmic contribution is not significant, except at sites with relatively low radioactivity. An estimate of 0.18 Gy ka^{-1} at a metre depth with attenuation increasing at depth by approximately 14% per metre in sediment or rock with a density $\sim 2 \text{ g cm}^{-3}$ is usually assumed (Aitken, 1985; 1998). Attenuation values for other situations are described by Prescott and Hutton (1988).

Water within the pore spaces of sediment can absorb a portion of the radiation that would otherwise reach the grains on which the D_e estimate is made, and must be factored into the age determination equation. Aitken (1985; 1998) provides practical steps for calculating and evaluating the moisture content of sample. The steps and equation for moisture correction are discussed in Chapter 3.

2.10.3 Equivalent dose (D_e) determination

The determination of D_e requires measurement of either TL or OSL in order to compare the ‘natural’ stored signal of a sample with ‘artificial’ signals acquired by doses of irradiation under controlled circumstances (Aitken, 1998). There are two basic approaches in determining the D_e , the ‘additive-dose method’ and ‘regenerative-dose method’. Following either of these two methods researchers can use the ‘multiple aliquot’ or ‘single aliquot’ approach, which is discussed below. Additive-dose requires prepared aliquots to be separated into groups with one reserved for the measurement of

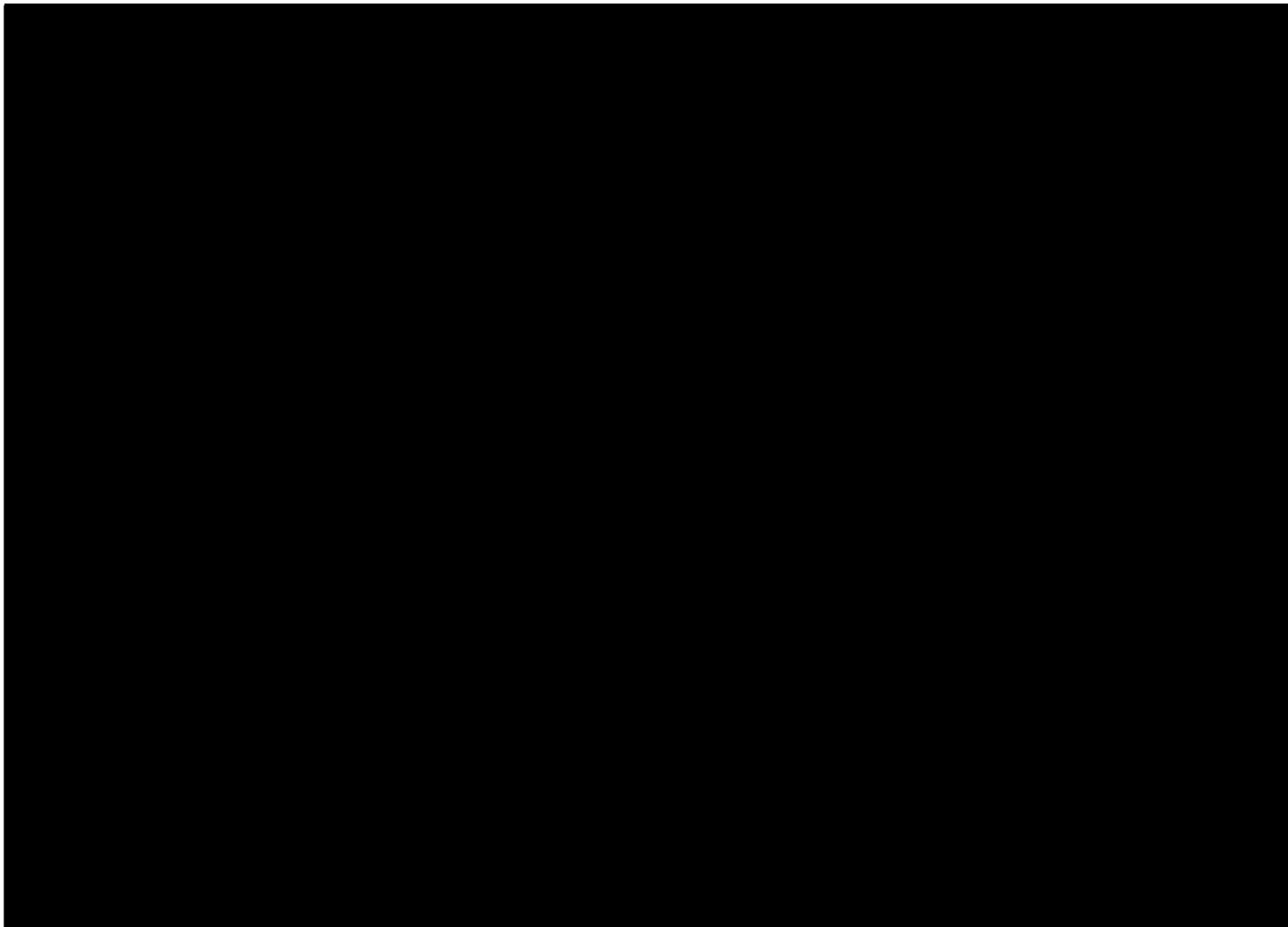


Figure 2-20. Additive-dose method for determining equivalent dose. Data points are averaged values from a group of aliquots. Each group has received a similar laboratory dose (except for N which was given zero dose). The growth is linear with increasing dose. The D_e value is determined from the intercept on the dose axis (x-axis) (adapted from Aitken, 1998).

the natural signal, while the other aliquots are given varying doses of radiation prior to measurement (Duller, 1996; Aitken, 1985; 1998). The luminescence signal intensity of the natural and dosed points is plotted against the given laboratory dose. The line of fit for these points is extrapolated back to the x-axis to give the burial dose, D_e (Aitken, 1985). The additive-dose method is quite suitable when the luminescence versus dose data is linear and an accurate extrapolation can be made (Huntley and Lian, 2000) (Figure 2-20).

The regeneration technique, suggested by Wintle and Huntley (1979), involves measuring the natural luminescence signal of a subset of aliquots while the remaining sample aliquots are bleached to remove their luminescence signal and then given incremental doses of radiation (Duller, 1996). The D_e is interpolated from the intersection of the natural luminescence (N) signal with the response curve derived from the regenerated luminescence signal (Figure 2-21). An advantage of the

regeneration method is that it involves interpolation rather than extrapolation, which eliminates the uncertainties that may arise from nonlinear growth (Aitken, 1998). More recently, variations upon the regeneration method such as, single aliquot regeneration additive dose (SARA) (Mejdahl and Bøtter-Jensen, 1994), single aliquot additive dose (SAAD) (Murray and Roberts, 1997), and single aliquot regeneration (SAR) (Murray and Roberts, 1998; Murray and Wintle, 2000b) have proven satisfactory.

Following either of these methods to determine the D_e (additive-dose or regenerative methods), researchers can use the 'multiple aliquot' or 'single aliquot' approach. Multiple aliquots require typically 20-80 sub-samples to construct a growth curve (Duller, 1996), and the literature is replete with a variety of protocols that can be implemented (e.g., Smith *et al.* 1986; Wintle, 1997).

The multiple aliquot approach was mainly used until about 1997, but since it proved to be costly, labour intensive, and required large quantities of material for analysis it was superseded by the single aliquot approach which has since dominated the field. Duller (1991) initially proposed procedures for the single aliquot method using potassium-rich feldspars stimulated with an infrared light source.

Murray *et al.* (1997) presented the first single aliquot additive dose protocol for quartz. This was followed by much research into the behaviour of quartz in order to develop a robust single aliquot protocol for that mineral (Murray and Roberts, 1998; Murray and Wintle, 1999; Wintle, 1997; Wintle and Murray, 1998; Wintle and Murray, 1999). Wintle and Murray (1998) demonstrated that there was a sensitivity increase due to preheating in the 230-330°C region when stimulating this mineral. Subsequent tests also revealed that sensitivity change was not only a function of preheat temperature but was also related to the radiation dose history. This phenomena had been extensively studied by others prior to Murray and Wintle (1998) (e.g., Zimmerman, 1970). It was noted that during measurements on two unbleached discs (one contained a natural dose while the other was bleached then irradiated with a dose equivalent to the natural), that the sensitivity change with preheat was different for the natural when compared to the laboratory dosed sample. It was further determined that sensitivity changes could be monitored using the test dose response of the TL 110°C peak (Wintle and Murray, 1998). Murray and Roberts (1998) followed up with the development of the single aliquot regenerative (SAR) dose protocol that incorporated a

procedure in which the observed OSL signals are corrected using the 110°C TL response. This SAR protocol was further refined by Murray and Wintle (2000b). Their approach used the OSL response to a test dose, applied subsequently to OSL measurements of each of the natural and regenerated points, rather than the 110°C TL peak, to correct for luminescence sensitivity changes.

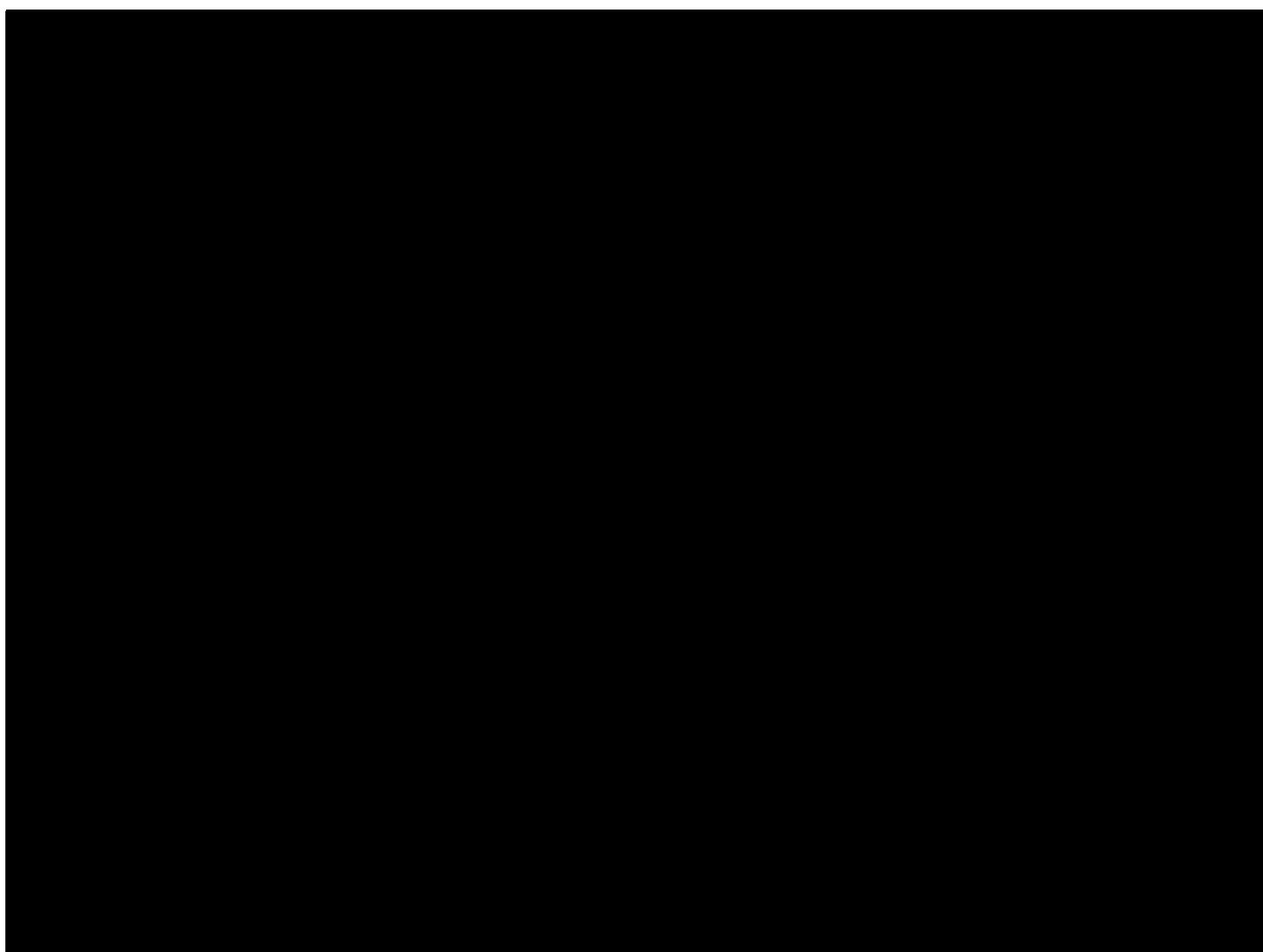


Figure 2-21. Regeneration growth/dose response curve. The natural luminescence (N) signal is measured from a subset of aliquots and compared to the regenerated signal from bleached aliquots that have been variably dosed. The D_e is interpolated from the intersection of the natural signal with the regeneration curve (adapted from Aitken, 1998).

The advantages of the single aliquot regeneration approach are basically: (1) the uncertainty is estimated from several independent interpolated D_e measurements, rather than uncertainties associated with extrapolating a single modelled growth curve fitted

to data, which was derived using additive dose multiple aliquot approaches (Murray and Olley, 2002); (2) separate D_e estimates on each aliquot make it possible to assess the distribution of doses within a sample (Duller, 1995; Duller, 1996; Murray and Olley, 2002); (3) D_e values of samples produced from single aliquots allow for data interrogation to check for partial bleaching and/or bioturbation. Developments with single aliquot regeneration techniques have led to an increase in the number of published quartz dates with age estimates ranging from a few decades to over 500 ka (e.g., Murray and Olley, 2002; Rich and Stokes, 2001; Stokes, 1999). Performance of the single aliquot technique is discussed in Stokes *et al.* (2000) (Appendix H).

2.10.4 Single aliquot regenerative (SAR) dose protocol

The D_e estimates calculated using the single aliquot regeneration (SAR) methodology following Murray and Wintle (2000b) (Figure 2-22). During the SAR protocol, each aliquot was dosed ($+\beta=0$ for natural) preheated, and optically stimulated iteratively to establish the natural OSL intensity and the aliquots' sensitivity to regenerated doses (Figure 2-22). Optical stimulation at $\lambda=470$ nm, with a power of 18 mW/cm^{-2}) was generally for 15 s at a measurement temperature of 125°C ($\sim 80\%$ signal depletion typically occurring during the first 2-5 s). Sensitivity changes were checked and corrected by a series of steps, which included a small test dose, a 250°C 10s preheat, and an additional optical stimulation (Murray and Wintle, 2000b). The data used to construct a growth curve is given by;

$$L_{n\text{corr}} = \frac{L_n - L_{n\text{bg}}}{T_n - T_{n\text{bg}}} \quad (2)$$

Where L_n and T_n are the luminescence from the natural ($n=0$) or regenerated ($n=1-4$) SAR cycles and test doses respectively (first 1.0 s of optical stimulation selected for both), and $L_{n\text{bg}}$ and $T_{n\text{bg}}$ are background signal levels, measured over the latter portions of the optical stimulation cycle. Examples of resulting SAR growth curves are presented in Figure 2-23. Approximately 9 aliquots per sample were used to define the resulting D_e and its variance, with an average calculated to provide the basis for age assessment.

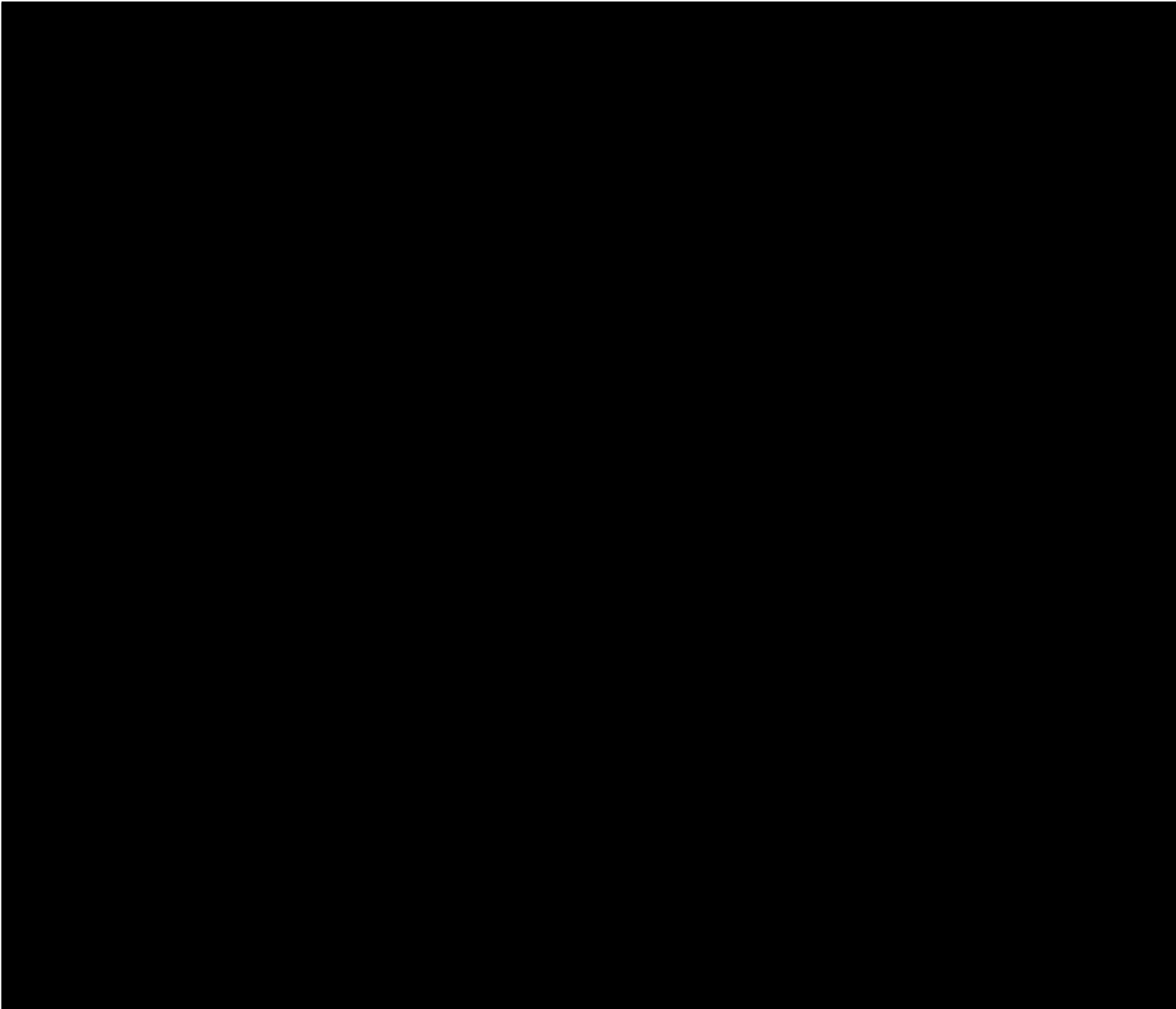


Figure 2-22. SAR protocol (adapted from Murray and Wintle, 2000)

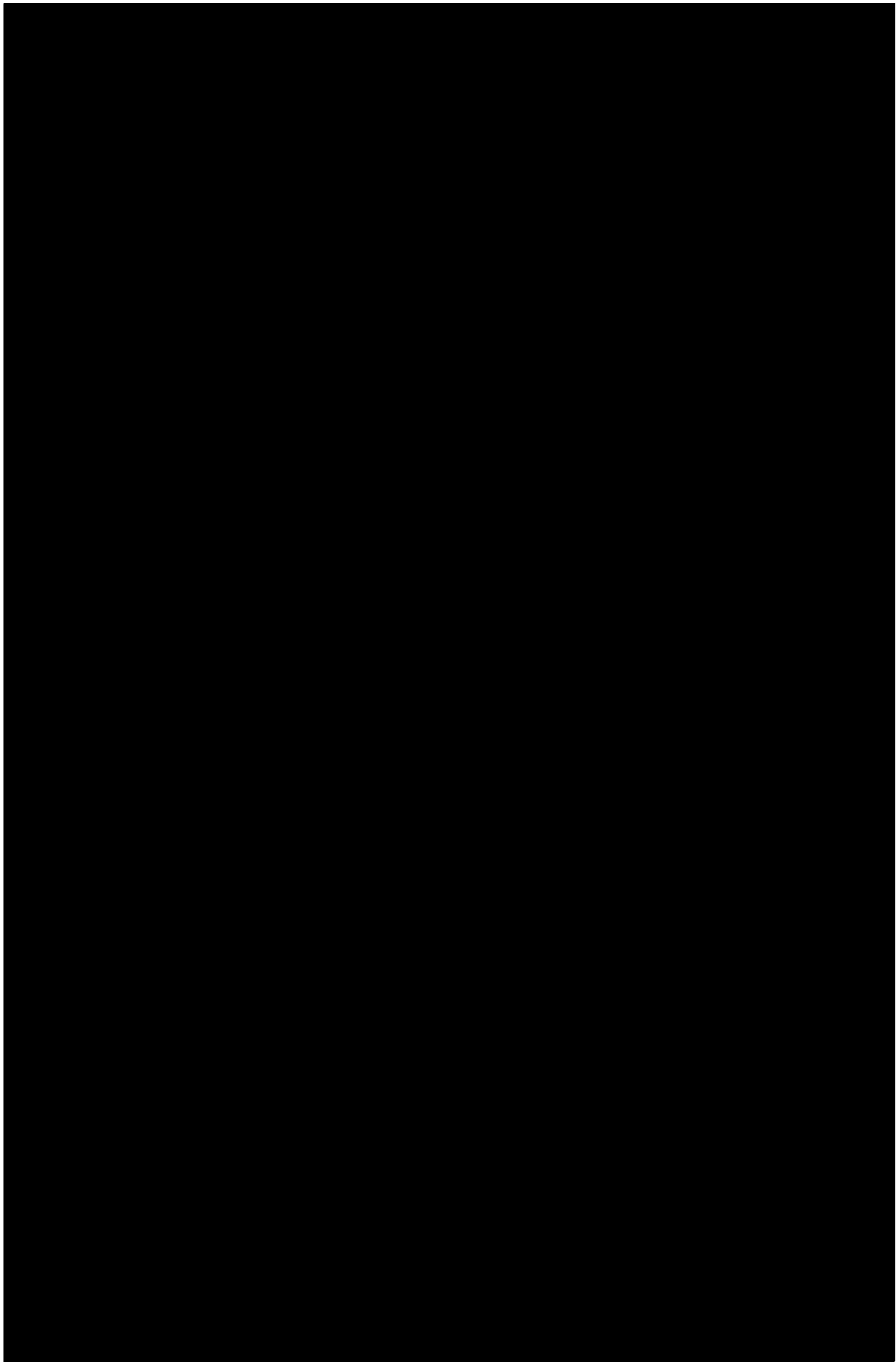


Figure 2-23. Examples of OSL depletion and SAR growth curves (inset) for lunette dune samples (a) 99/3/6B, (b) 98/4/2, and (c) 98/5/1 from the Southern High Plains of Texas and New Mexico.

SAMPLE COLLECTION AND PREPARATION

Chapter overview

Chapter 3 discusses the field collection of samples that are to be processed for optical dating. This chapter also presents the sample preparation approach that is required in order to obtain refined quartz for the optical dating process, and a discussion on aliquot preparation, field moisture and dose-rate samples, plus the determination of equivalent dose. This is followed by a section that describes the sample collection sites, which provides a general overview of the area and includes a site map, and stratigraphic cross-section of each sample location. Also presented is a discussion of the timing of sediment deposition based on the optical dating results.

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SAMPLE COLLECTION AND PREPARATION

3.1 Sampling approach

The collection and preparation of samples for optical dating has three main objectives, equivalent dose (D_e) evaluation, dose-rate determination, and estimation of moisture content (Aitken, 1998). To meet these objectives, basic procedures were followed for sample collection and preparation, with particular reference to four distinct depositional features found on the Southern High Plains: (1) lunettes, (2) lacustrine material, (3) tufa, and (4) coversands. The ability to date samples from diverse sedimentary environments makes optical dating an extremely applicable technique. An implicit assumption when dating sediments is that the mineral grains were exposed to daylight when they were being transported, and that exposure to this light removed any electron-charge signal, and reduced their equivalent dose, or D_e , to zero or near zero (Aitken, 1998). Upon burial, and effectively cut-off from light, the mineral grains act as dosimeters, recording exposure to ionising radiation from the decay chains of uranium and thorium and the decay of potassium (Wintle, 1997). Since it is the depositional event that is being recorded by the sediments, proper zeroing of the luminescence signal is important (refer to Chapter 2, section 2.5.1).

The most useful samples are those collected and dated as part of a stratigraphic sequence. Sample depth is also an important consideration. The cosmic-ray dose-rate a sample receives depends on the amount of shielding the overlying sediments provide (Aitken, 1985; 1998) and should be a factor when determining how close to the surface a sample can be taken. According to Aitken (1998), the cosmic contribution is not significant except at sites with relatively low radioactivity, unlike the Southern High Plains. An estimate of 0.18 Gy ka^{-1} at a metre depth with attenuation increasing at depth by approximately 14% per metre in sediment or rock with a density $\sim 2 \text{ g cm}^{-3}$ was used. All Southern High Plains samples were taken where at least 30 cm of homogeneous strata surrounded the collected sediment. This was done in order to

maximize uniformity in the dose-rate environment and to obviate potential radioactive inhomogeneities.

When sampling the sedimentary strata, attention was given to units that had either a sharp or gradational boundary. If there was a change in the sediment nature (i.e., colour, texture, distinct contact, etc.) within ~0.3 m of the sample this was recorded and samples taken on both sides of it. Also when sampling, interruptions in the natural sediment bedding were avoided because bioturbation processes may have occurred, creating inhomogeneous sediments. These post-depositional alterations include the effects of burrowing animals, root growth, freezing and thawing near the surface, and can involve the translocation of sediments to a lower horizon disrupting the stratigraphic and thus chronologic sequence.

3.2 Collection procedures

Proper sampling in the field is a significant part of the analytical procedure, and must be done under very strict conditions, during which time, the sample is not exposed to light. Often, samples were taken from a vertical exposure e.g., where the sediments had been incised by stream erosion (gullying), or graded for a road/railroad thoroughfare (Figure 3-1). In addition, a trench was dug in order to access the underlying, undisturbed sediments (Figure 3-2). Opaque, polyvinyl chloride (PVC) tubing (standard size ~6 cm diameter by ~15 cm long) was hammered vertically into a freshly cleaned sediment face. Once filled with material, the cylinder was removed, the exposed ends capped, then immediately sealed in a light-tight plastic bag. If the tube was not completely filled, the ends were plugged with packing material to prevent the sediment shifting during transportation. The sample ID was marked on both the sampling cylinder and plastic bag with indelible pen.

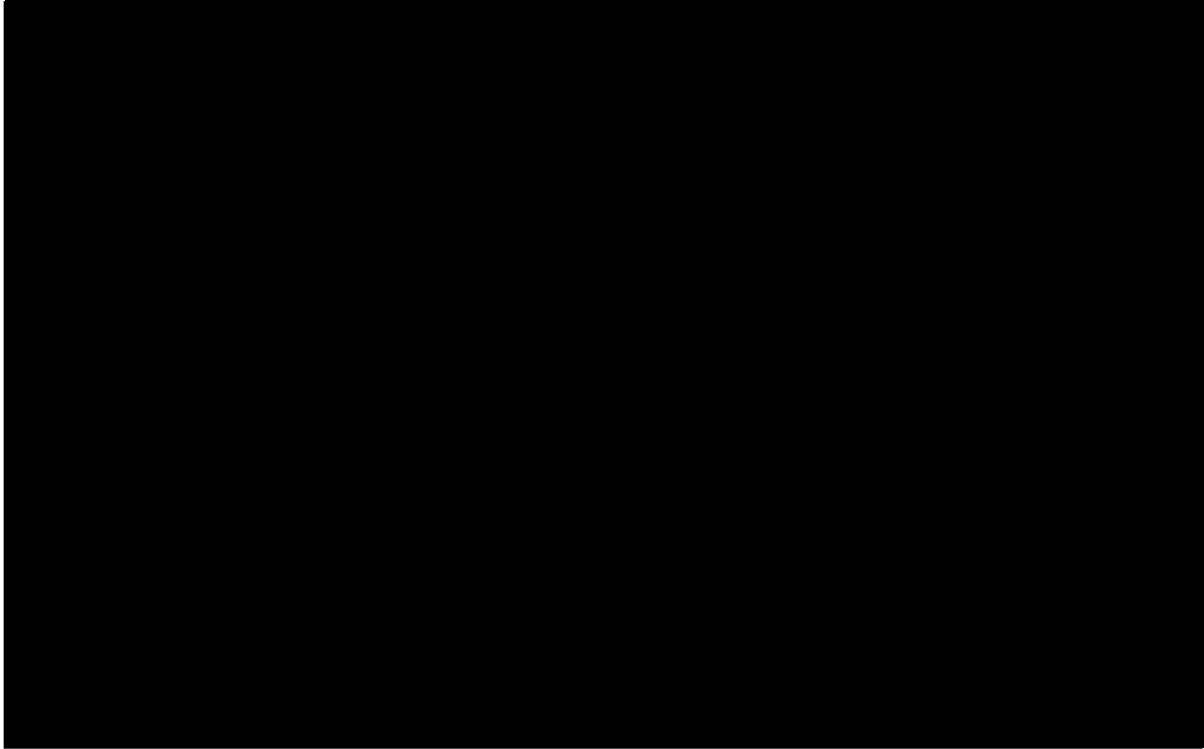


Figure 3-1. Sampling exposed aeolian sediments at a road cut site.

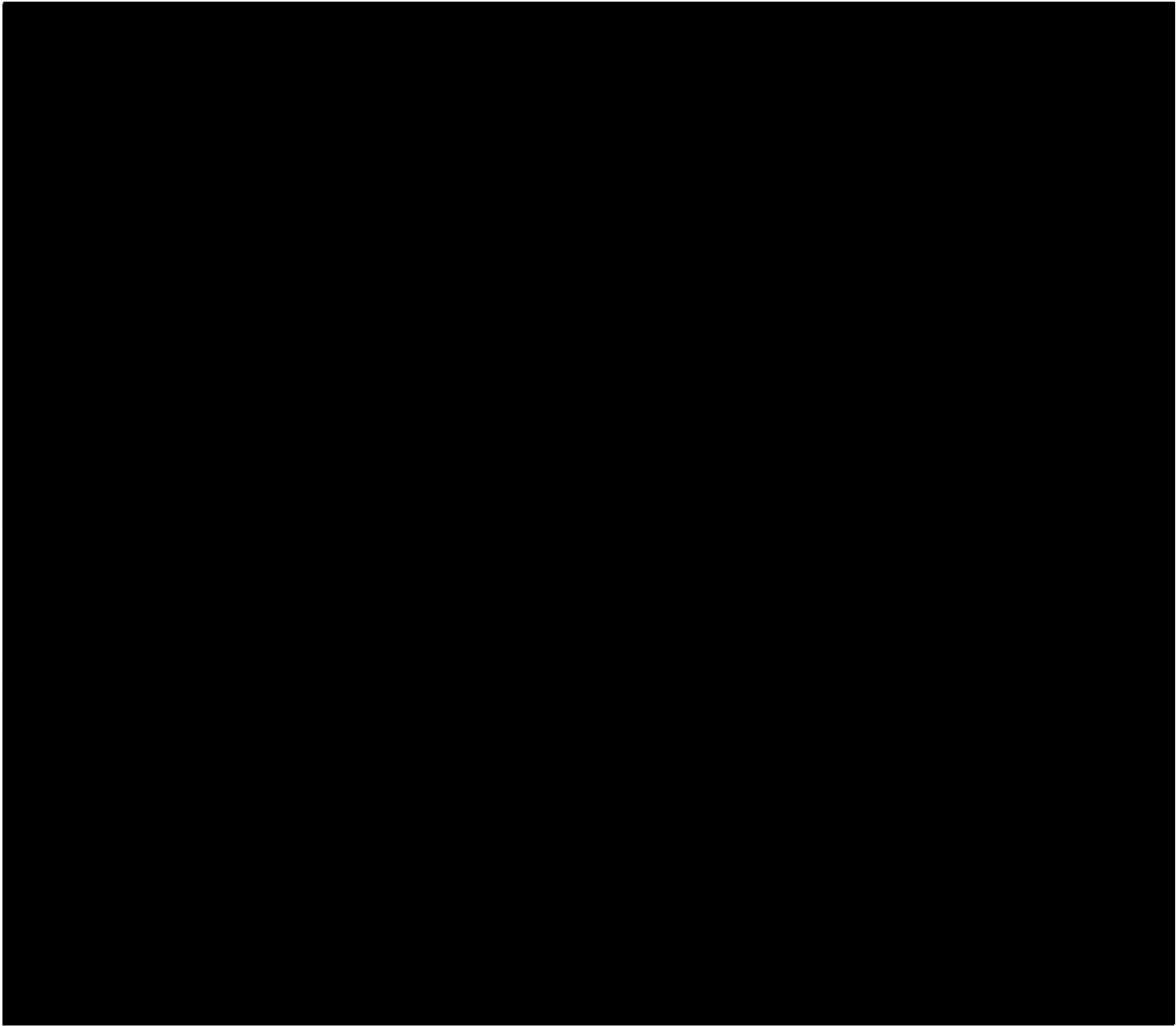


Figure 3-2. Trenched Red Lake lunette with samples taken at 1 m intervals.

Hardened or excessively dried out sediments that were too difficult to sample using PVC tubing required other sampling methods to be employed. These indurated materials were collected by chiselling a block from a cleaned vertical face and immediately wrapping the sample in a light-tight bag. Three samples from the Red Lake lunette and all the tufa samples were taken as blocks of material.

In addition to the samples taken for equivalent dose (D_e) evaluation, a separate sample is needed for dose-rate determination. In most instances, portable gamma spectrometry ($P\gamma S$) was used, in order to estimate the rate at which the sample absorbs ionizing radiation. Where this approach was not viable (i.e. a core of drilled sediments), a supplementary sample was taken for dose-rate determination.

Additional field samples were collected for the evaluation of present-day moisture conditions from each sampling site. Water within the pore spaces of sediment absorbs a portion of the radiation that would otherwise reach the grains on which the D_e estimate is made; thus ignoring the amount of soil moisture can affect the age estimation (Aitken, 1998). Small plastic containers were used to collect sediments from deep in the section, avoiding near-surface sediments that had dried out. The container was tightly closed and sealed with tape to avoid accidental reopening or moisture loss. This was placed in re-sealable bag, which had all air expelled before securing. Collected samples and other information were documented with minimum delay, with details recorded in a field notebook under the following column headings:

- 1) Sample ID.
- 2) Date of collection.
- 3) Grid reference or latitude/longitude of sampling site.
- 4) Elevation of sampling site.
- 5) Moisture sample ID.
- 6) Bulk sample ID.
- 7) Munsell colour description.
- 8) Sediment texture (clay, silt, fine sand, or coarse sand)
- 9) Description of sampling site and sketch of sample location (note proximity and depth of any burrows and/or roots indicating possible bioturbation).
- 10) Description of surrounding site including surface vegetation.
- 11) Photograph number.
- 12) Sequence number of portable gamma spectrometry (if applicable).

Mechanised extraction of sediments on the Southern High Plains was accomplished with drill rigs, which can successfully penetrate thick sections of sediments to a selected depth. Two types of drilling devices were used to core sediments, a wire-line continuous corer inside a hollow stem 'split spoon' auger (Figure 3-3), and a 'High Boy' Geddings rig (Figure 3-4). Split-spoon augers are designed to 'split' apart allowing the cored material to be sampled and provided an optimum approach for efficiently extracting sample sediments. The Geddings auger was effective for sampling, but not as efficient as the split spoon auger, for it required the sediments to be extruded through the hollow stem.

A temporary field darkroom was set-up adjacent to the drilling rigs to avoid any exposure of sediments to daylight as samples were being taken (Figure 3-5). With the removal of each cored segment from the ground, the encased material was immediately taken to the temporary darkroom, where the casing was either 'split open' or the sediments extruded, and samples taken at selected intervals. Light-tight film canisters were pushed into the core material, and were completely filled, leaving no air space between the container and the lid. Canisters were then placed in opaque bags and labelled.

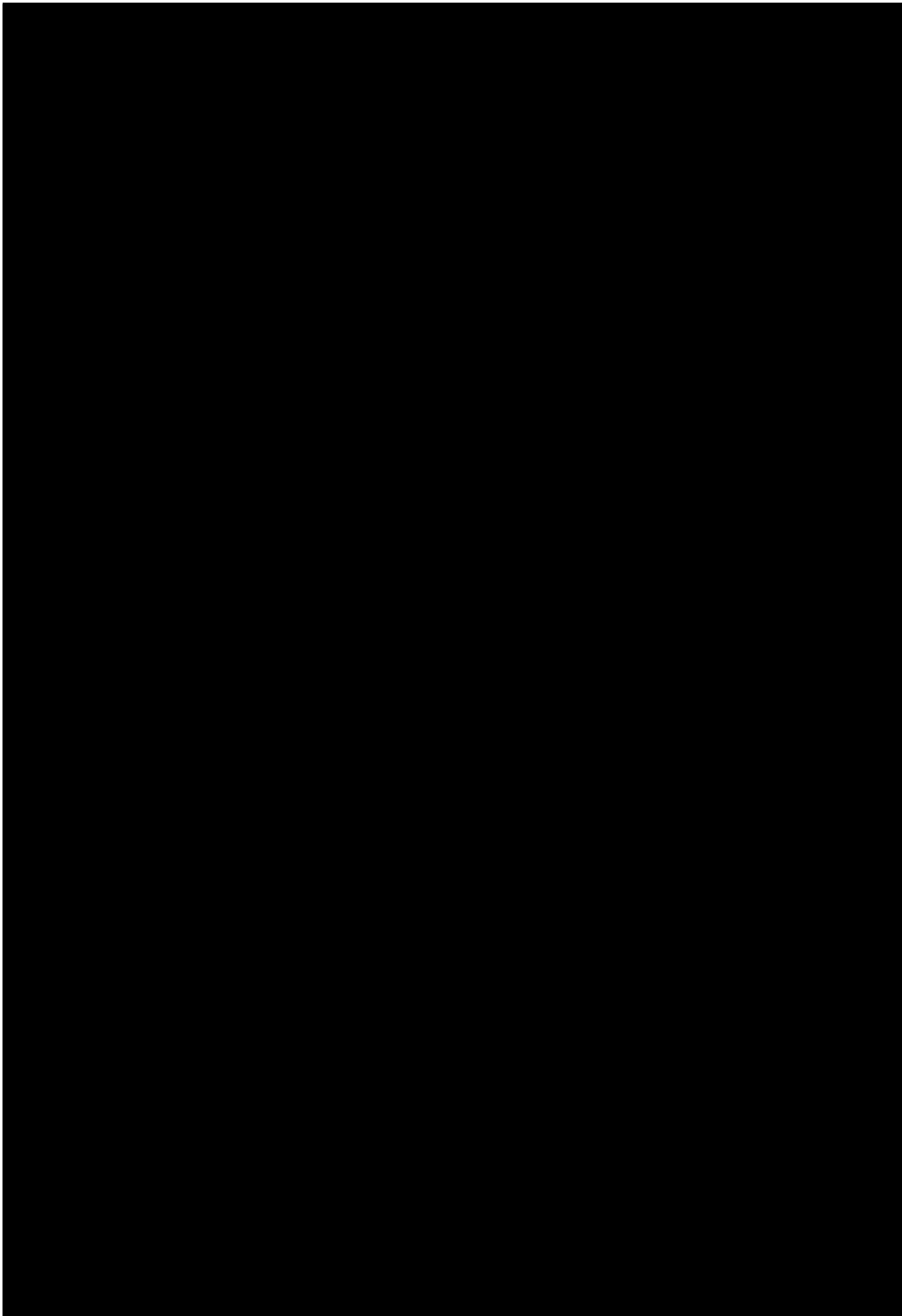


Figure 3-3. Drill rig auguring lunette dune at Double Lakes. This rig uses a continuous wire-line ‘split spoon’ auger.

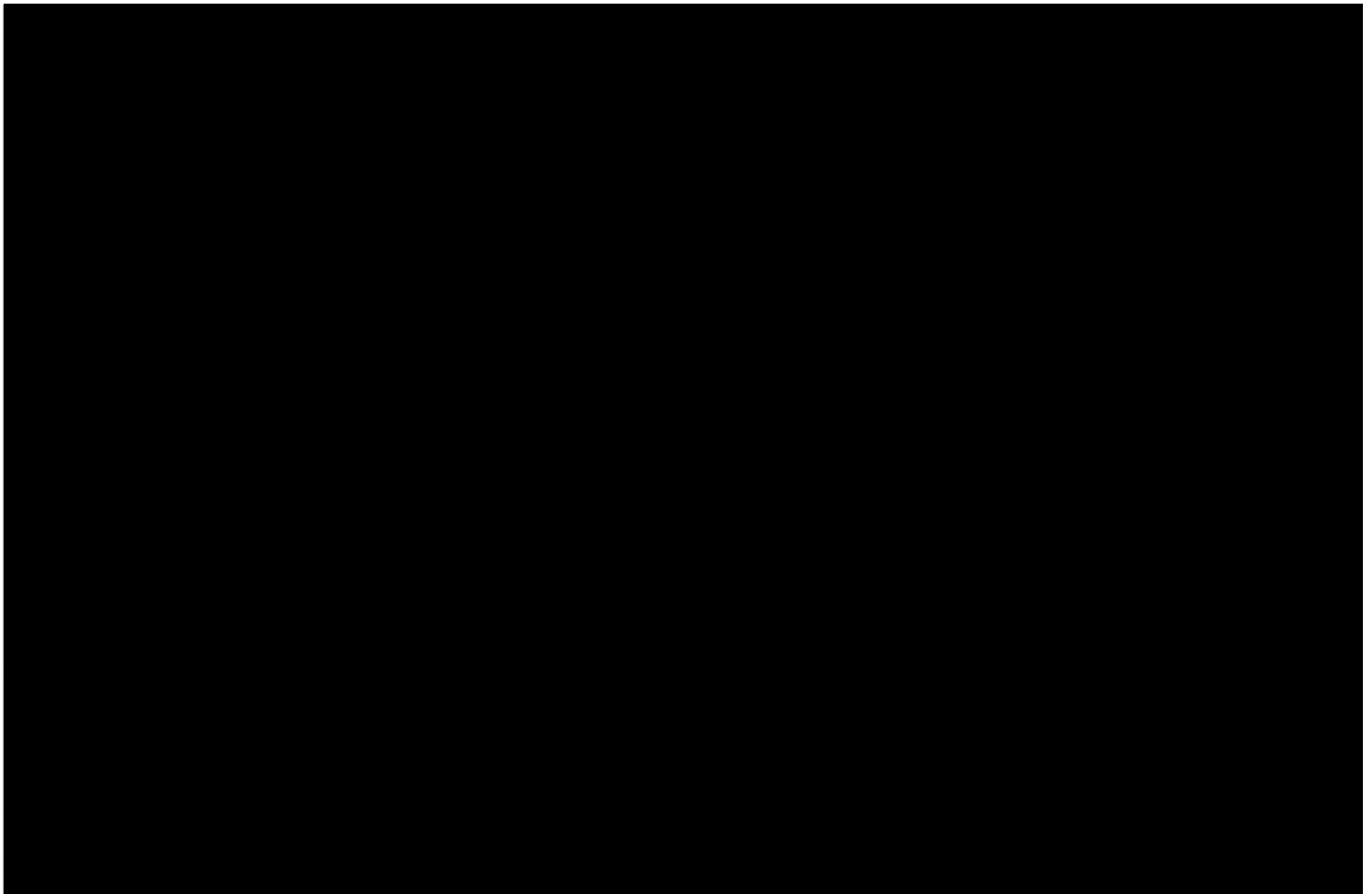


Figure 3-4. 'High Boy' Geddings drill rig.

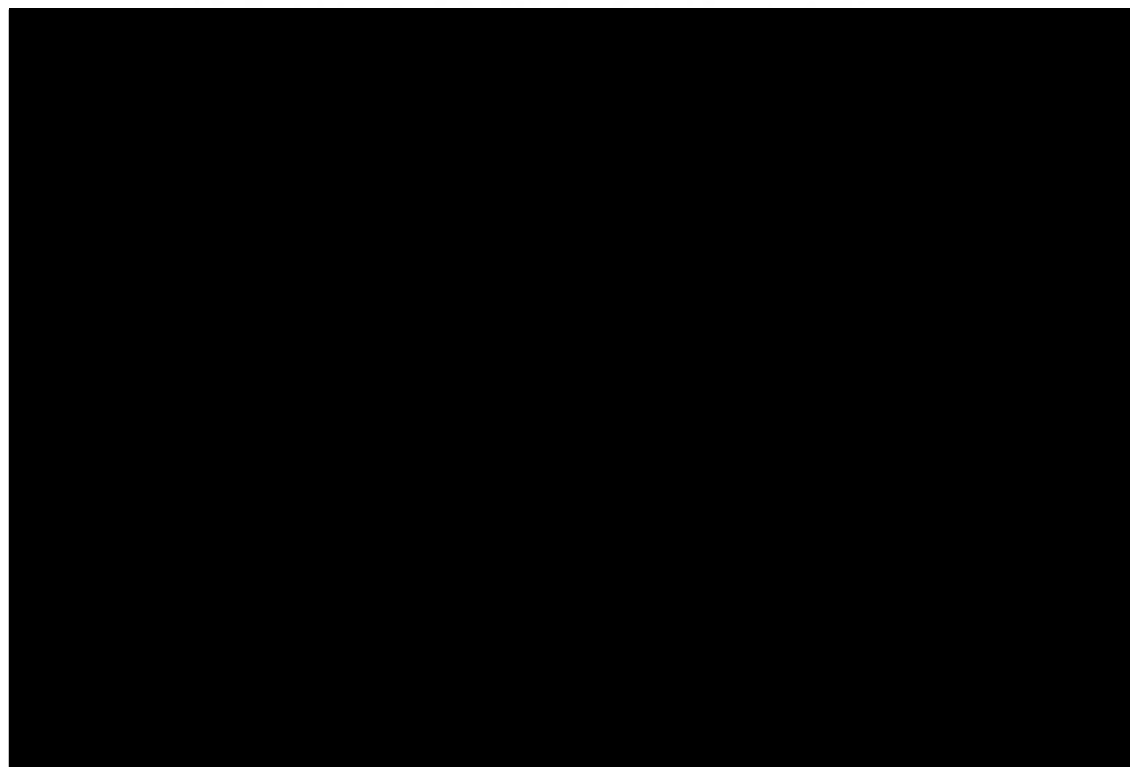


Figure 3-5. Temporary field darkroom.

3.3 Preparation procedures

The following is a description of preparation procedures applied to Southern High Plains samples. These procedures were carried out in a luminescence laboratory, which was specially equipped for processing light-sensitive samples, and illuminated with a red light (>630 nm), effective for processing quartz. Under these lighting

conditions, samples collected using PVC pipe were extruded and the outer 3-4 cm of exposed sediment removed from each end. The indurated material collected as blocks, from the Red Lake lunette and Double Lakes tufa, had the outer 3-5 cm trimmed, and was gently crushed into smaller pieces ($\sim 2-8 \text{ cm}^3$) then placed in an 8 % HCl bath to break down the cemented grains. This solution was refreshed daily until fragments were disaggregated.

As part of the sample refinement process for optical dating, sediments were placed in beakers and immersed in 10% HCl (150 ml) overnight or until carbonates were removed and reaction ceased. Grain size selection was carried out following the HCl bath. Wet sieving was used as an effective means of separating silt and clay from coarser material. Tap water was used to sieve bulk samples through 90, 150, and 250 μm screens (Figure 3-6). Overloading the sieves with too much sediment was avoided, which may have reduced the efficiency of the sieving process. The 90-150 μm sediments were retained, washed in distilled H_2O , and dried overnight at 40°C . The other size fractions were stored for possible future analysis.

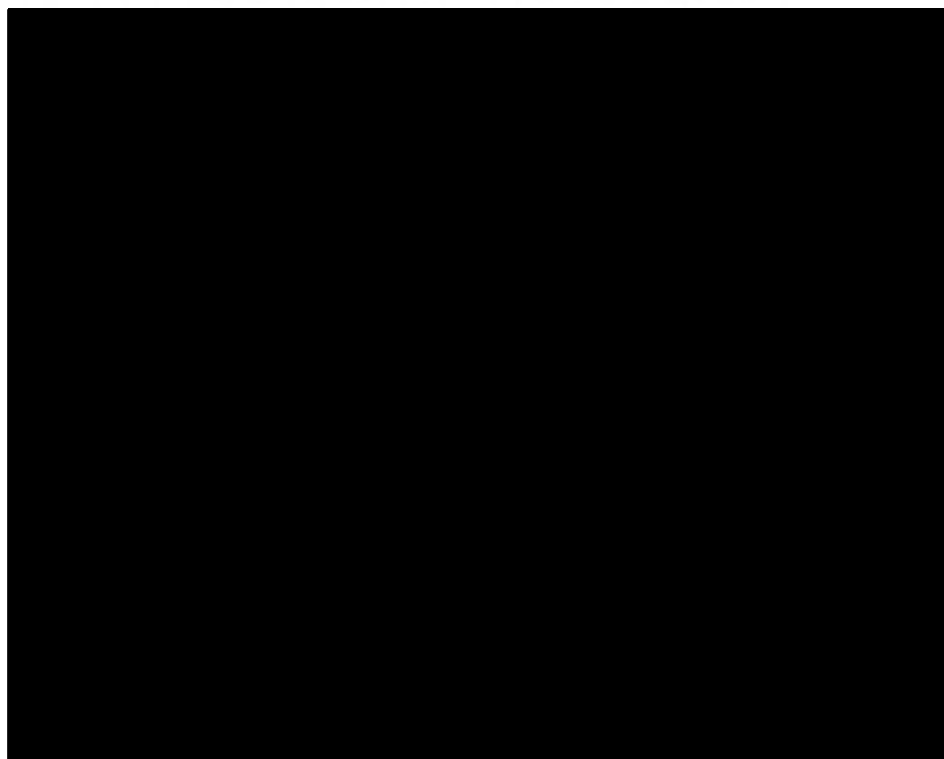


Figure 3-6. Wet sieving screens.

The retained 90-150 μm sediments were further refined using heavy liquid (sodium polytungstate) as part of the mineral separation process. Quartz is heavier than feldspar and usually has a density of $>2.62 \text{ g cm}^{-3}$. Potassium feldspars are the lightest mineral with densities between $2.58-2.54 \text{ g cm}^{-3}$. Separation of the quartz and feldspar sediments from heavier minerals (e.g., magnetite, ilmenite, etc.) was performed by

pouring a small amount (~2.5 g) of dry sediment into standard centrifuge tubes. These tubes were then filled three-quarters full with sodium polytungstate ($\rho=2.72 \text{ g cm}^3$). This was followed by centrifuging for three-minutes and placing in an ultra sonic bath for eight-minute, which assisted with the separation process. If the separation was efficient, a clear liquid middle resulted with the lighter mineral fraction on top and heavier minerals on the bottom of the tube. If the middle liquid was not clear, clay was present or too much sediment was placed in the tube; thus, further washings or less sediment was used. The heavier ($>2.72 \text{ g cm}^3$) fraction was isolated in the tube by freezing the bottom with liquid nitrogen then pouring off the unfrozen lighter fraction and heavy liquid into a clean beaker. These sediments were washed with distilled H_2O to remove the heavy liquid then dried in an oven at 40°C . Dried sediments were checked to be free flowing; any clumping of material indicated adherence of residual heavy liquid to the grains, and was remedied with a rewash. Further sediment refinement was accomplished by a 60-minute treatment in 48% HF and 26% HCl, to remove feldspars and fluorides. The refined quartz fraction was then thoroughly rinsed in distilled H_2O and dried in an oven at 40°C .

3.4 Deposition on discs

Refined quartz material was dispensed on ~10 mm diameter, 0.5 mm thick stainless steel discs, which could then be placed on a disc carrier fitted to a Risø TL/OSL reader. Before dispensing the refined sediments, a spray mask was used to isolate the silicone oil (*Silkospray*) in the disc center while masking the perimeter the disc, then a monolayer of dry refined sediments (~ 3-4 mg) was deposited in the centre of each disc (Figure 3-7). Aitken (1998) recommends leaving the outer 1mm perimeter of each disc blank because of “radial non-uniformity of the dose delivered by alpha and beta sources” and the “possible spatial non-uniformities in stimulation power and detection efficiency”.

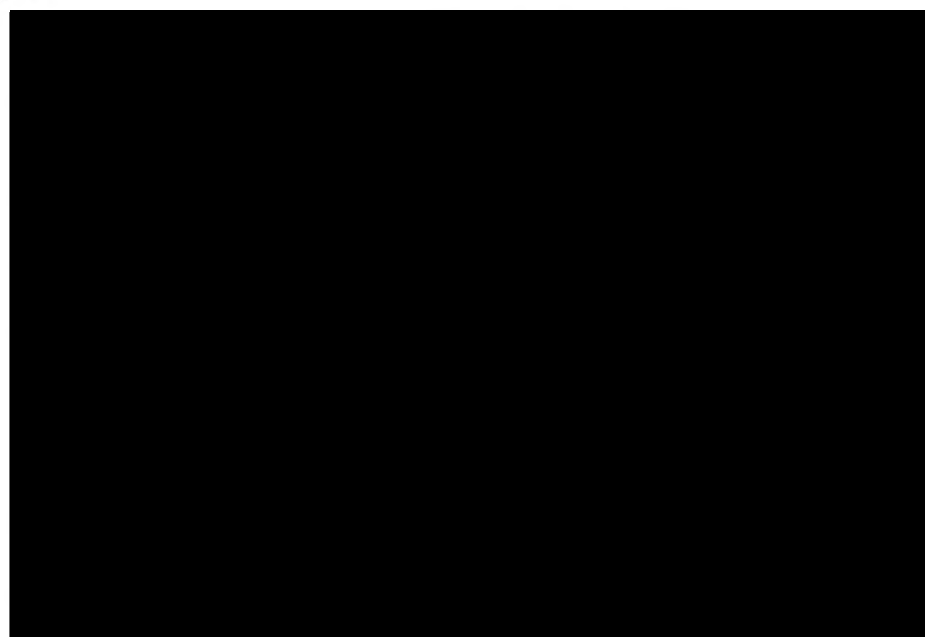


Figure 3-7. Spray mask disc carrier.

3.5 Moisture content measurement

The extra samples that were collected to estimate the degree of sample site moisture were measured, and the appropriate correction made to the dose-rate contributions (Aitken, 1998). Steps for calculating the saturation content (W) and fractionation of saturation (F) are adapted from Aitken (1985; 1998) and are given below (see Appendix C for table of results):

$$W = \frac{V_w}{X_d} \quad (3)$$

$$F = \frac{W_g}{V_c - (X_d / 2.7)} \quad (4)$$

where

- W = saturation content;
- F = fraction of saturation;
- V_w = volume of water;
- X_d = dry weight of sediment;
- W_g = weight of water;
- V_c = volume of container

3.6 Dosimetry analysis samples

In most instances portable gamma spectrometry was used to collect information on radiation activity for the determination of the dose-rate. When this approach could not be used (e.g. core section) an additional sample was taken for dosimetry analysis. This dosimetry analysis sample was thoroughly dried (1-48 hours, or longer depending on moisture content) then milled to a grain size $<4 \mu\text{m}$. The milling produced a talc-like texture, which maximised sample homogeneity. These prepared samples were sent to Bequerel Laboratories in Canberra, Australia and analysed using either Neutron Activation Analysis (NAA), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), or Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). These results, along with data recorded using field gamma spectrometry, were used in the optical age calculation. Results and the type of dosimetry used for each sample are listed in Appendix D.

3.7 Equivalent dose (D_e) determination

All OSL measurements were made using a Risø automated TL/OSL reader equipped with a calibrated $\text{Sr}^{90}/\text{Y}^{90}$ β source and a high-power blue ($\lambda=470 \text{ nm}$) LED unit, employed at 90% of full diode current providing approximately 18 mW/cm^2 (Bøtter-Jensen *et al.*, 1999) (Figure 3-8). All measurements were made at 125°C and the emitted luminescence signal was detected with a type 9235QA photomultiplier filtered with two Corning U-340 glass filters.

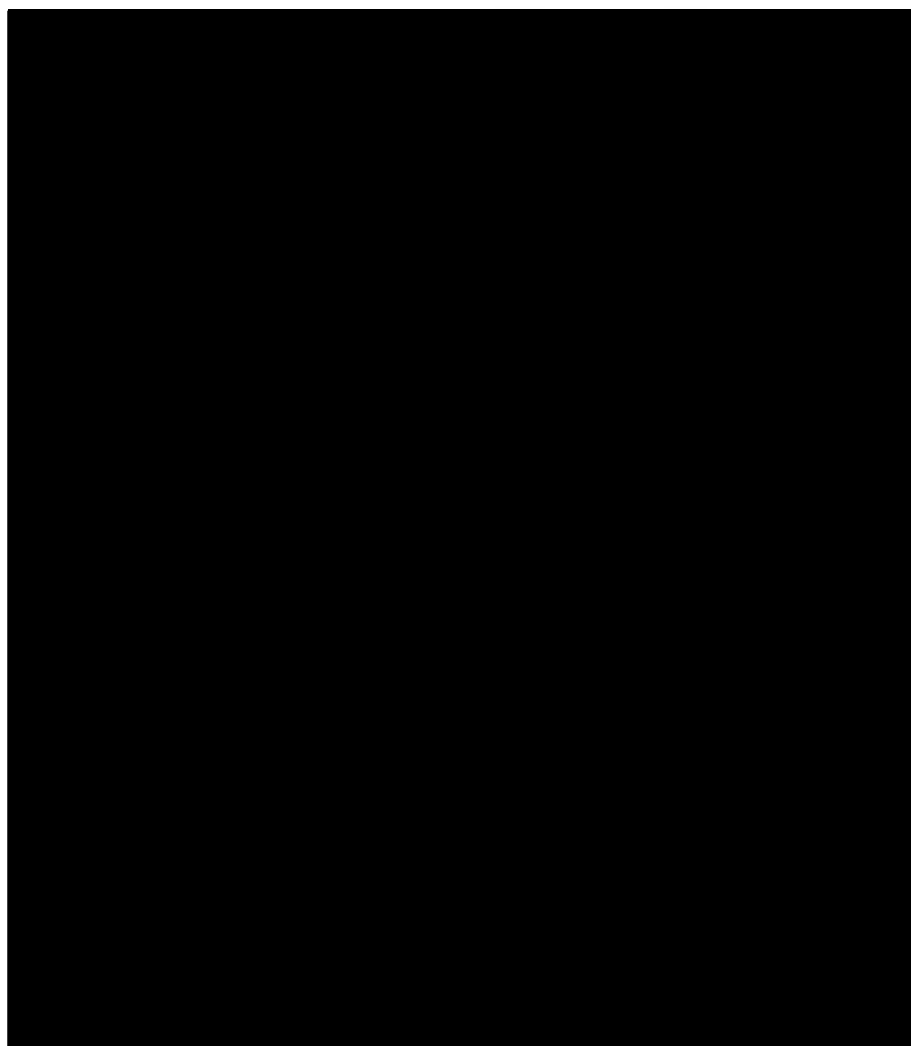


Figure 3-8. Automated Risø TL/OSL reader.

D_e evaluation for the Southern High Plains aeolian, lacustrine and tufa sediments was achieved using the single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000b). Each aliquot was dosed ($+\beta = 0$ for natural) then preheated to 250°C for 10 s. The natural OSL signal was measured by stimulating at 125°C for 15 s. A fixed test dose (~3-5 Gy) was applied, with a cut heat of 160°C, then stimulated again to measure the OSL response. This step monitored and corrected sensitivity changes during the measurement procedure. The entire SAR cycle was repeated iteratively following application of a regenerative-dose. Four regenerative doses were applied to each aliquot, bracketing the expected natural dose. The first 1 s of OSL was used to describe the luminescence intensity of both the natural and regenerated OSL. A background value (estimated over the last 5 s) was subtracted from the initial luminescence (see the SAR procedure flowchart (Figure 2-22) and the age formula (2) in Chapter 2, section 2.5.2 that give the optical age) (see Appendix B, C, E, and F).

To test that the SAR procedure corrected for sensitivity changes, a further dose – preheat – optical stimulation cycle was incorporated with the dose corresponding to the initial regeneration dose given at the beginning of the procedure. The ratio of the

corrected signals, a recycling ratio, indicates whether the use of a test dose corrects sufficiently for sensitivity changes, occurring through successive measurement cycles, and the acceptability of the sensitivity correction (Murray and Roberts, 1998; Murray and Wintle 2000b). A further preheat and optical stimulation cycle was incorporated to establish the extent of charge transfer (recuperation) (Murray and Wintle, 2000b).

Initial tests were carried out on all collected samples from the Southern High Plains to determine if the refined quartz from lunettes, lacustrine material, tufa, and coversands had feldspar contamination. Measurements were made using the automated RISØ TL/OSL DA-15-System reader fitted with an infra-red (IR) solid state laser diode OSL unit (830 nm). The OSL unit was employed at 80% of full power and provided approximately 370 mW/cm^2 (Bøtter-Jensen *et al.*, 1999). Most samples displayed a non-decaying IR signal. Stokes (1994) also recognised that pure quartz, from a wide range of geographical locations, did not display any rapidly decaying infra-red stimulated luminescence (IRSL) when stimulated at a wavelength of $\sim 880 \text{ nm}$. Only 2% of the Southern High Plains samples displayed a slowly depleting IR signal (*c.* $20\text{-}100 \text{ cts s}^{-1}$) above the electronic background level. These counts were inferred to be from microinclusions within the quartz matrix. A repeat of etching following Stokes (1994), of 20 minutes in 40% HF, was found adequate to remove any remaining slowly depleting IR signal.

3.8 Sample collection sites

Sample collection focused on a variety of sediments, the majority of which came principally from aeolian contexts (lunettes and coversands). Other sediments were taken from lake basins or tufa environments. Selected sites were either mechanically cored using a drilling rig or sampled manually. Over one hundred samples ($n=111$), from a wide variety of localities, were collected, refined, analysed, and optically dated (see Appendix A).

The following subsections are divided into groups of sample types and provide a brief rationale for sampling these contexts. Below is a key (Figure 3-9) for the individual site figures included in the following subsections:

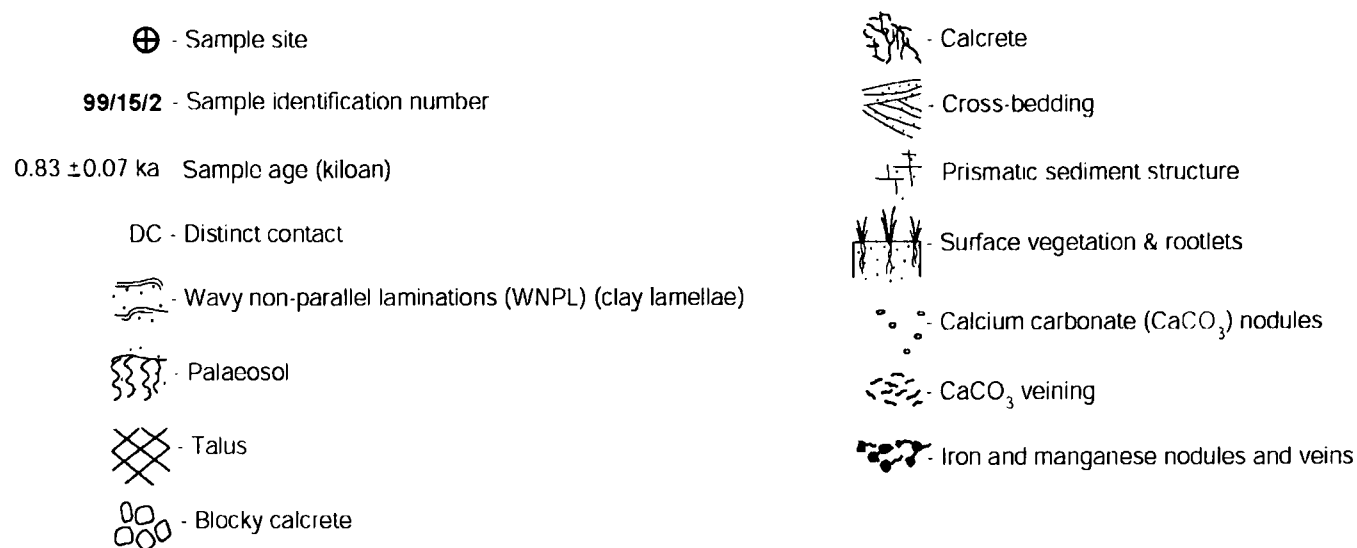


Figure 3-9. Key for individual site locations

3.8.1 Small playa lunettes

Aeolian lunette sediments associated with both small playas and large lake basins were collected to compare depositional timing of the two dune types. Five small playa basin lunettes, located across the Southern High Plains, were investigated in order to establish a chronological record for these dune types. This record allows for cross comparison of depositional timing between large lake lunettes and small playa dunes. United States Geological Survey maps (Scale 1:24,000) were reviewed and five sites were selected based on the following criteria:

- 1) playa basin surface area was 5 km² or less;
- 2) lunette height from edge of basin was at least 2 m;
- 3) dune could be easily accessed from either a paved or dirt road.

The following subsections give a brief description of the five selected small playa basins and their adjacent lunette including the number of samples collected, and their optical ages.

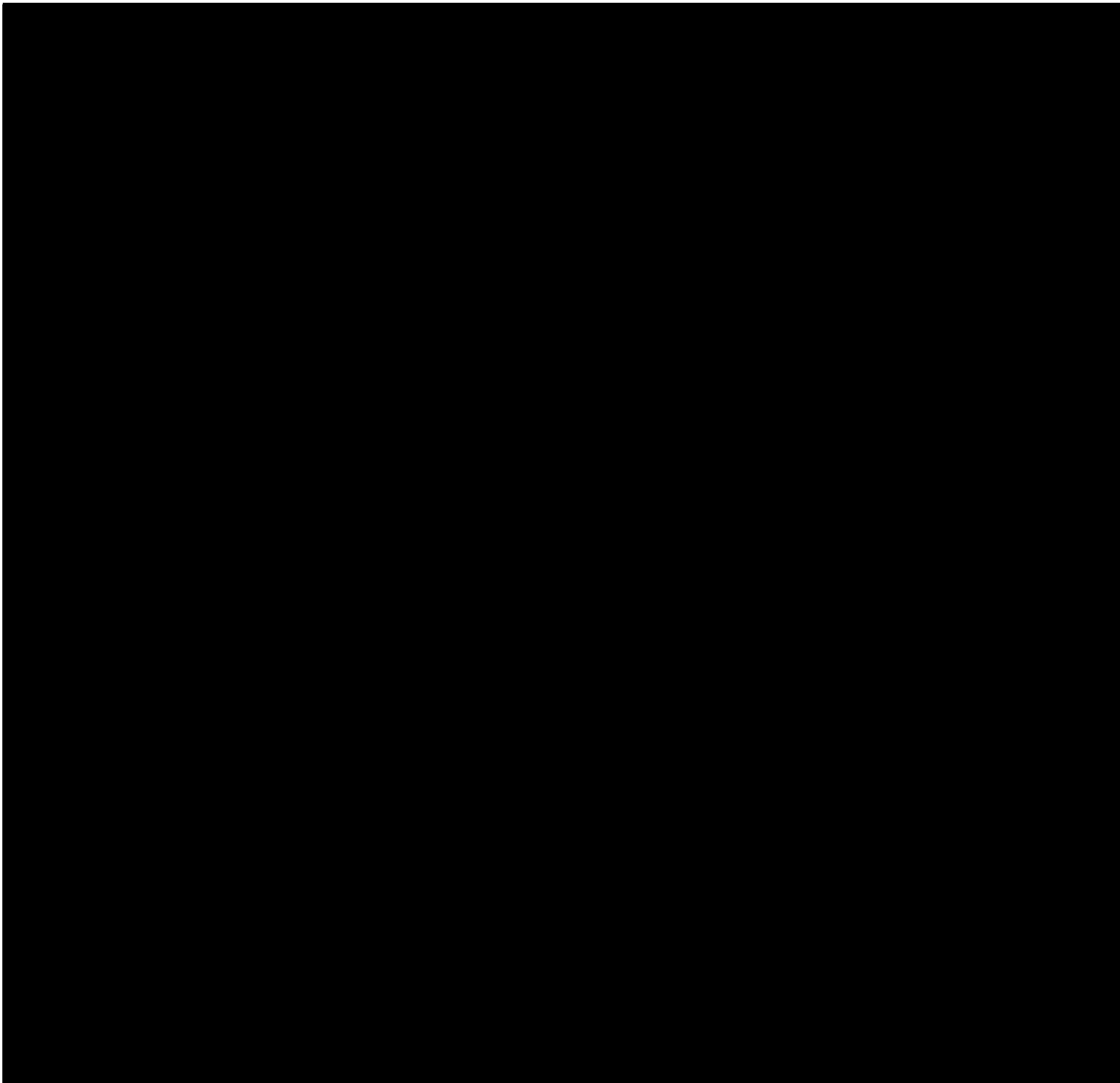


Figure 3-10. Southern High Plains lunette sample localities.

3.8.1.1 *White Lake*

White Lake (sample site 98/1) is located in Bailey County, Texas, approximately 32 km south of Muleshoe, and occupies a 1.5 km diameter basin that is positioned within the upper Yellow House Draw (Figure 3-10). This small playa basin has an arcuate-shaped dune 2 km long, 0.5 km wide that rises roughly 5 m above the lake basin surface. Sparse vegetation covers the dune, which is primarily dominated by buffalo grass.

Two samples of sandy loam lunette material were taken at 1 and 3 m intervals, where the dune was incised by fluvial erosion (Figure 3-11). Results indicate that sediments associated with samples 98/1/2 and 98/1/1 were emplaced during the late Holocene and historic periods approximately 1.73 ± 0.24 and 0.29 ± 0.11 ka, respectively.

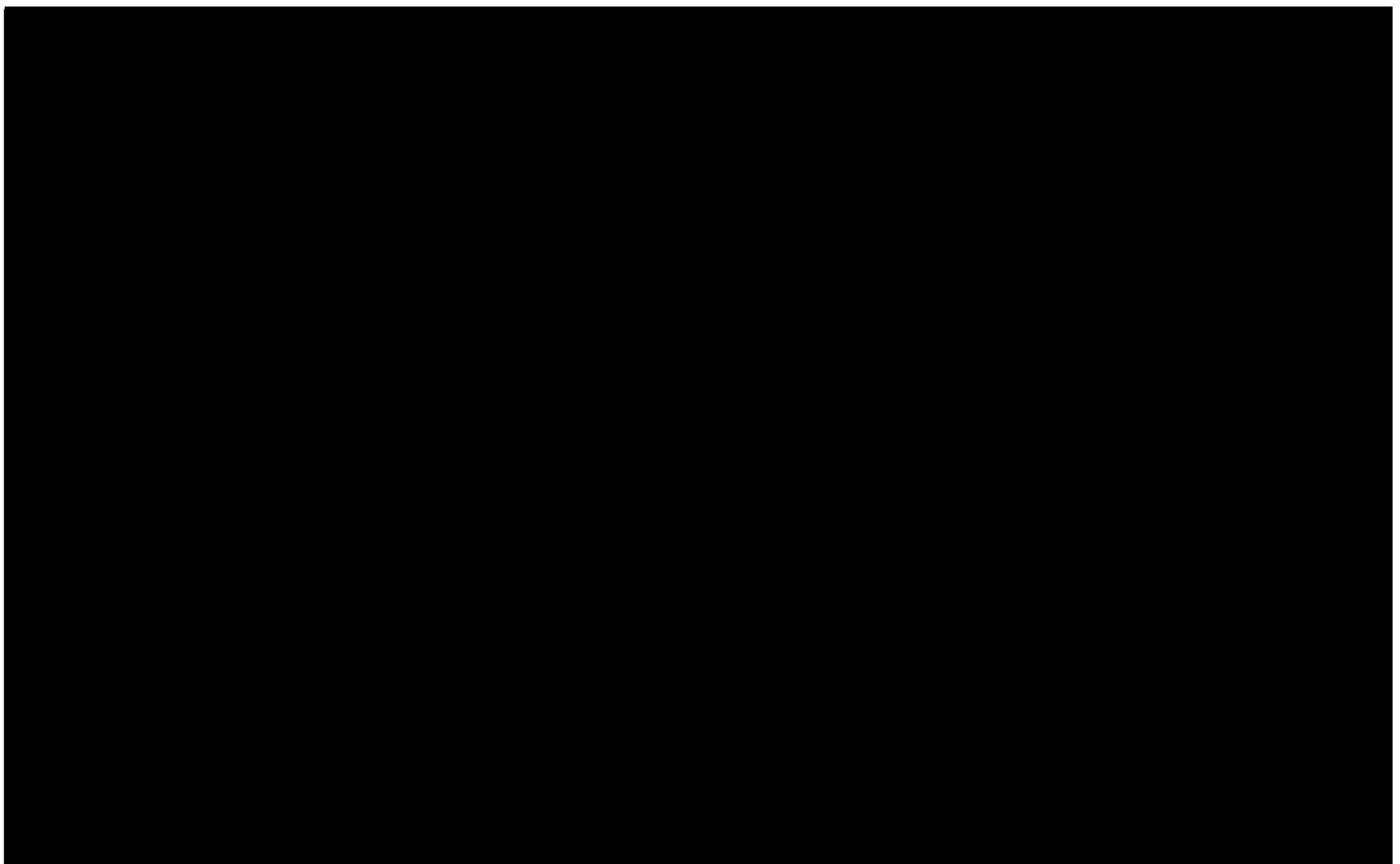


Figure 3-11. White Lake location map (sample site 98/1).

3.8.1.2 Silver Lake

Silver Lake (sample site 98/3) is a polygonal basin located 17 km northeast of Morton, Texas on the Cochran-Hockley County line (Figure 3-10). This small playa is approximately 1 km² in area and is flanked on the east by a single lunette that is 1.3 km long by 0.5 km wide, with its ridge ~26 m above the present day lake level. A fringe of tamarask trees divide the playa basin from the lunette.

The front face of the lunette was excavated back approximately 1 m towards the middle of the dune in order to expose undisturbed sediments from which two samples were collected at 1 and 2 m depths (Figure 3-12). These samples were deposited during the historic period approximately 400 and 310 years ago.

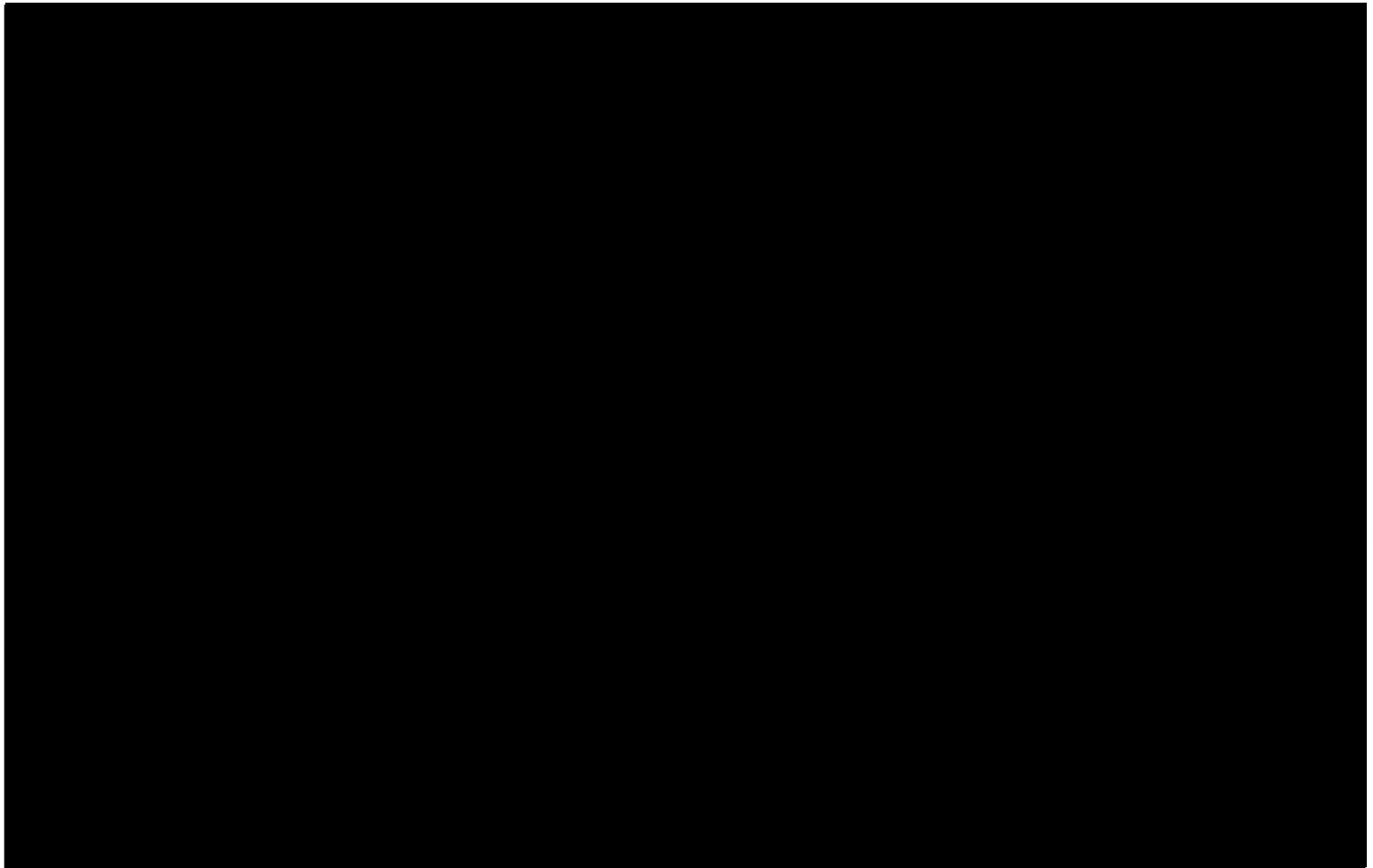


Figure 3-12. Silver Lake location map (sample site 98/3).

3.8.1.3 Jackson Hill

Jackson Hill is located 25 km northeast of Tulia in Swisher County, Texas (Figure 3-10). This lunette is 1.5 km long and 0.4 km wide with a ~12 m ridge height that can be accessed from route #146. Jackson Hill dune is adjacent to a dry, vegetated 3 km diameter oval playa basin (Figure 3-13).

A landfill pit approximately 6 m deep by 15 m wide on the western slope of Jackson Hill had previously been excavated by mechanical equipment exposing the centre of the lunette material, which consists of compacted fine to very fine clayey sands with prismatic sediment structure. Sediments near the base of the lunette have hues ranging from yellowish red (5YR 5/6) with dark yellowish brown (10 YR 4/4) material near the upper surface. Three samples were taken along the south wall of the pit at depths of 4.6, 3.1, and 1.8 metres that were determined to have been emplaced 207 ± 16 , 105 ± 10 , and 55 ± 4 ka (Figure 3-13).

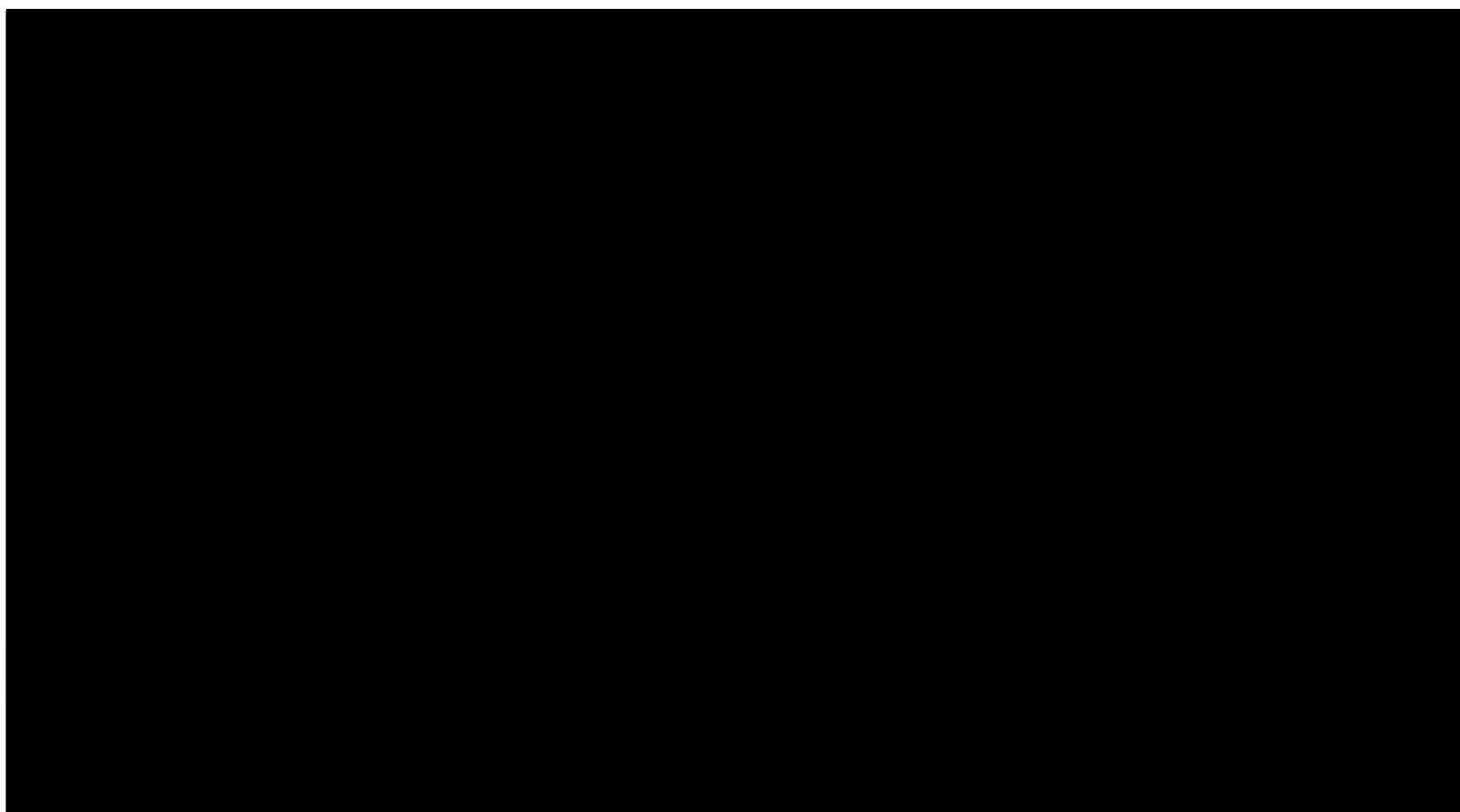


Figure 3-13. Jackson Hill location map (sample site 98/5).

3.8.1.4 *Julia Lake*

Julia Lake lunette is located in Hale County, Texas, 23 km south of Plainview (Figure 3-10). This dune is approximately 1 km long, 0.25 km wide, and 3.5 m high. It is a sparsely vegetated sandy-clay dune, formed on the southeastern perimeter of a 1.2 km diameter oval playa.

Three samples were taken from the interior of the dune (sample site 98/6) where it has been bisected by a county road. The basal sample (98/6/3) taken at 2 m below the surface was deposited 23 ± 2 ka. The two stratigraphically higher samples (98/6/2 and 98/6/1) are divided by a possible palaeosol or distinct contact separating lower sediments that were deposited during the late Wisconsin from upper material emplaced during the historic period (Figure 3-14).

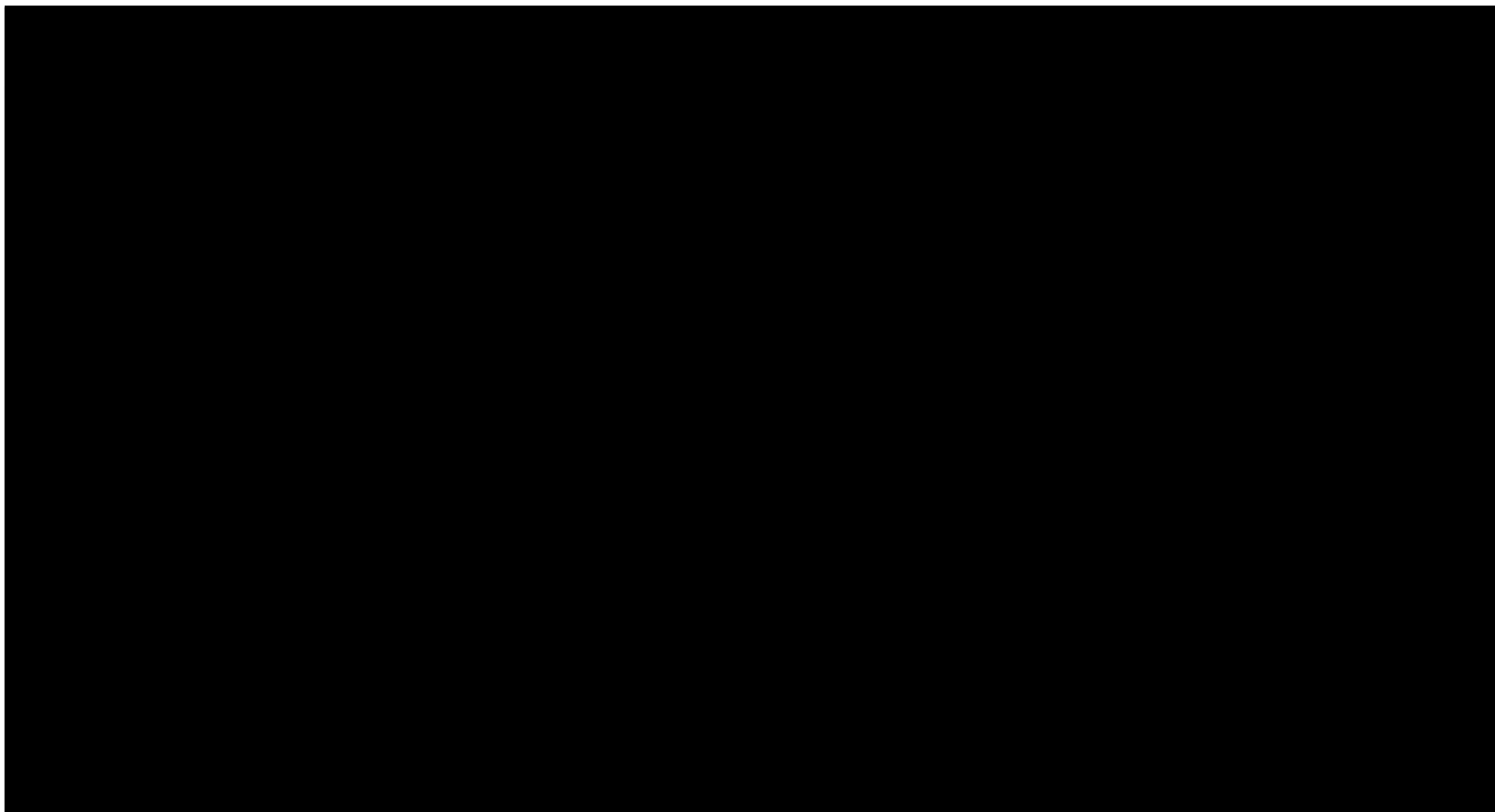


Figure 3-14. Julia Lake location map (sample site 98/6).

3.8.1.5 Red Lake

Red Lake and adjacent Boggy Lake are located in a $>450 \text{ km}^2$ area of subsidence, known as Lomax Basin (Frye and Leonard, 1964; Reeves, 1966), located 20 km west-southwest of Big Spring, Texas, in Howard County (Figure 3-10). The larger Red Lake and its smaller partner Boggy Lake are flanked along their southeastern margin by a compound lunette composed of an inner and middle dune, which become joined along their extreme southern limbs.

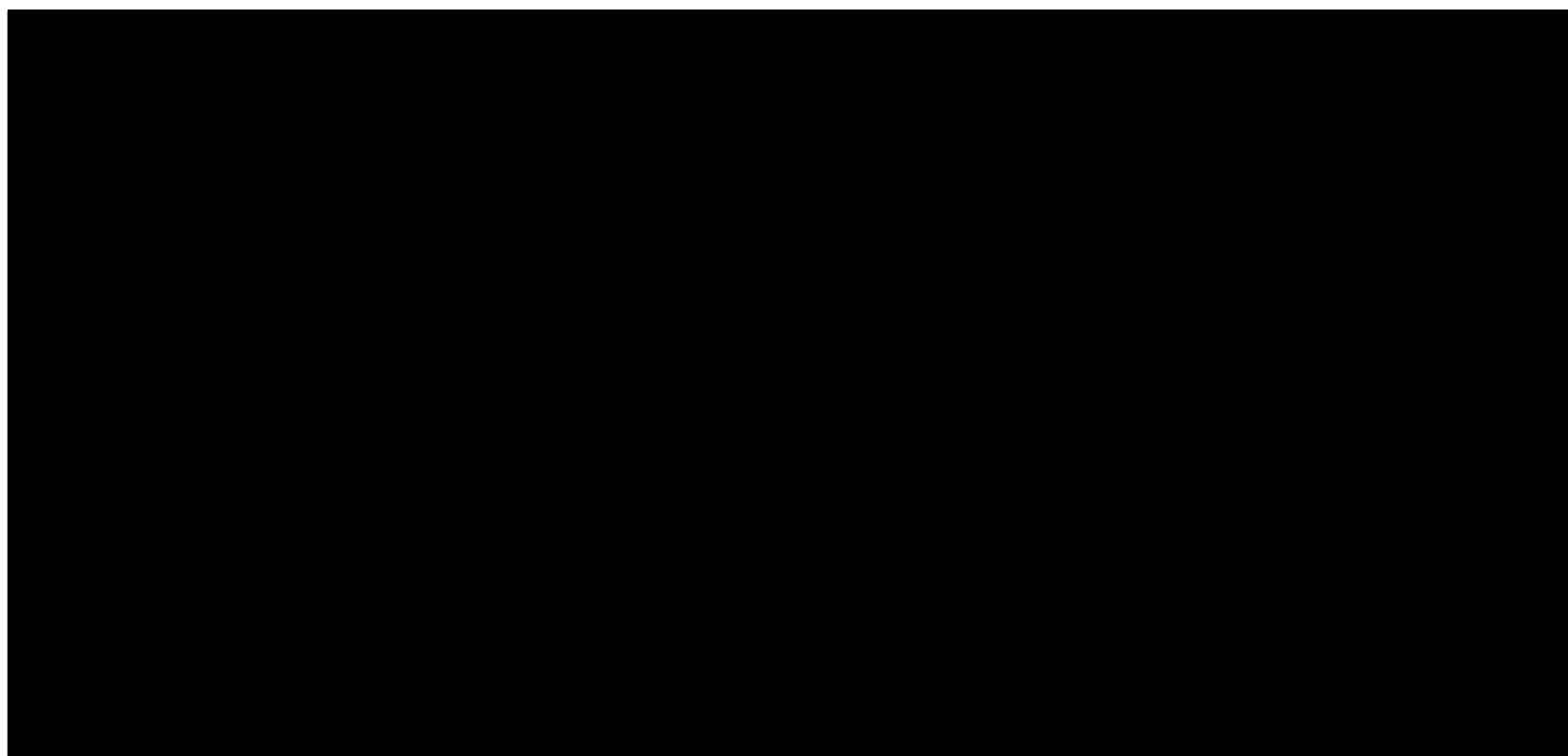


Figure 3-15. Red Lake location map (sample site 98/9).

The Red/Boggy Lake lunette is bisected near its midpoint by Interstate 20 and the Santa Fe Railroad. The inner dune (sample site 98/9) is positioned 14 m above the present lake level and is $\sim 0.5 \text{ km}$ wide. Four samples were taken at 1 m intervals down the north face of a large cut that had been excavated for the Santa Fe Railroad (Figure 3-15). Samples 98/9/2, 98/9/3, and 98/9/4 have optical ages that are statistically indistinguishable averaging approximately $37 \pm 4 \text{ ka}$. Sample 98/9/1 generated an age estimate of $16 \pm 1 \text{ ka}$.

3.8.2 Large lake lunettes

The optical dating programme carried out on large lake basin lunettes concentrated primarily on Double Lakes, with additional samples taken at Yellow and Illusion Lakes. Double Lakes was selected due to previous United State Geological Survey (USGS) research that had been conducted on this lake for several years (e.g., Wood *et al.*, 1992; Wood and Jones, 1990; Wood and Osterkamp, 1987; Wood and Sanford, 1990). Yellow and Illusion Lakes were sampled because of the accessibility to the lunette, which had good exposure of dune strata.

The majority of the lunette samples (approximately three-quarters) are from Double Lakes where a deep drilling program was carried out on the three southeast flanking, concentric lunettes, while the outermost (4th) lunette (located near High Lonesome windmill) was manually trenched (Figure 3-16). The drilling rig that was used to auger Double Lakes inner and outer lunettes used 'split-spoon' sections, 1.5 m in length and 5 cm in diameter. The inner lunette was drilled to a depth of 18 m while the outer lunette had 5.3 vertical metres of material extracted. The middle lunette was sampled to a depth of 9.5 m with the 'High Boy' Geddings rig, and uses metre length, 5 cm diameter sections for sediment retrieval.

Additional lunette samples, taken from Yellow and Illusion Lakes, were manually collected from sites where fluvial erosion had incised the sediments and created a gully, or the dune had been excavated for either a road or railroad thoroughfare. Opaque PVC tubing was hammered into freshly cleaned exposures to obtain sediment samples.

3.8.2.1 Double Lakes

Double Lakes basin is located in Lynn County, Texas ~40 km south of Lubbock (Figure 3-10). The two associated lakes are oriented northeast-southwest, with their surface drainage flowing from the north and northwest (Figure 3-16). The basin is inset 20 m below the mean elevation of the Southern High Plains (Sanford and Wood, 1995) into both the Blackwater Draw and Ogallala Formation beneath it (Reeves, 1976). Double Lakes is fringed on the southeasterly margin by a set of four parallel lunette ridges. The most prominent is the inner lunette, which runs the length of both the two lakes (8.5 km), having a maximum height of ~30 m above the lake's level with a width

of approximately 0.7 - 0.9 km. This inner lunette (sample site 99/3) was cored along its ridgeline to a depth of ~18 m (Figure 3-16), from which twenty-four samples were taken at ~0.5 m intervals (Figure 3-17).

The middle lunette is less than half the size of the inner lunette, being 3.5 km in length, 0.8 km wide, and is oriented parallel to the inner lunette with their respective ridgelines positioned ~1 km apart (Figure 3-16). A 9 m core was drilled near the highest point of approximately 966 m above msl (sample site 99/12), with eighteen samples collected at ~0.5 m intervals (Figure 3-18).

The 6 km long outer lunette rises to an elevation of 971 m above msl (~33 m above the lake level) (Figure 3-16). This dune was augured to a depth of 5.3 m and 10 samples from the cored sediments were extracted at 0.4-0.6 m intervals (Figure 3-19).

A review of aerial photographs and topographic maps of the Double Lakes area indicates a possible fourth lunette (sample site 99/1), positioned near High Lonesome windmill, approximately 1 km southeast of the outer lunette (Figure 3-16). This less prominent lunette was not cored, but a trench was dug and a sample taken at a depth of 0.65 m (Figure 3-19).

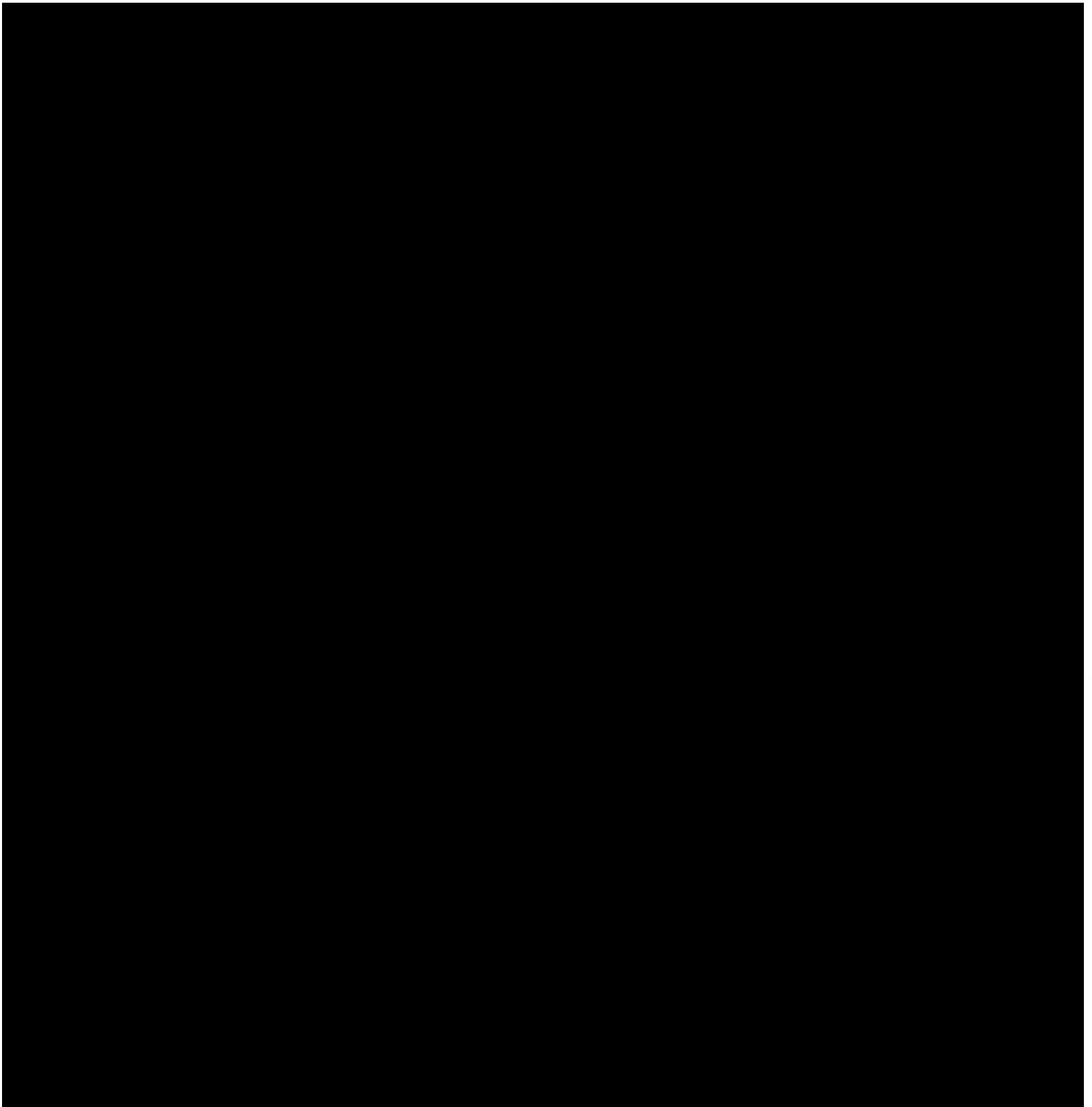


Figure 3-16. Double Lakes location and sample site map.

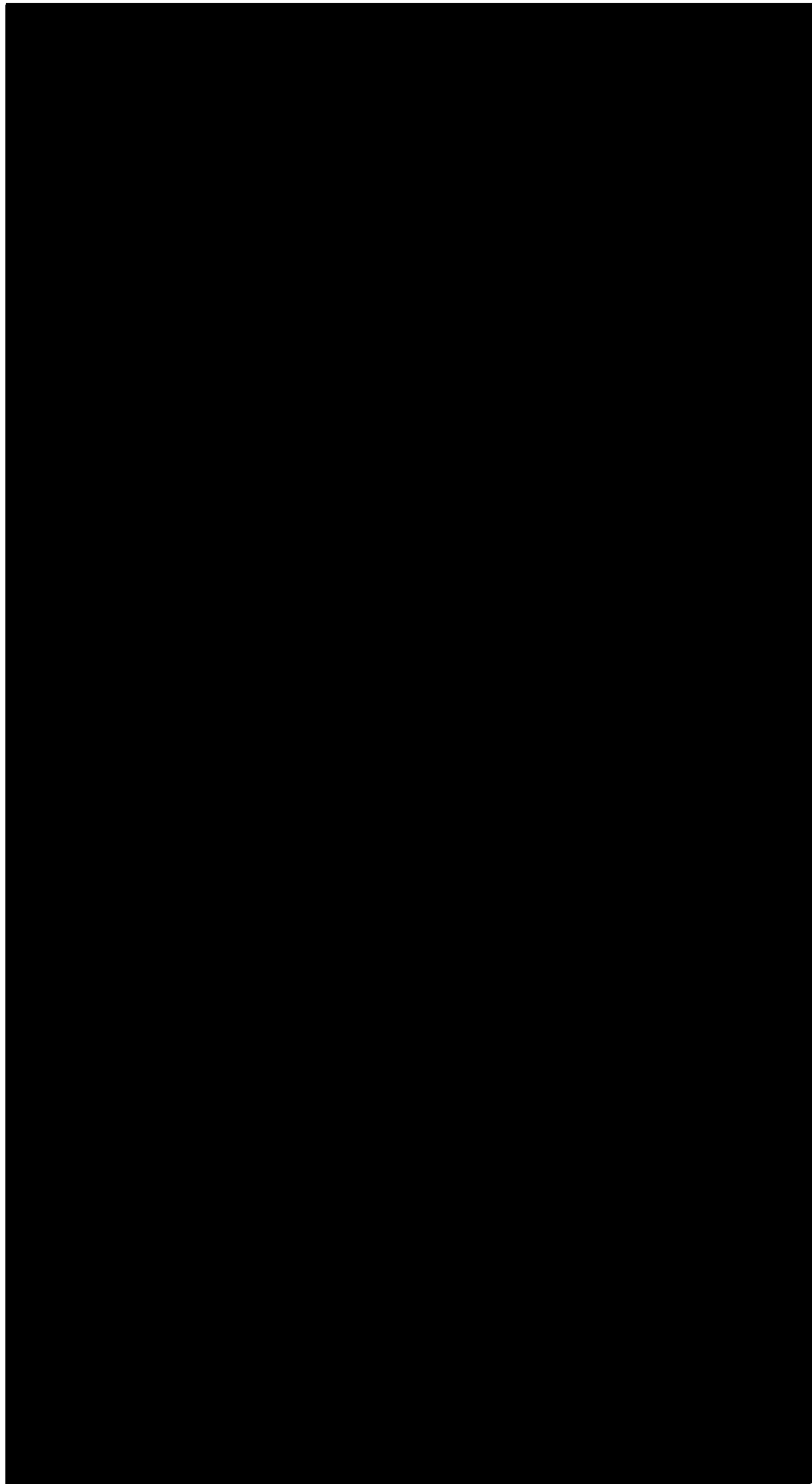


Figure 3-17. Cross-section of inner lunette core at site 99/3.

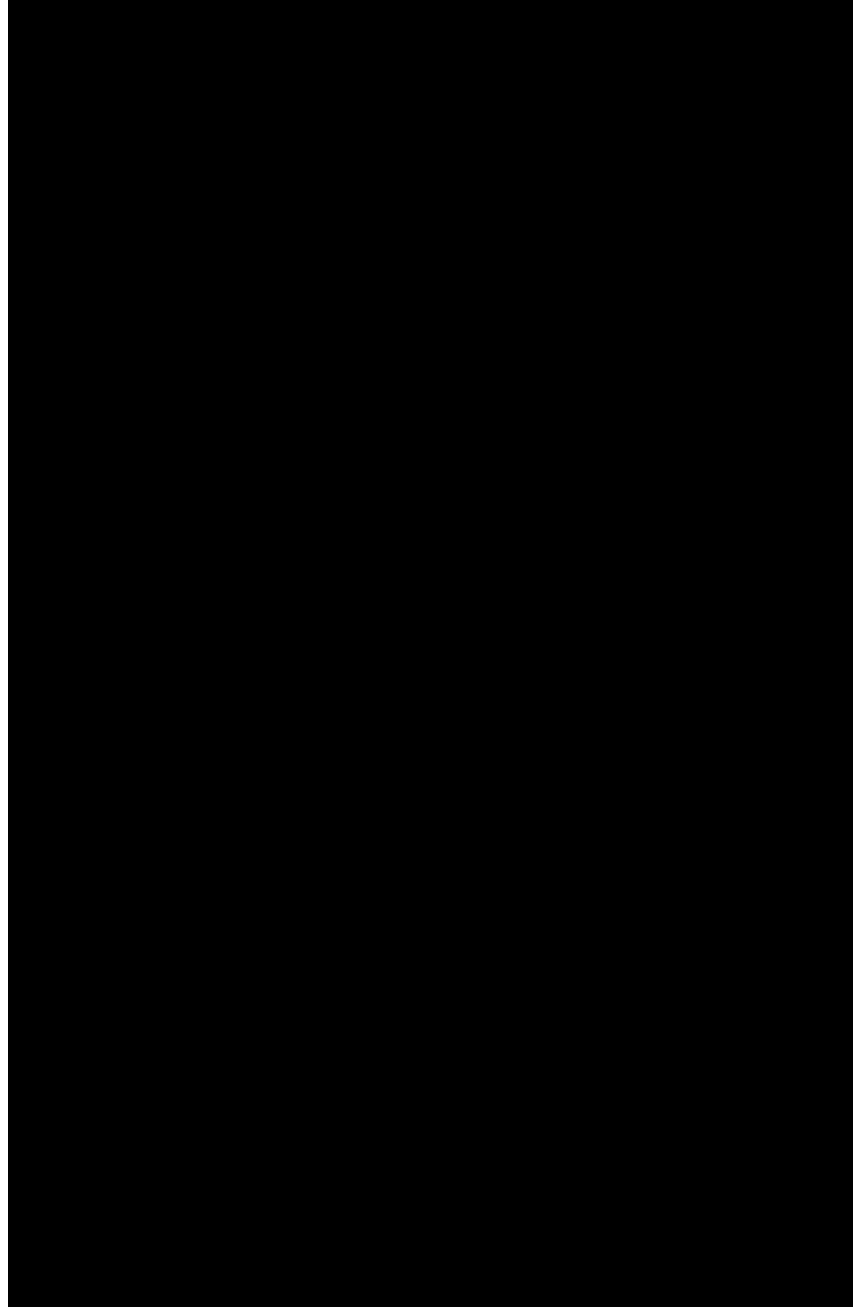


Figure 3-18. Cross-section of middle lunette core at site 99/12.

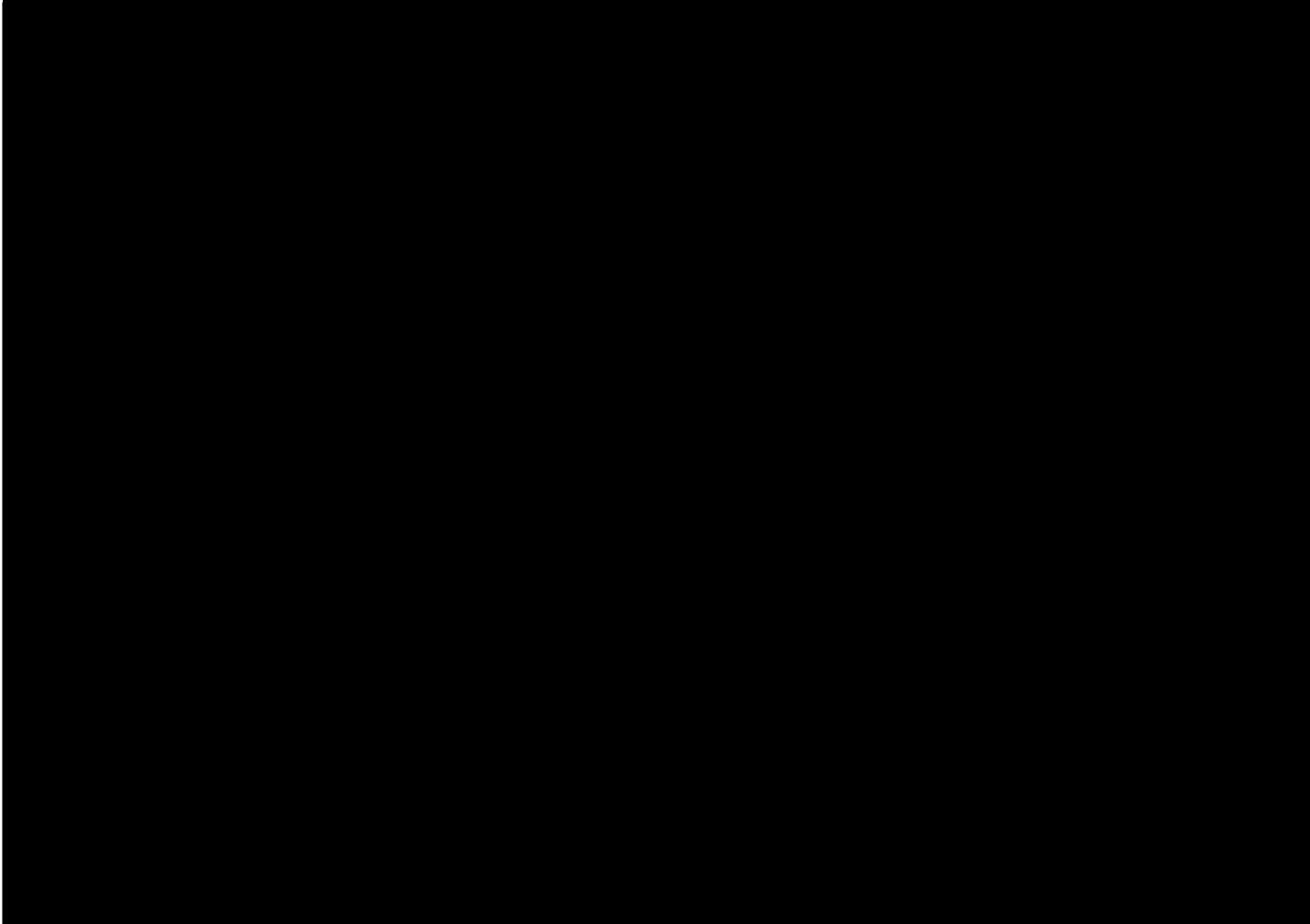


Figure 3-19. Cross-section of outer lunette core at site 99/4 and manually
trenched lunette (site 99/1) near High Lonesome windmill.

3.8.2.2 *Yellow and Illusion Lakes*

Yellow and Illusion Lakes lie in close proximity to each other, and are located ~15 km southwest of Littlefield, Texas in Hockley and Lamb Counties (Figure 3-10). Paralleling the eastern shoreline of these two lakes is a fairly continuous lunette, 8 km long and approximately 1 km wide (Figure 3-20). Two samples were obtained from this lunette where the dune had been incised by a transverse gully (sample site 98/4), at a location adjacent to Illusion Lake. Both samples were taken from clayey sands at depths of 1.8 and 0.8 m and produced optical age estimates of 1.94 ± 0.13 and 0.57 ± 0.04 ka, respectively. Further south, along the dune ridge near Yellow Lake, a third sample (99/9/1) was taken at a depth of 3m, which yielded an age of 0.92 ± 0.08 ka (Figure 3-20). These dune sediments were comprised of compacted sand with no evidence of palaeosols, or distinct contact throughout.

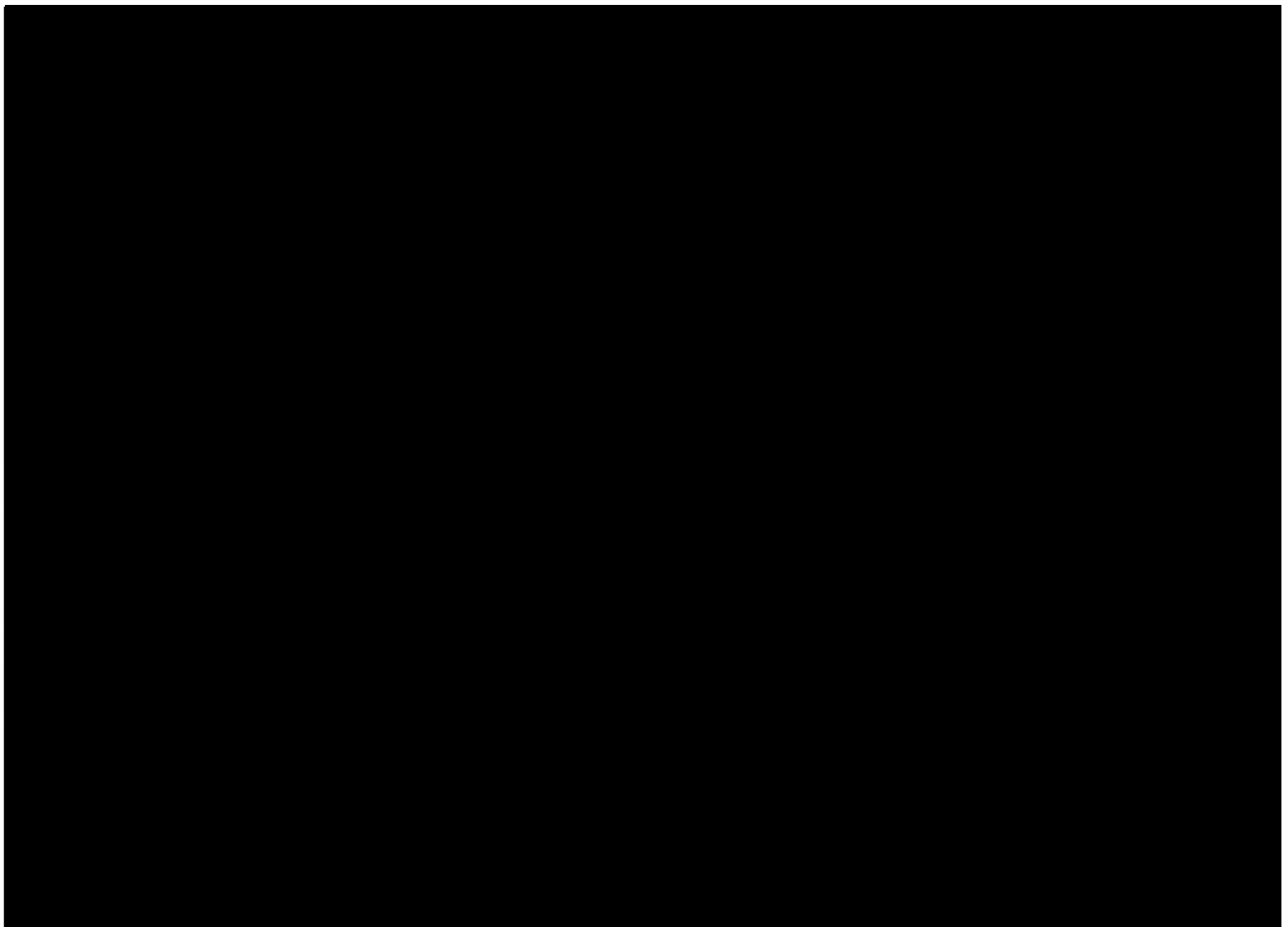


Figure 3-20. Yellow/Illusion Lakes and cross-sections for sample sites 98/4 and 99/9.

3.8.3 Coversands

Coversands comprised of dunes and low-angle aeolian sand sheets encompass more than 10,000 km² on the western half of the Southern High Plains, and are divided into five groups or dune fields comprising the Muleshoe, Mescalero, Lea-Yoakum, Monahans, and Andrews Dunes (Figure 3-21) (Holliday, 2001). A total of 37 coversand samples were collected from road cuts, dune blowouts, and dug pits in a wide range of localities that were considered representative of the region's sand sheets and dune systems (Figure 3-21). Most often coversand samples were manually collected from sites that had been previously excavated for a road thoroughfare or had been incised by fluvial erosion. Where no man-made or natural erosion existed, a pit was dug to access undisturbed material. At each of these sites opaque, polyvinyl chloride tubing was hammered horizontally into freshly cleaned exposures in order to collect the coversand material.

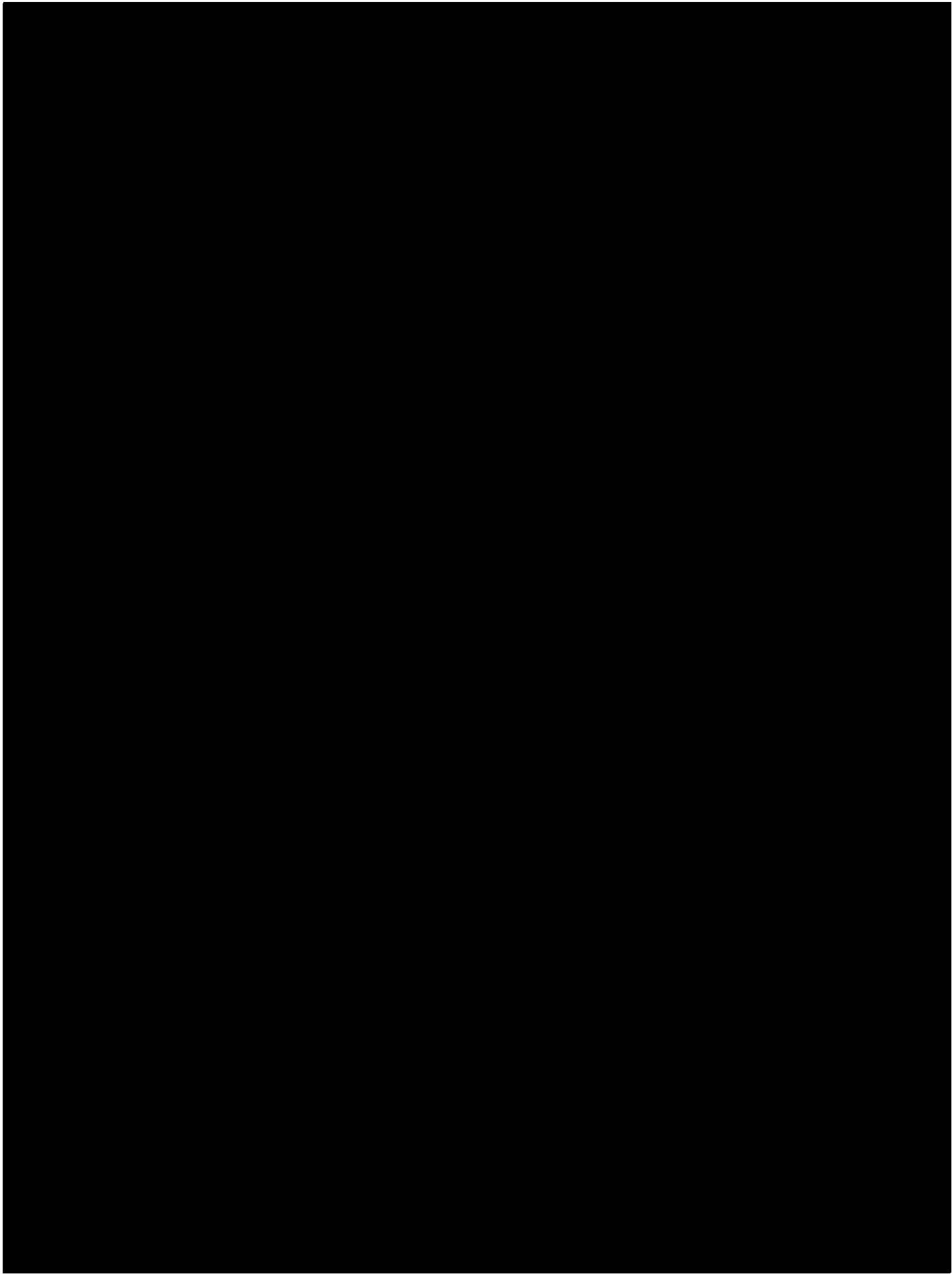


Figure 3-21. Southern High Plains coversand location map and sample sites.

3.8.3.1 Muleshoe Dunes

The Muleshoe Dunes extend approximately 160 km west to east and varies between 8 and 18 km in width. This sand sheet extends across both the Portales Valley, a re-entrant feature on the western escarpment, and the upper course of the Blackwater Draw (dry river valley). The Muleshoe Dune field is dominated by parabolic dunes with some blowout and barchanoid dune forms covering an area of over 1850 km² (Holliday, 2001) (Figure 3-21). Eighteen samples were collected from six different localities, stretching from ~45km to ~100km, from the western edge of the Muleshoe Dunes.

Sample site (99/14) (Figure 3-22) is located near the western edge of the Muleshoe Dunes along highway number 40 where the dune had been bisected by the thoroughfare. Calcrete was exposed near the base of the road cut and was overlain by coversand sediments. Three samples were collected at this site with the deepest (sample 99/14/1) taken at a ~3 m depth. Sample 99/14/2 was taken from the ubiquitous yellowish-red sediments that were representative of the area which were deposited during the later Pleistocene. An upper mid-Holocene aged sample (99/14/3) was collected from aeolian material overlying a well developed palaeosol.

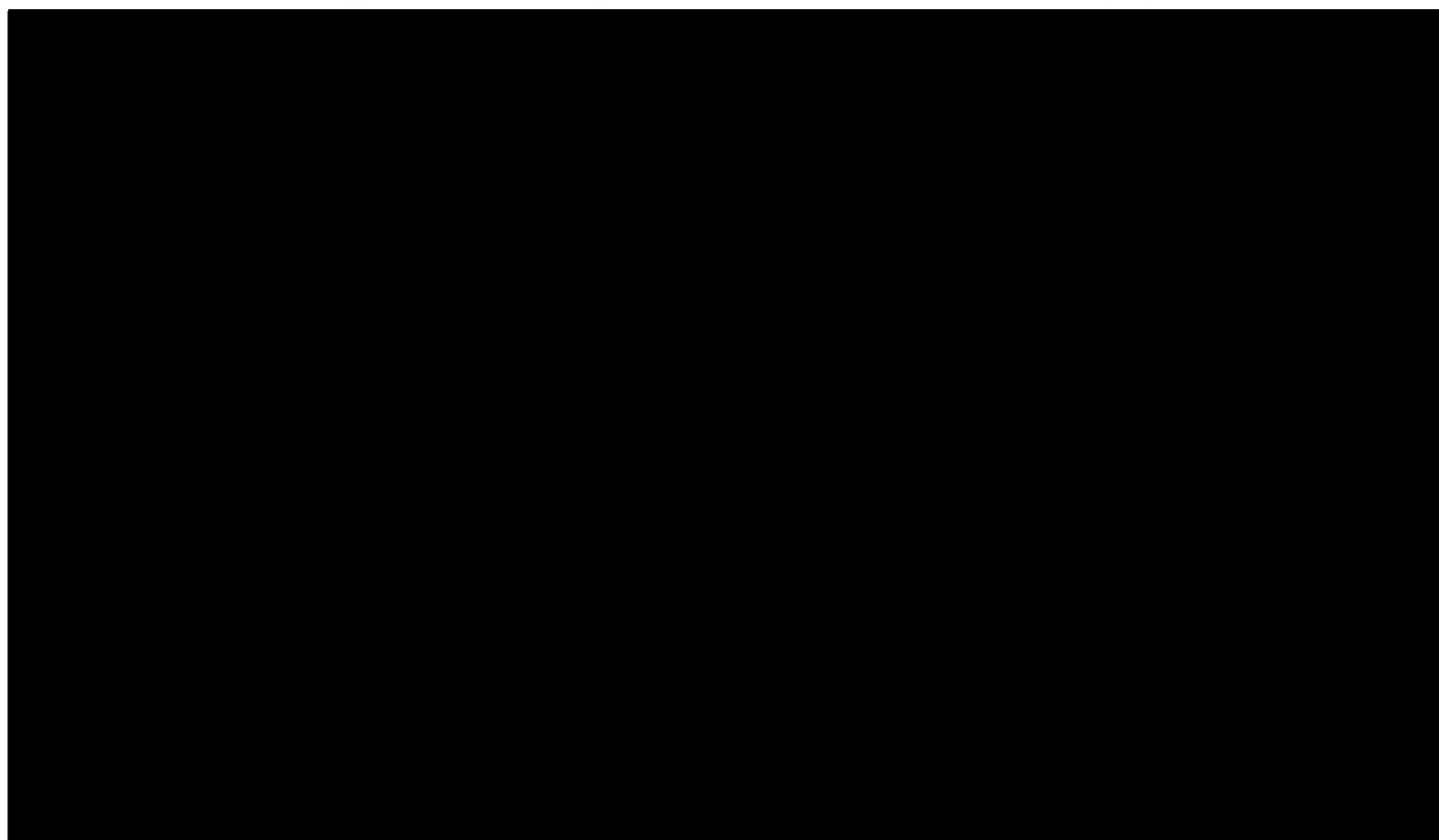


Figure 3-22. Location map and cross-section for sample site 99/14.

Sample site 99/15 was located in an excavation pit off route 467 between Portales, New Mexico and Cannon Air Force Base (Figure 3-23). Surrounding the perimeter of the pit was a low relief dune with a lamination crust, beneath which were compacted, well-developed prismatic sediments. This dune was sampled in order to compare the depositional timing to nearby topographically higher dunes (>1245 m) positioned to the north-east of the pit. The basal dune material at this location was well-bedded aeolian sands from which a single sample (99/15/2) was taken, which were emplaced approximately 830 ± 70 years ago. A distinct palaeosol separates the lower sediments from upper loose friable sand. Another single sample (99/15/3) was taken from upper sediments within this strata a few metres to the southeast. These sediments, represented by sample 99/15/3, were deposited during the ‘Dust Bowl’ event that impacted the central United States during the 1930’s.

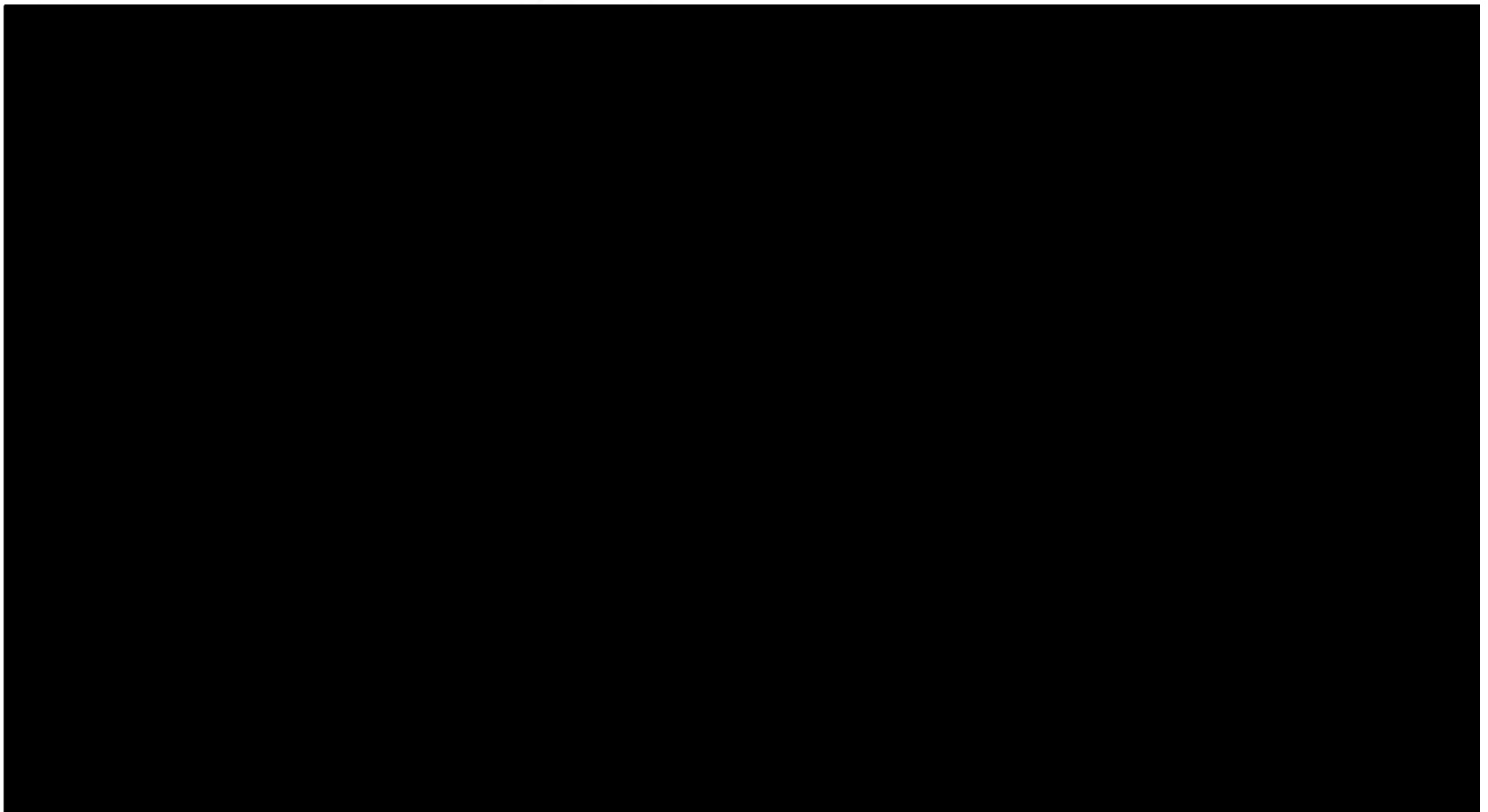


Figure 3-23. Location map and cross-section for sample site 99/15.

Sample sites 99/13 & 16 are located 18 km southwest of Muleshoe, Texas in a location where dunes surround a blow-out (Figure 3-24). A trench was dug to a depth of over 1 m in order to sample sediments beneath the resistant layer. These samples (99/13/1 & 2) had statistically indistinguishable age estimates and were deposited

during the later Pleistocene. The other four samples were taken from dune sediments overlying the resistant layer. These dunes have prominent cross-stratification and wavy non-parallel laminations (Figure 3-24). An inter-bedded palaeosol continues through the coversands at this site separating later Holocene aged sediments, represented by samples 99/16/1, 99/13/3 & 4, from historic sands (sample 99/13/5). The resistant layer divides Pleistocene-aged sediments from the overlying Holocene-aged materials.

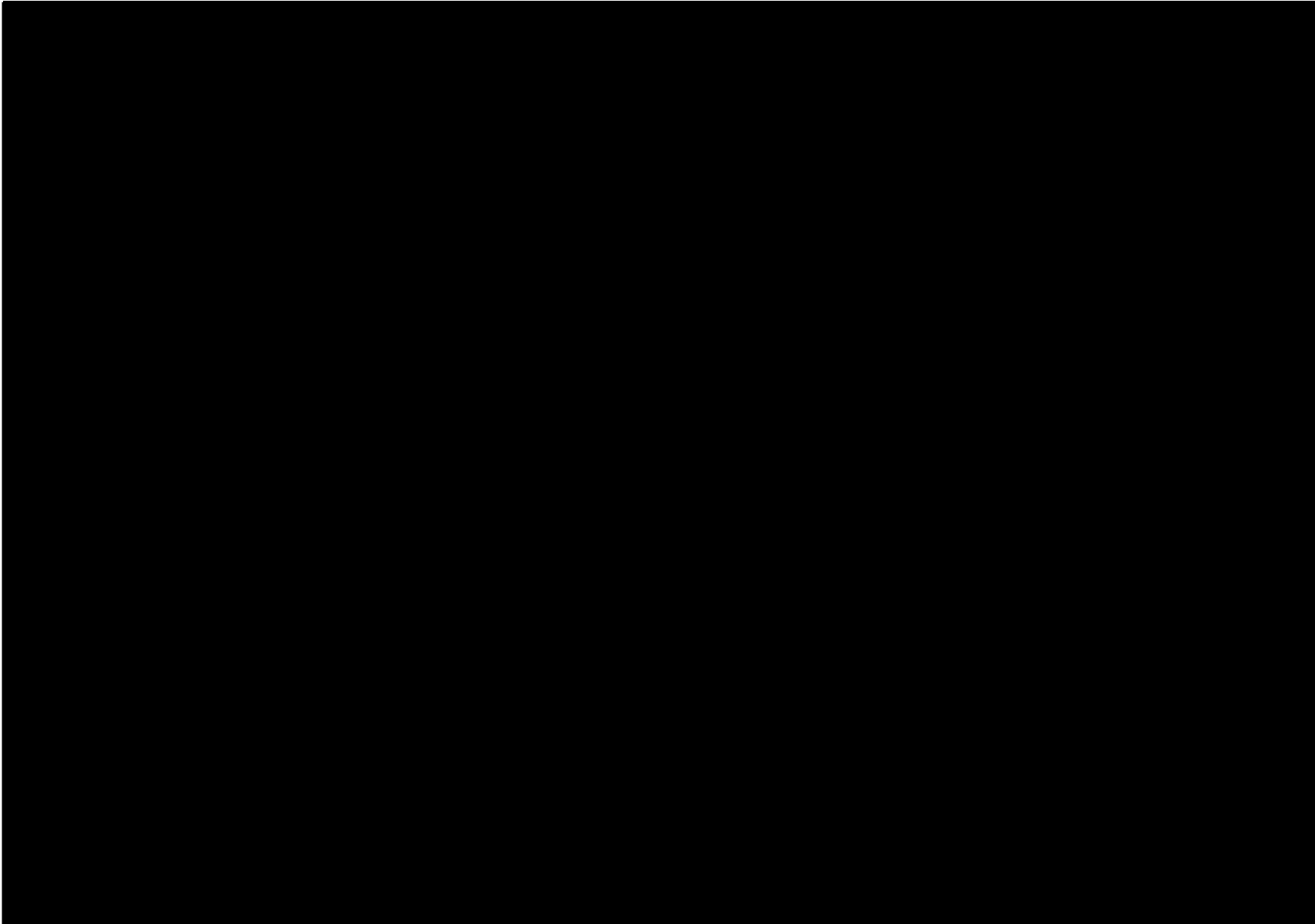


Figure 3-24. Location map and cross-section for sample sites 99/13 & 16.

Sample site 99/17 is located north of localities 99/13 & 16 at a road cut along route #1731 (Figure 3-25). Only one sample (99/17/1) was taken at this location, due to an interruption by a severe thunderstorm that made further sample collection at this site nearly impossible. This site exhibited the best degree of soil development that was seen throughout the Muleshoe Dune complex, having a pronounced prismatic soil structure from the surface to a depth of 50 cm. The sample, taken from ubiquitous yellowish-red sediments, had an optical age estimate of 1.2 ± 0.1 ka (see Figure 3-25).

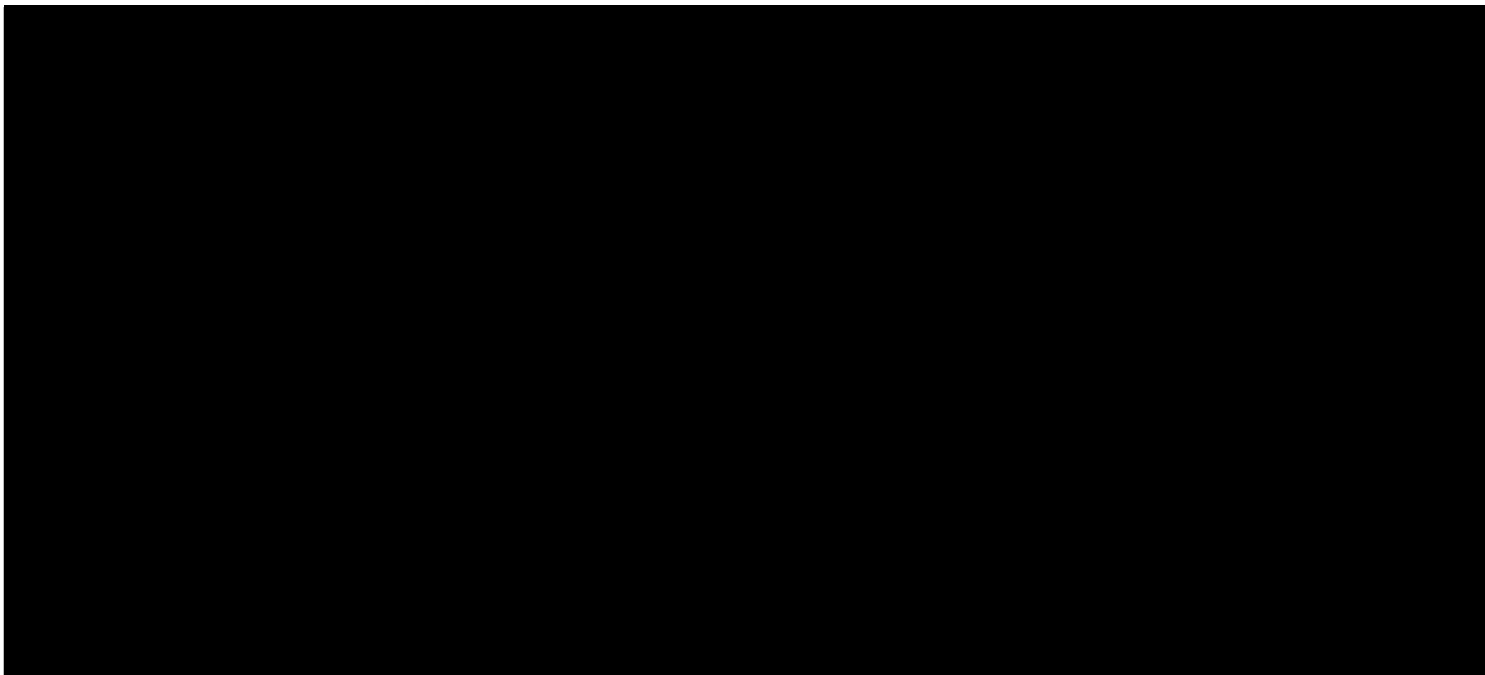


Figure 3-25. Location map and cross-section for sample sites 99/17.

Sample site 98/2 is located about 50 km from the Texas-New Mexico border in the eastern portion of Muleshoe Dune field (Figure 3-21). This location offers comparison of results from eastern as well as western coversand localities. Site 98/2 is positioned at a road cut off state highway 84 on the outskirts of Muleshoe, Texas (Figure 3-26). The coversands at this location are only about 3 m thick, making deep sampling difficult. The lower sample (98/2/2) from a depth of ~2 m, is estimated to have been deposited 62 ± 6 ka. The upper sample was taken from material deposited ~100 years ago during the Historic period.

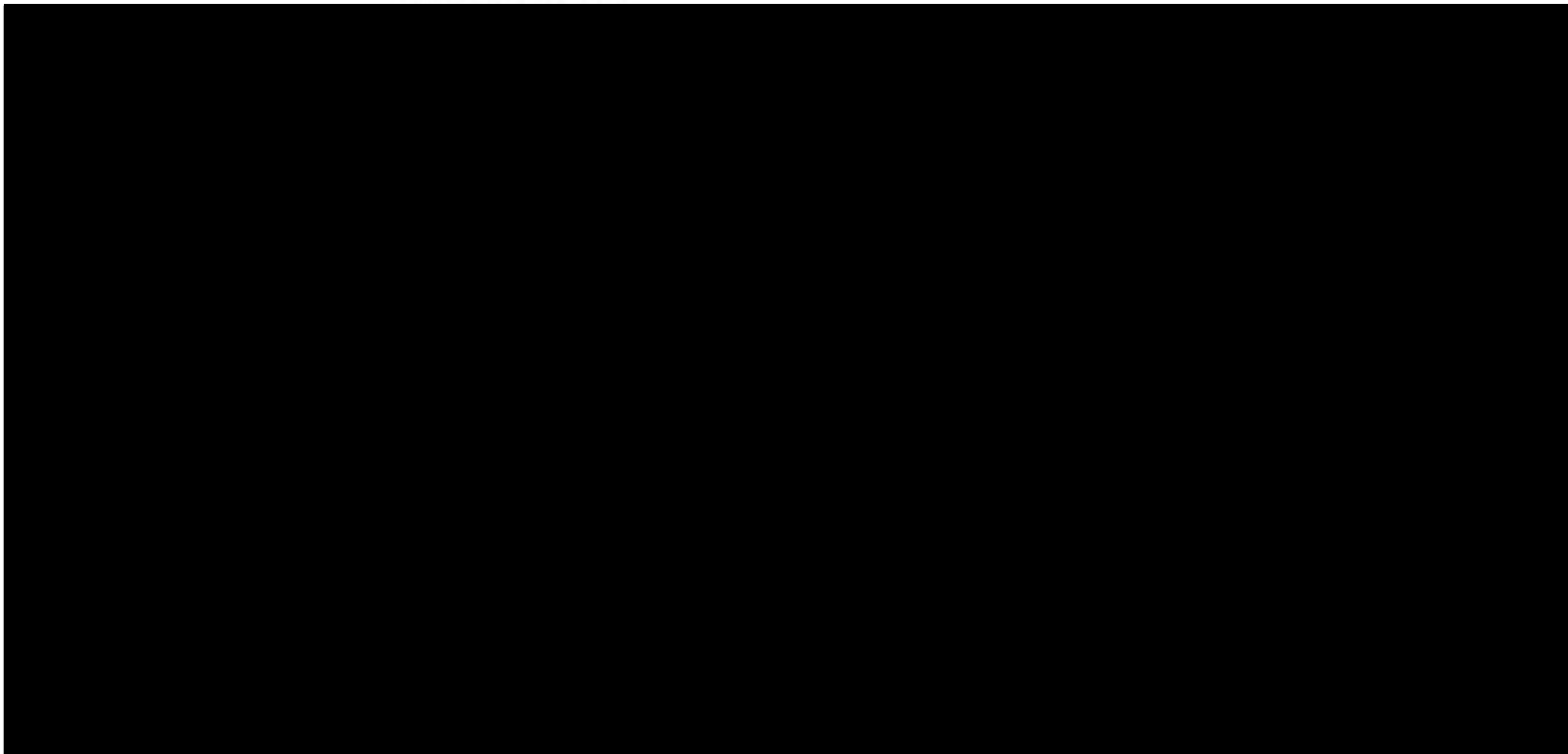


Figure 3-26. Location map and cross-section for sample site 98/2.

3.8.3.2 *Lea-Yoakum Dunes*

The Lea-Yoakum Dunes are comprised of a series of individual west-east trending coversands occupying portions of Sulphur Draw and Seminola Valley (Figure 3-21). The principal features in the Lea-Yoakum are parabolic dunes with their associated blowouts. Fence-row dunes are also found in the area, which represent Historic-aged sands deposited along 20th century field boundaries (Holliday, 2001). Three samples from Lea-Yoakum Dunes were collected at a single site along the southern edge of Sulphur Draw. These were taken from a road cut where approximately ~2 m of sediments were exposed along route #125 (Figure 3-27). The stratigraphically lowest sample (99/18/1), located in loose friable sand, was taken from sediments deposited during the late Pleistocene. The two younger upper samples (99/18/2 and 99/18/3) are divided by distinct contacts with the stratigraphically lower sediments deposited during the middle Holocene while the upper sample was collected from Historic-aged sediments deposited ~100 years ago (Figure 3-27).

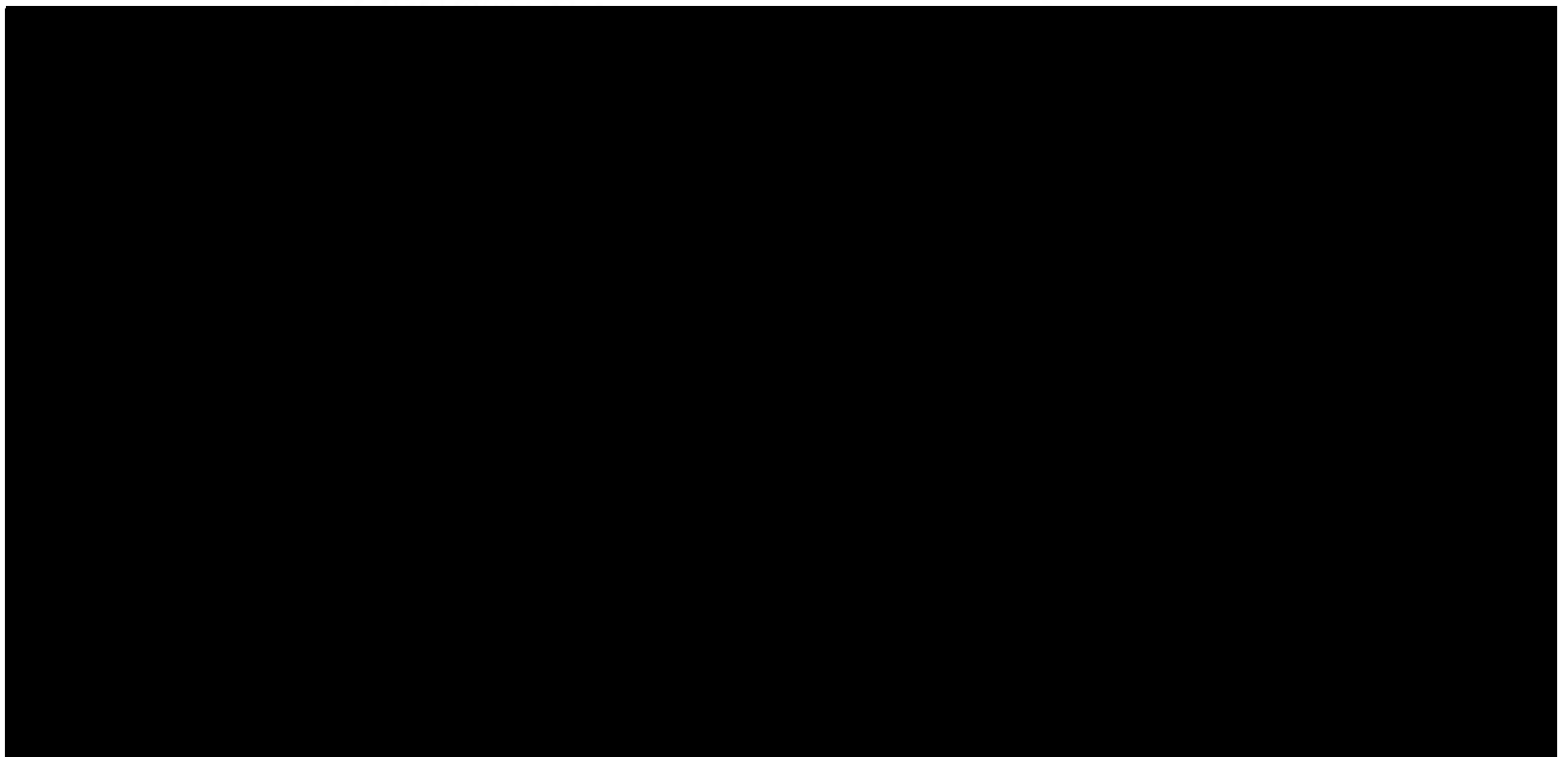


Figure 3-27. Location map and cross-section for sample site 99/18.

3.8.3.3 Mescalero Dunes

The Mescalero Dune system is oriented roughly north-south, and covers an area of approximately 3000 km² (Figure 3-21). This dune field is ~10-20 km wide and follows the western escarpment of the Southern High Plains for ~200 km. The dune types within this system include barchan, coppice, and blowout dunes. Due to the north-south trend of the dune field, two sample sites were chosen, with one being located in the extreme northern area, the second in the south of the region. A total of five samples were collected in the north from the Mescalero Dunes State Park (Figure 3-28). Two large, 4 m high, coppice dunes were sampled that were adjacent to each other. An optical age estimate on basal sediments from the northern dune, taken at a depth of 5.5 m, indicated emplacement approximately 81±8 ka (sample 99/19/1). Stratigraphically higher samples, from both dunes (99/19/3, 2A & 2B), indicated that these sediments were deposited during the middle to late Holocene. These samples were positioned beneath a palaeosol that was visibly evident in both coppice dunes (see Figure 3-28). The aeolian sand overlying the distinct palaeosol were modern, having been deposited during the 1930's North American 'Dust Bowl' event, which correlates with other coversand sites on the Southern High Plains.

Three additional samples were taken from two separate sites (99/24 and 99/23) near the southerly extent of the ~200 km long Mescalero dune field. A single sample was collected from aeolian sediments located off route #18 (site 99/24) (Figure 3-29). This site was a former gravel pit with an exposure of yellowish-red sand in contact with a massive calcrete exposure. Talus spoil resides on the top of the dune material, which presumably covers younger sediments. The sample taken from the aeolian sediments, positioned between the spoil heap and calcrete base, was deposited during the late Pleistocene ~47±6 ka. A moderately developed, prismatic palaeosol is found in the upper portion of the reddish-yellow sands, and possibly represents a period when the Southern High Plains landscape was experiencing relatively wetter conditions and/or reduced evaporation.

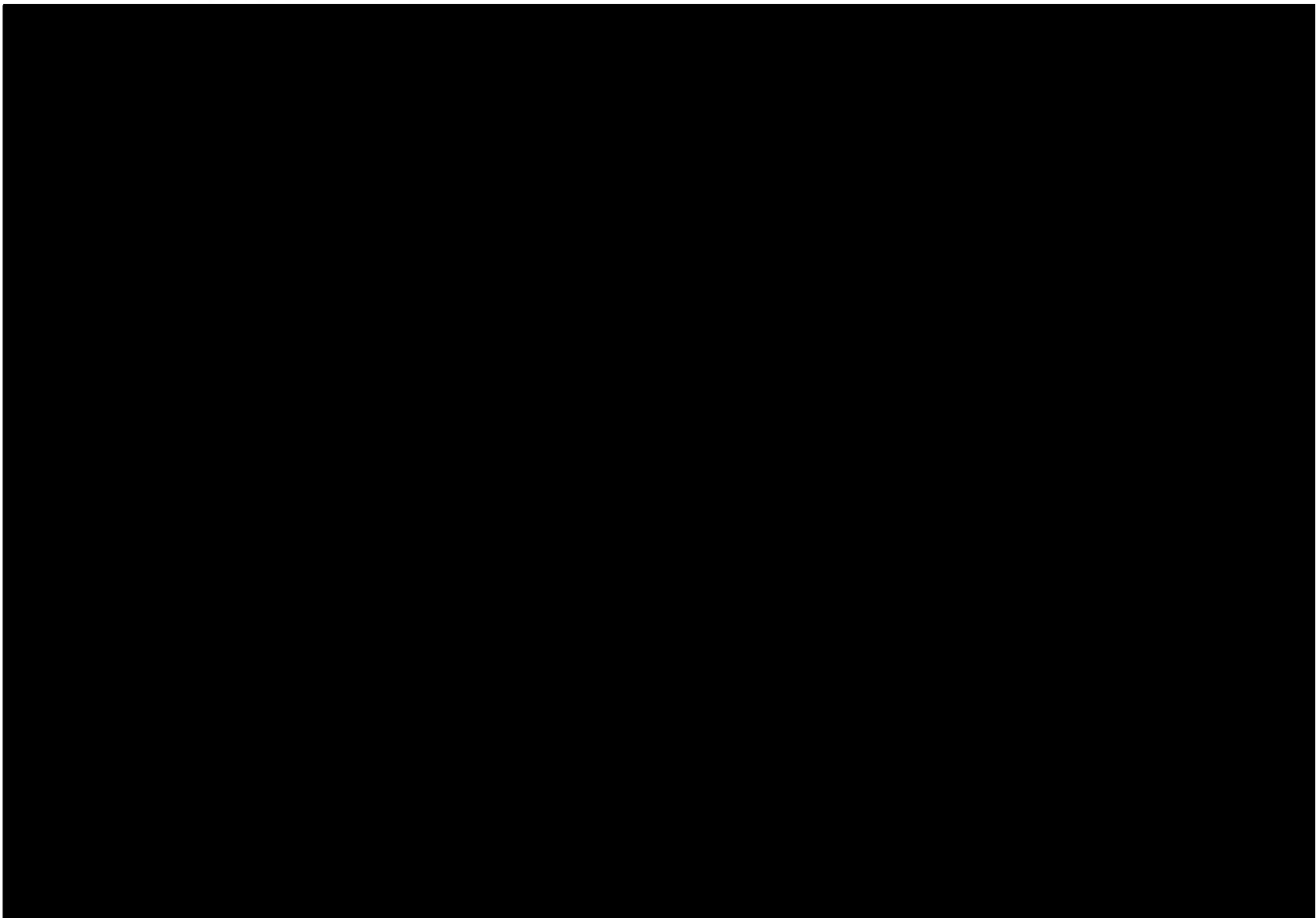


Figure 3-28. Location map and cross-sections for sample site 99/19.

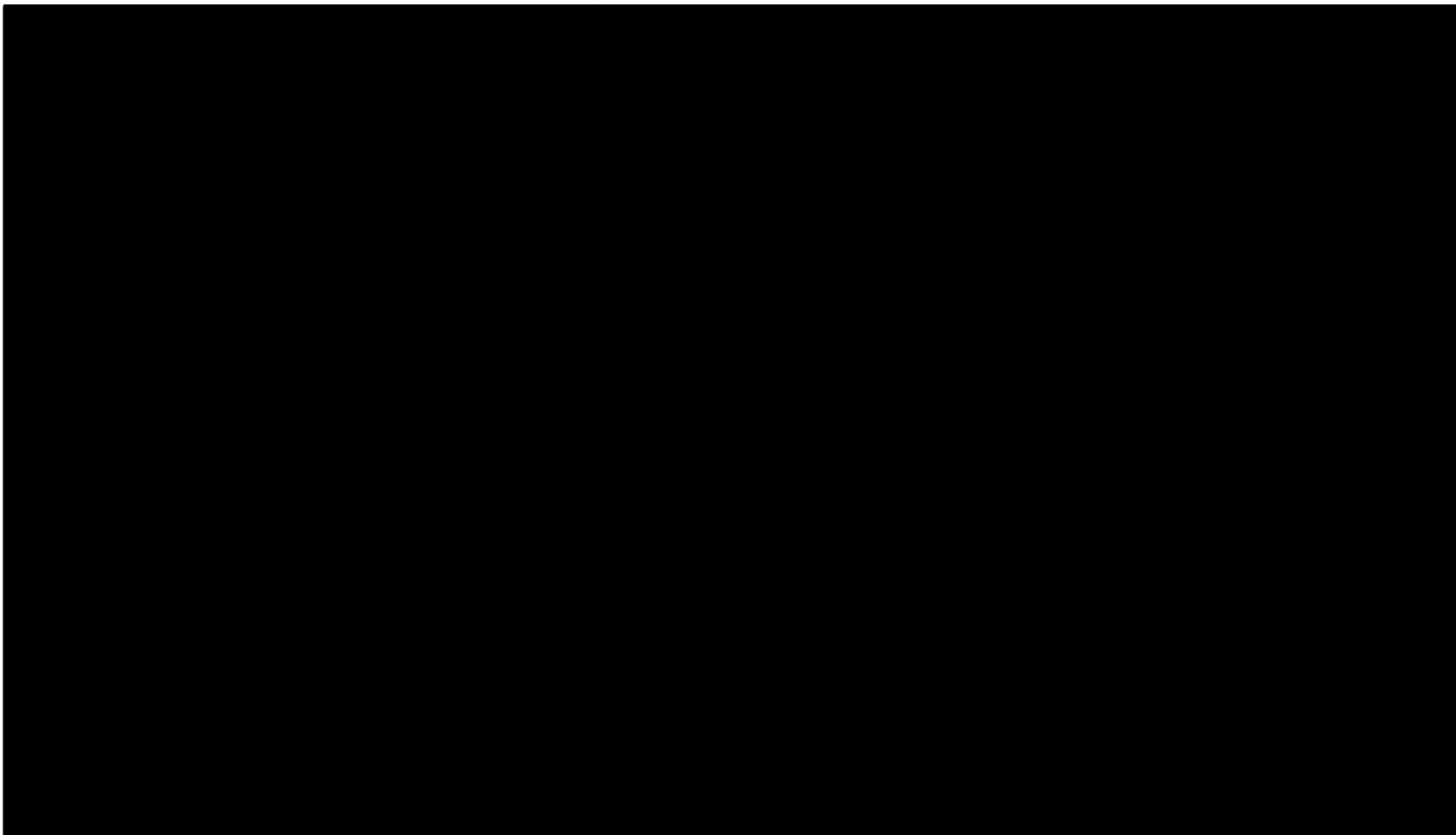


Figure 3-29. Location map and cross-section for sample site 99/24.

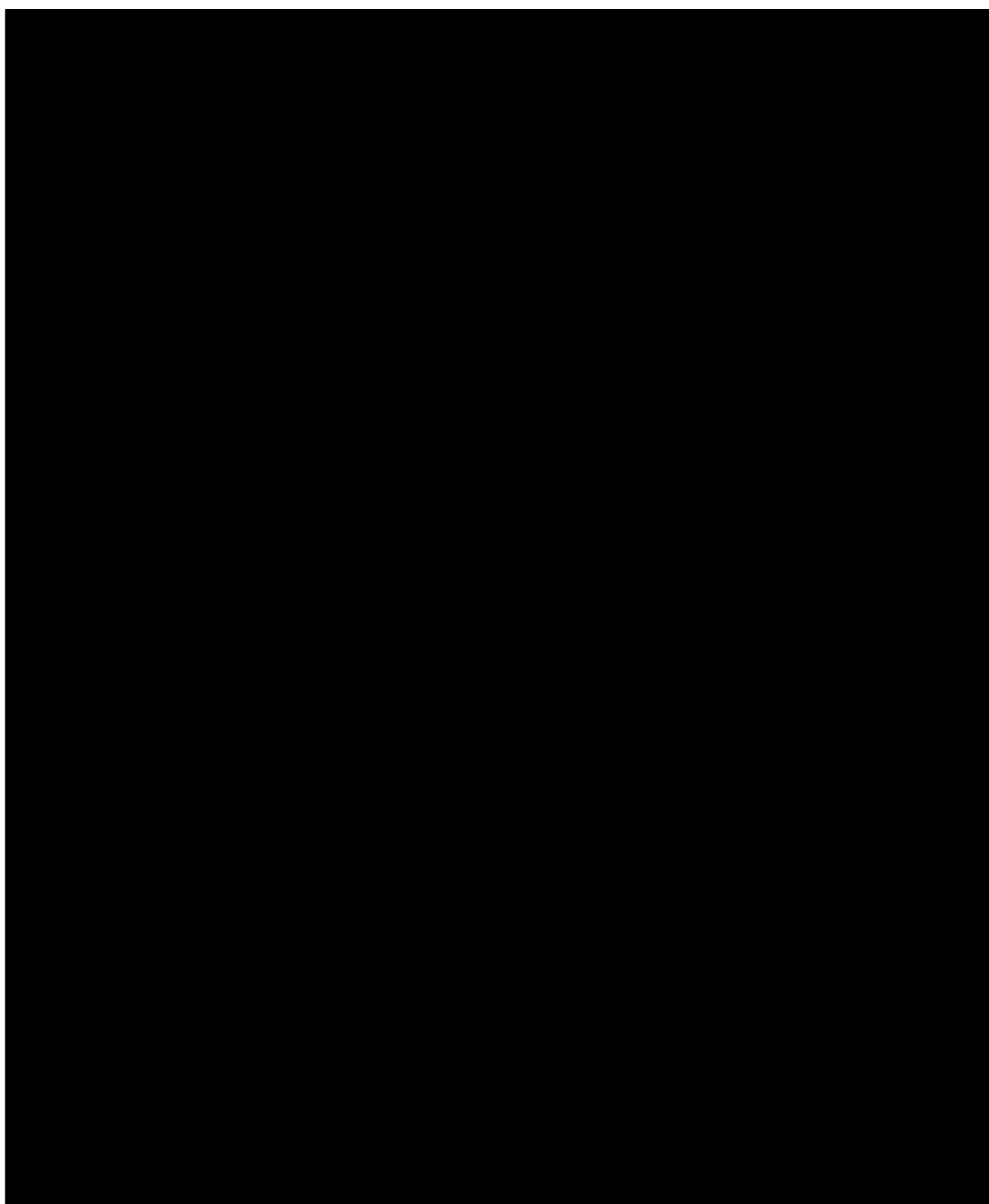


Figure 3-30. Location map and cross-section for sample site 99/23.

Route #18 was followed further south to an additional southerly location of the Monahans Dunes (Site 99/23) in a section called Toboso Flats, located 10 km south of Jal, Texas (Figure 3-30). The flat had sparse vegetation and was surrounded by coppice dunes. Aeolian sediments were sampled 1 m beneath one of these coppice dunes (sample 99/23/2) and the age estimate obtained from the sample indicated it was deposited 29 ± 3 ka. A trench was dug near site 99/23/2 to access sediments beneath the resistant surface of Toboso Flats. Sample (99/23/1) was taken in structureless sands where there was no obvious soil development that could be recognised in these exposed sediments at site 99/23 (Figure 3-30).

3.8.3.4 *Monahans Dunes*

The Monahans Dune field is the most southerly dune complex of the Southern High Plains (Figure 3-21). Aeolian sediments at this location traverse the Pecos River Valley up to the Southern High Plains escarpment, with an extension into the Winkler Valley where the deposits are known as the Andrews Dunes. The Monahans/Andrews dunes cover a combined area of $\sim 2570 \text{ km}^2$ and are the most active dunes on the Great Plains (Muhs and Holliday, 1995). Dune forms include barchan and barchanoid ridges, parabolic with blowouts, and coppice dunes (Machenberg, 1984).

A total of four samples were collected at two sites (99/20 & 21) within the Monahans Sandhills State Park (Figure 3-31). Site 99/20 was located in a blowout surrounded by salt cedars. A 2 m trench was dug vertically into sediments beneath the basal level of the blowout. Approximately 4 cm of discontinuous iron-rich lamination crust capped underlying sediments, and two samples were taken at 0.5 and 1.45 m depths from very pale brown sediments, which contained wavy non-parallel laminations (Figure 3-31). These sediments also exhibited iron staining and mottling throughout. Some of the oldest optically dated coversand sediments from the Southern High Plains were from this site which exhibited age estimates of 100 ± 9 and 204 ± 22 ka.

Site 99/21 was located near the headquarters at the southern end of the State Park. The upper sediments of a barchan dune were sampled, which was representative of the many dunes within the park. Optical ages determined on samples taken at depths of 0.75 and 2.75 m were 2.0 ± 0.3 and 7.5 ± 0.8 ka respectively, indicating mid and late Holocene aeolian activity for this region (Figure 3-31).

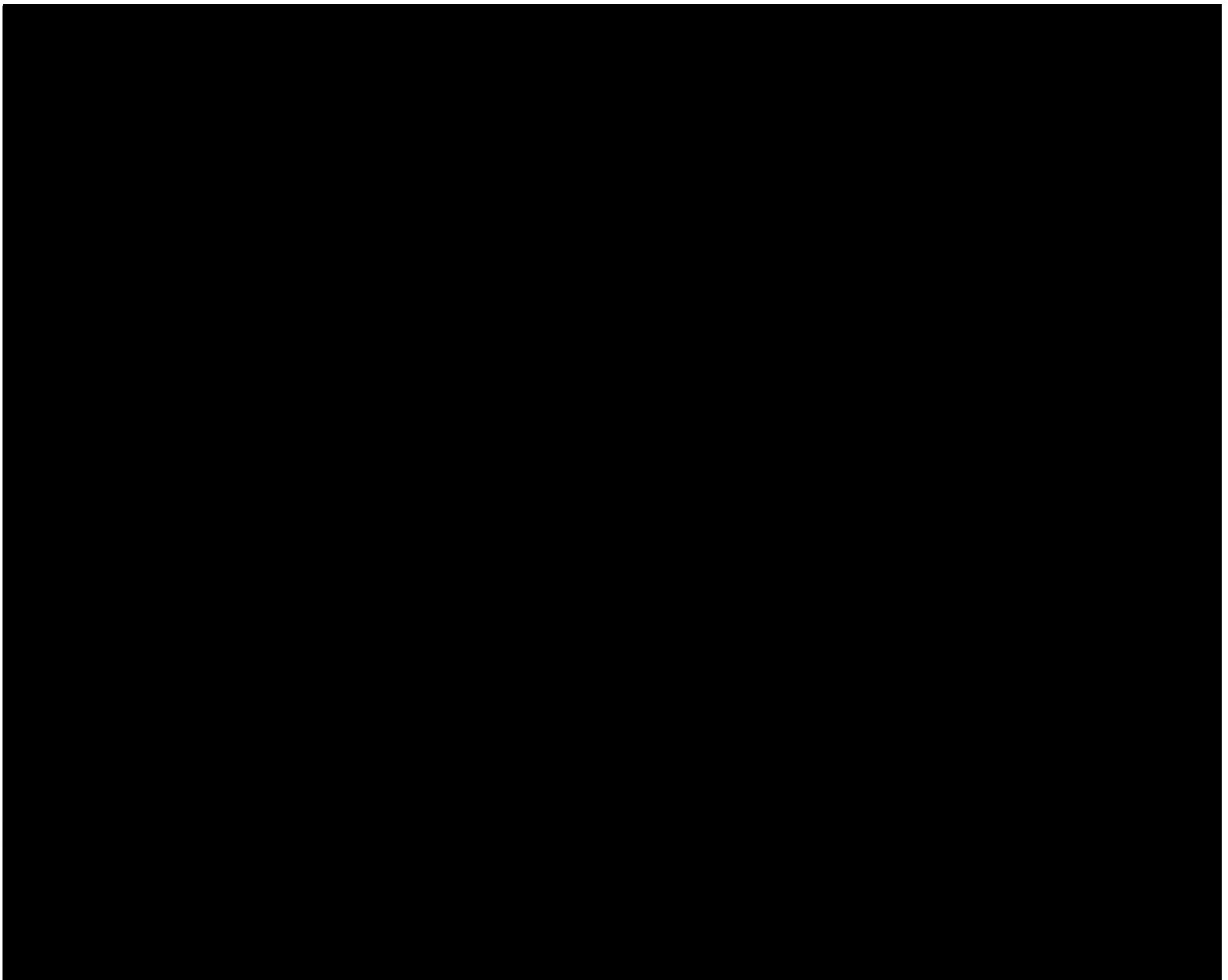


Figure 3-31. Location map and cross-section for sample site 99/20 & 21.

3.8.4 Lacustrine sample sites

Lacustrine samples were collected from two Southern High Plains large lake basin localities. This was done in order to investigate the timing of lake sediment deposition with regards to lunette accretion intervals, and provide further insight into the lake basin and lunette dune relationship.

A total of four lacustrine samples were collected from both Yellow and Rich Lake basin. Yellow Lake is presently ~3.5 km long, approximately 1 km wide, and is adjacent to the northerly Illusion Lake. A single Yellow Lake sample (99/8/3) was taken near the southeastern shoreline from exposed lacustrine sediments positioned above the present day lake level (Figure 3-32). Three other samples were collected from the same exposure, but following the sediment refinement process, there was not enough refined quartz that remained for analysis. The result from sample 99/8/3 indicates that a period of lacustrine deposition occurred at Yellow Lake $\sim 20 \pm 2$ ka.

Rich Lake has a crescent-shaped basin that is roughly 2 km in length and 0.6 km wide, with the present elevation 980 m above mean sea level. Surrounding Rich Lake are previously emplaced lacustrine sediments that were deposited when the lake was a higher level. Four lacustrine samples were taken along the northern margin of Rich Lake at depths of 2.0, 1.5, and 1.0 m (Samples 98/7/3, 98/7/2, 98/7/1) (Figure 3-33). These samples are stratigraphically coherent and represent lacustrine deposition approximately 57 ± 3 , 39 ± 5 , and 40 ± 3 ka.

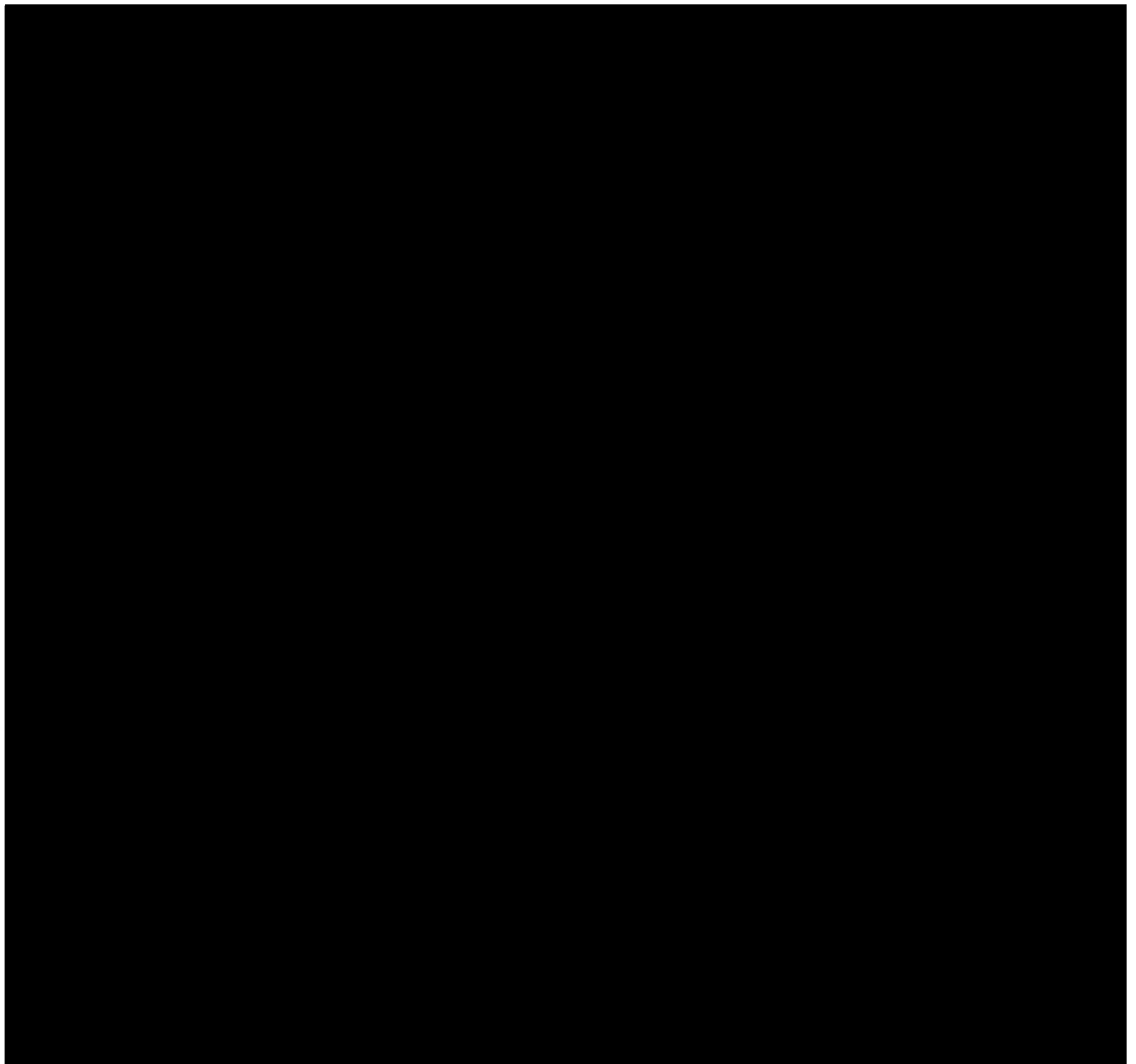


Figure 3-32. Yellow Lake location map with lacustrine sample site 99/8.

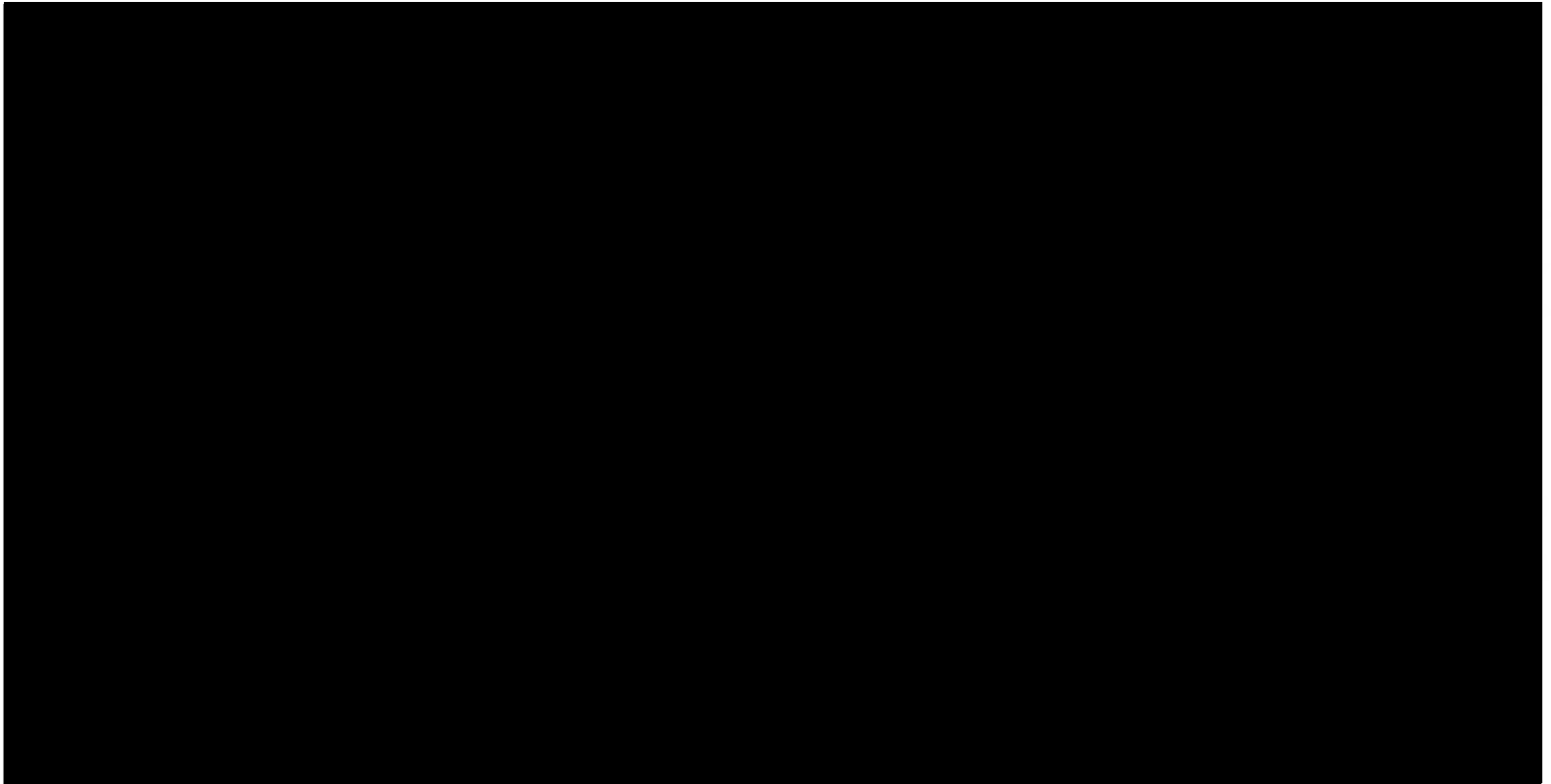


Figure 3-33. Rich Lake location map with lacustrine sample site 98/7.

3.8.5 Tufa sample site

A tufa deposit associated with Double Lakes is positioned ~4 m above the present lake bed (elevation = 943 m) in an ephemeral (intermittent) stream channel that flows into the northeastern lake (Figure 3-34). The indurated tufa exposure is a tabular, horizontally stratified deposit, varying in thickness from 1.0-2.0 m (Figure 3-35). Four samples were taken from the tufa exposure, three located at 33° 14' 25" N, 101° 54' 21" W, with an additional sample collected ~20 m upstream from this location. Blocks of indurated tufa material, approximately 10,000 cm³, were chiselled from the outcrop for sediment refinement and subsequent optical dating. The dating approach concentrates on the entrained quartz grains, rather than the carbonate material (micrite). These quartz grains can be identified in a scanning electron micrograph (SEM) image as having a relatively smooth, rounded surface consistent with an aeolian transportation mechanism (Figure 3-36, image shows micrite-encrusted quartz grains, centre of photo). Detrital sediment grains introduced into a tufa-forming environment may arrive via aeolian or other process and be deposited concurrent with the precipitation of calcium carbonate

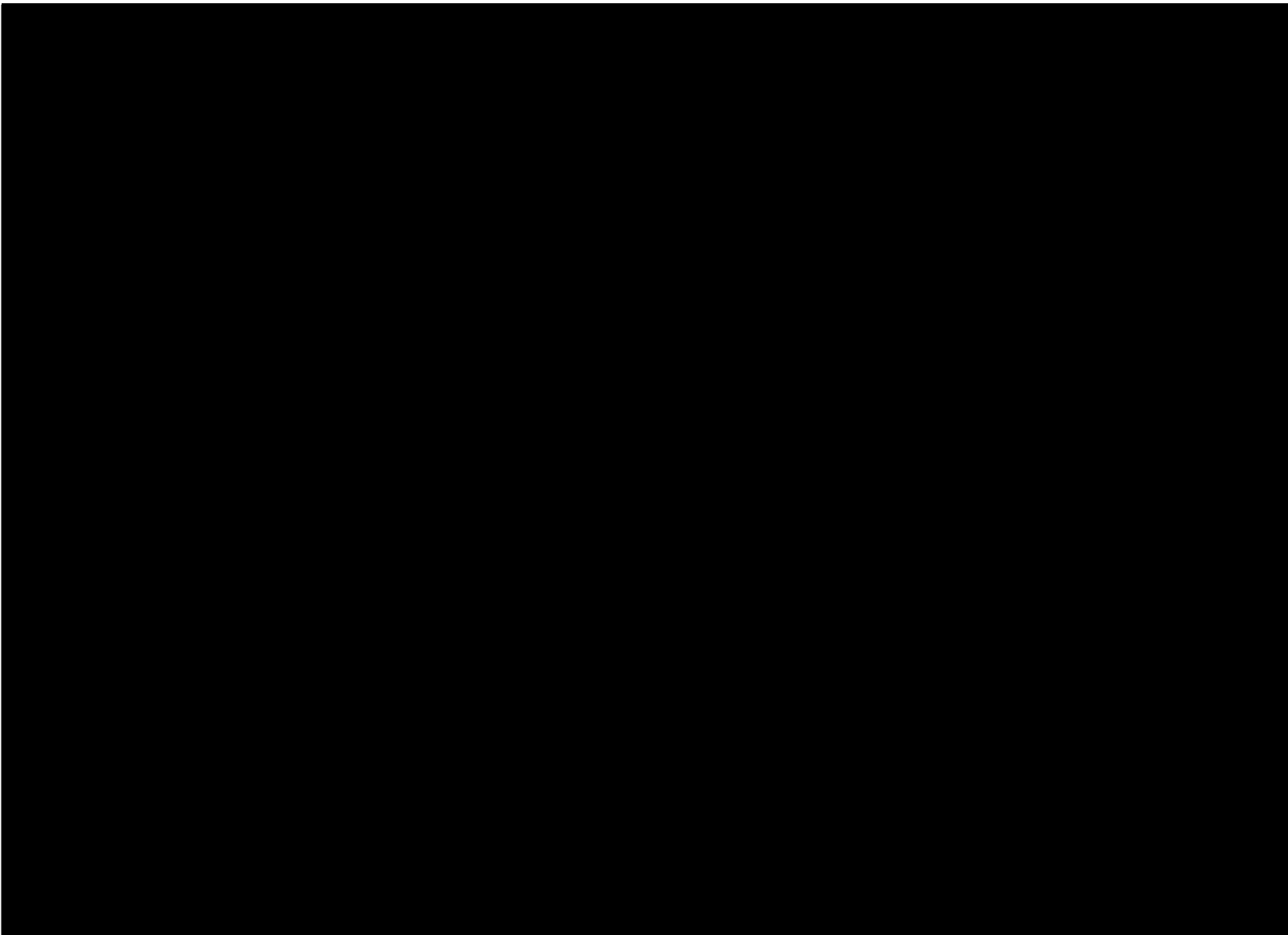


Figure 3-34. Double Lakes tufa location map.

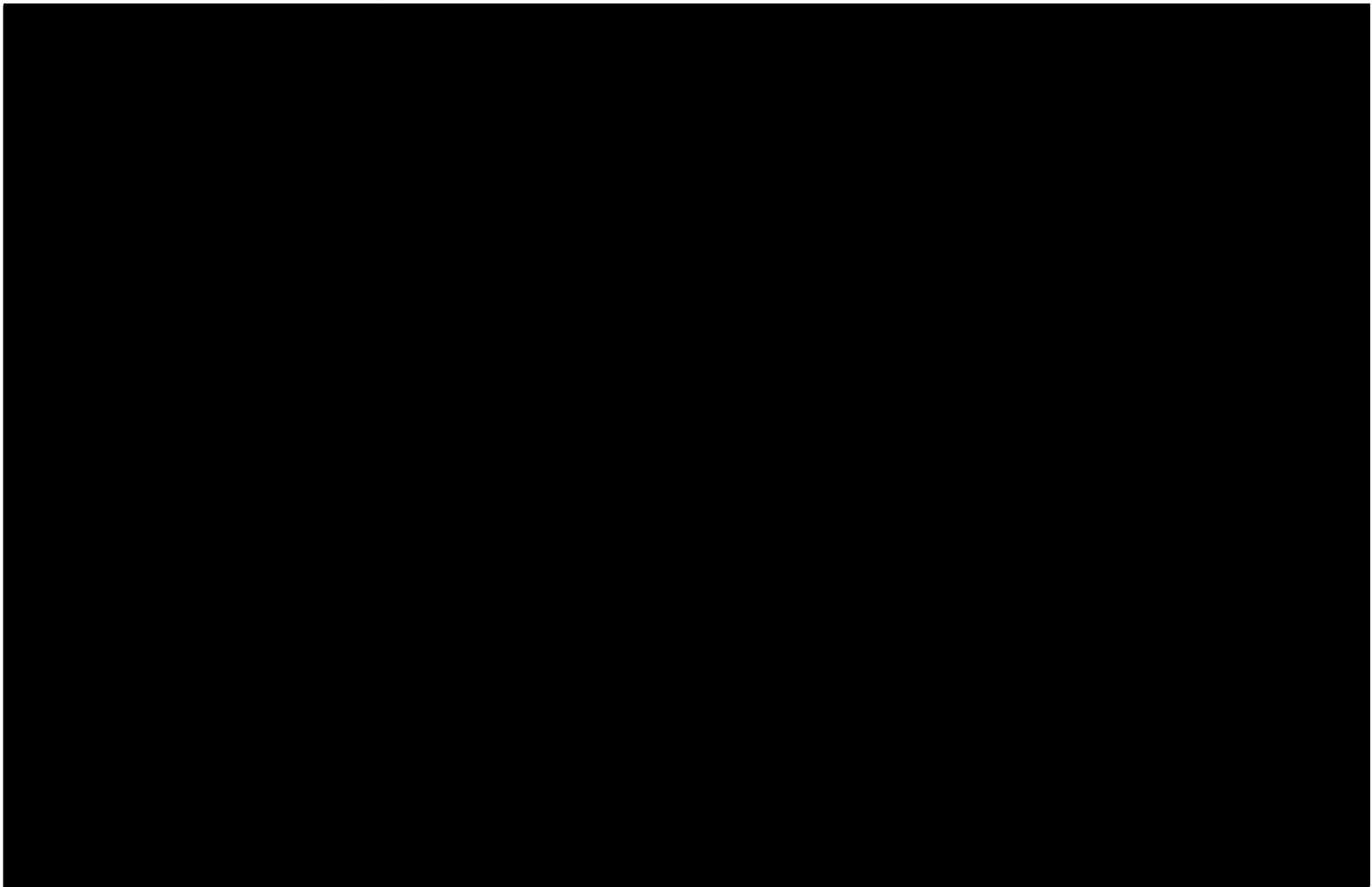


Figure 3-35. Horizontally stratified tufa deposit positioned northwest of Double Lakes. Four tufa samples were taken from outcrop (three are shown with the fourth taken 20 m north).

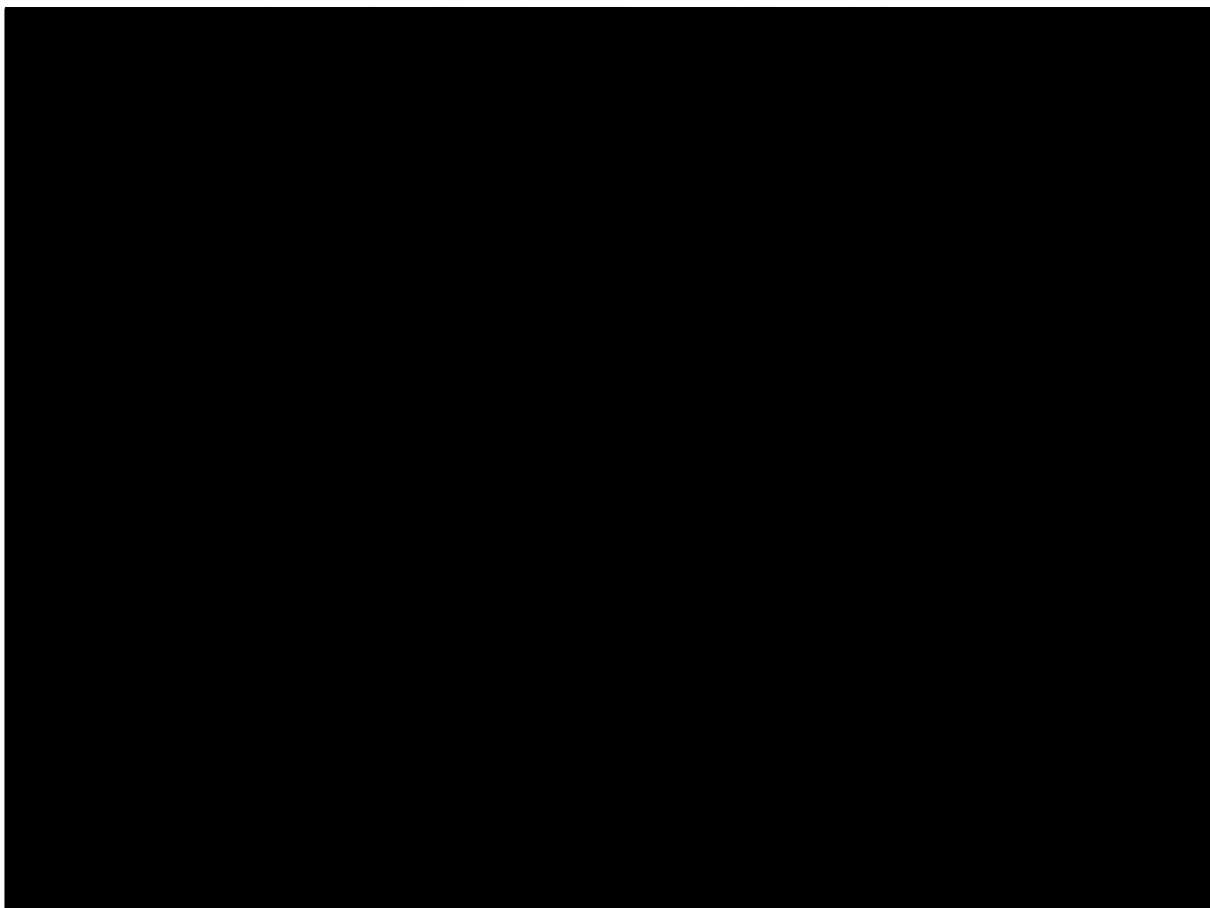


Figure 3-36. SEM image of unrefined tufa sample 99/2/1. Scale bar 20 μm .

SOME TESTS RELEVANT TO THE OPTICAL DATING PROCEDURE

Chapter overview

Chapter 4 contains information on experiments, which were carried out on selected Southern High Plains samples that relate to the optical dating procedure, namely pre-heat plateaus, test-dose variance and recycling ratios, in order to test the robustness of the dating approach.

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SOME TESTS RELEVANT TO THE OPTICAL DATING PROCEDURE

4.1 Dependence of D_e on preheat temperature

It has been demonstrated that sensitivity changes within a sample are temperature dependent, thus it has been suggested that measurements should be carried out using different preheat temperatures to see if a plateau in D_e values is observed (Wintle and Murray, 2000). This approach, to checking dependence of D_e on pre-heat temperature, was carried out on select Southern High Plains samples. These samples were taken from the Monahans Dune field (sample 99/20/1), a lunette located at Red Lake (a small playa basin dune) (sample 98/9/3), Double Lakes lunette (a large lake dune) (sample 99/12/1A), and a fresh water tufa deposit positioned near Double Lakes (sample 99/2/1). These are representative of the variety of sediments collected for this D.Phil. research.

Sample preparations and measurement settings on the Risø TL/OSL T1-DA-15 reader were followed as outlined in Chapter 3. Checking the effects of pre-heat temperatures on the D_e estimate, involved using the single aliquot procedure (following Murray and Wintle, 2000b), which was previously discussed in Chapter 2. Twenty-four aliquots for each sample were run in groups of three with each receiving a different preheat. The preheat temperature was increased in 20°C increments for each set of aliquots, with the first set receiving a preheat of 160°C and the last group of aliquots 300°C. Following the preheat, the natural OSL of each aliquot was measured and then a small test dose was applied (typically 1-6 Gy). The application of regeneration doses for the aliquots varied depending on the particular sample (Figure 4-1).

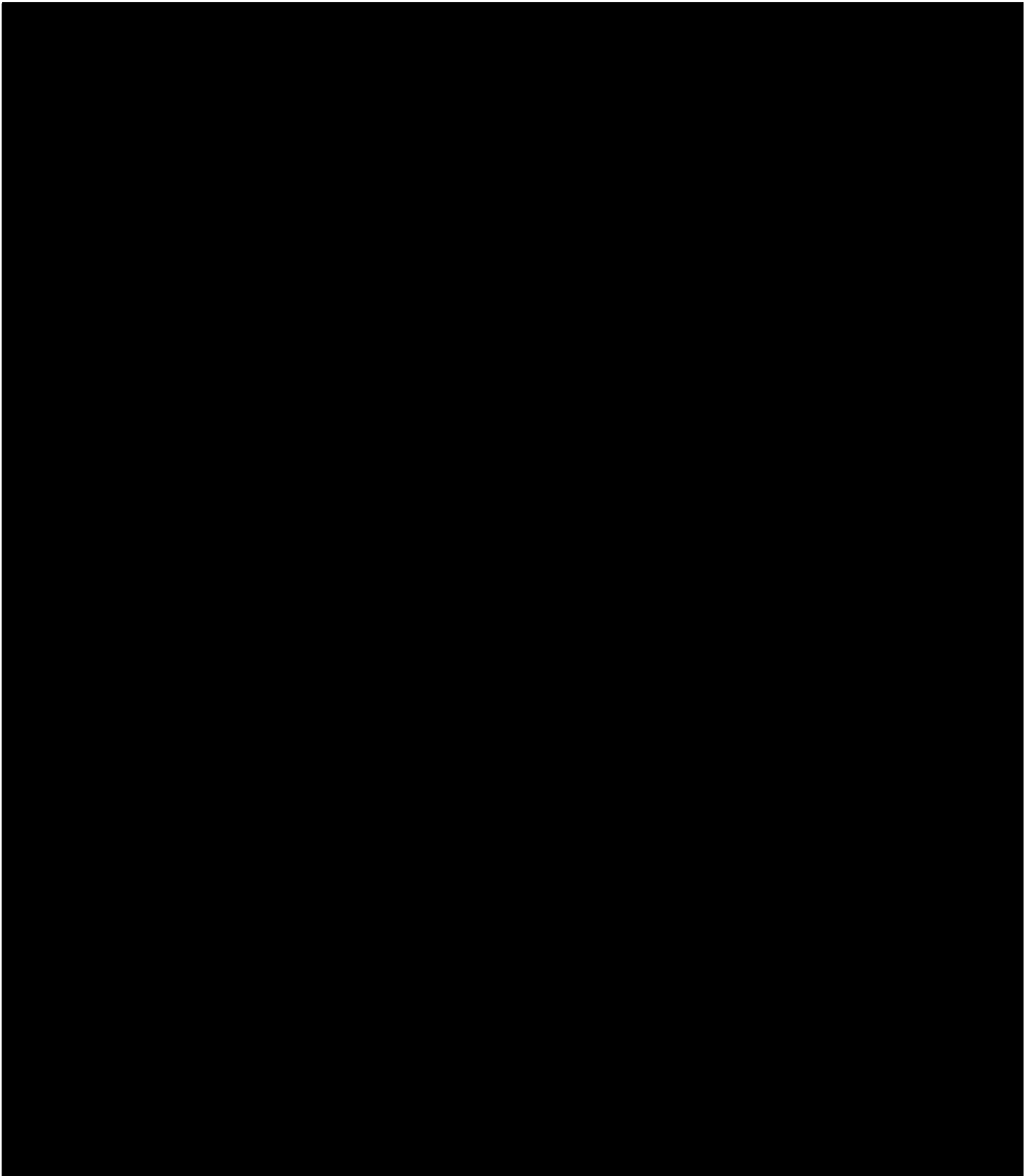


Figure 4-1. SAR protocol for testing D_e dependence on preheat temperature. L_n and T_n are derived from the initial OSL signal (1 s) minus the background estimated from the last part of the stimulation curve (Murray and Wintle, 2000b).

Figures 4-2 to 4-6 show the preheat plateaus for samples 99/20/1, 98/9/3, 99/12/1A, 99/12/1B, and 99/2/1 obtained using the SAR protocol. Samples 99/20/1, 98/9/3, and 99/12/1A demonstrate that their D_e values had relatively no dependence on preheat temperatures as groups of samples were given incrementally higher preheats between 160 and 300°C. Sample 99/12/1B had a variance in D_e values (ranging from

81-109 Gy) with preheat temperatures between 160-220°C. For preheat temperatures between 240-300°C the D_e values plateaued. A similar response was demonstrated with sample 99/2/1.

Overall, results demonstrate a lack of systematic variation in D_e with preheat temperatures ranging from 240 to 300°C. This offers evidence that thermal transfer of charge from naturally-filled thermally-shallow light-insensitive traps is insignificant when compared to the charge that is naturally stored in the OSL traps before preheating (Murray and Wintle, 2000b). In other words, thermal transfer from traps that are incompletely emptied is not a problem for these samples from the Southern High Plains. When using the SAR protocol, a preheat temperature of 280°C was used for all Southern High Plains samples.

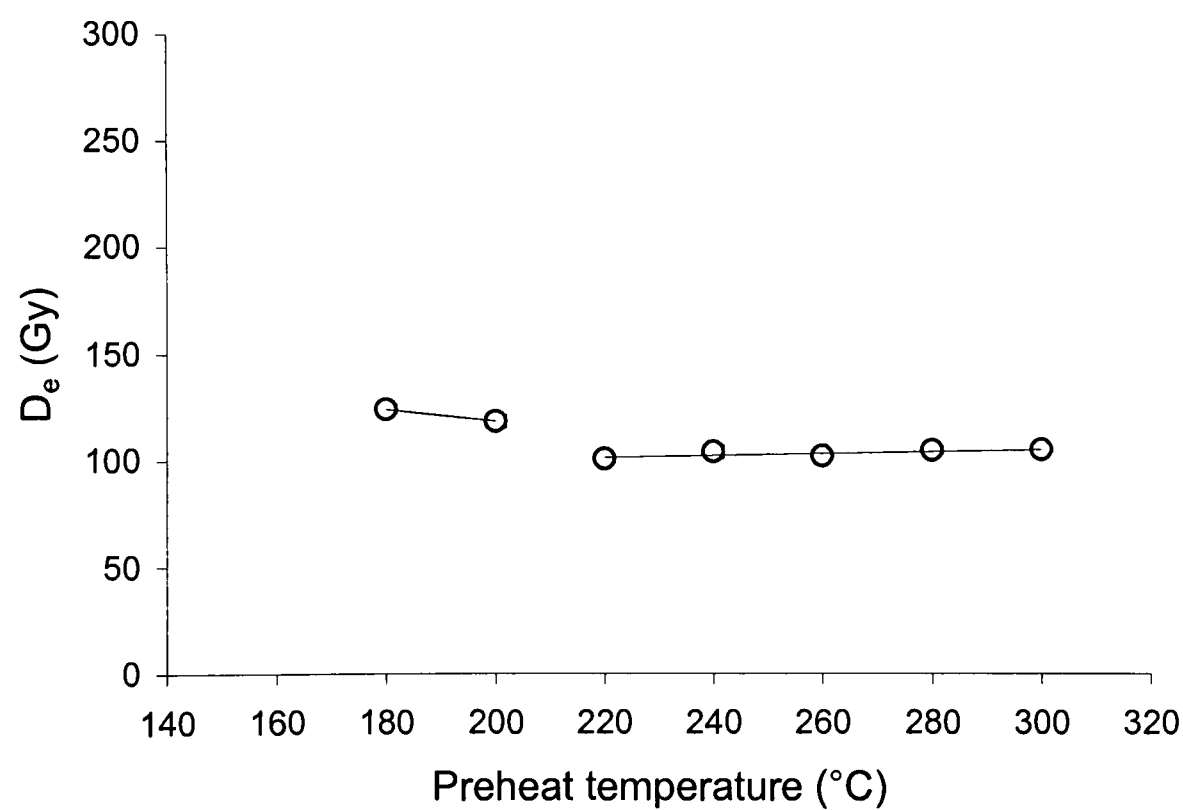


Figure 4-2. Preheat plateau for quartz extracted from a coversand sample (99/20/1) taken at Monahans dune field. Aliquots were measured in groups of three, using eight different preheat temperatures that are held for 10 s during the measurement process.

Disc	D _e (Gy)	Mean D _e values (± s.e.)	Preheat temperature (°C)
24	107.2 ±1.1	105.1 ±1.6	300
23	106.2 ±1.6		
22	101.9 ±2.2		
21	93.1 ±1.8	104.8 ±1.7	280
20	113.2 ±1.8		
18	108.0 ±1.5		
17	100.6 ±1.3	102.3 ±1.7	260
15	104.0 ±2.2		
14	107.9 ±2.7	104.1 ±2.2	240
13	104.1 ±2.2		
12	100.5 ±1.8		
11	104.3 ±1.5	100.8 ±1.7	220
10	98.8 ±2.2		
9	99.4 ±1.4		
8	113.7 ±3.1	118.7 ±2.6	200
7	121.5 ±2.3		
6	120.8 ±2.4		
5	120.8 ±2.5	124.3 ±1.9	180
4	128.8 ±1.6		
3	123.3 ±1.5		

Table 4-1. Equivalent dose values derived from SAR protocol for coversand sample (99/20/1). Averaged D_e value with standard error for each of the seven groups is shown. Preheat temperatures ranged from 180 to 300°C.

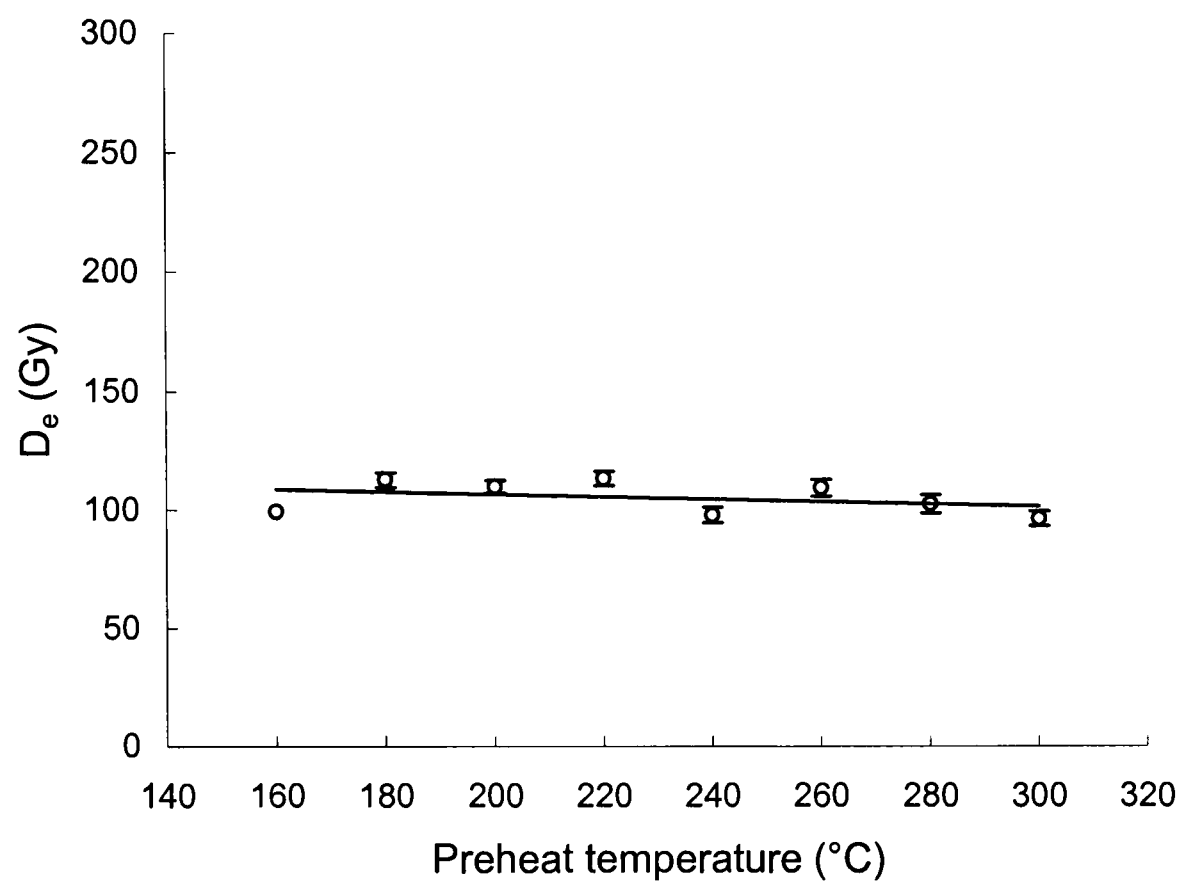


Figure 4-3. Preheat plateau for quartz extracted from a lunette sample (98/9/3) taken at Red Lake. Aliquots were measured in groups of three, using eight different preheat temperatures that are held for 10 s during the measurement process.

Disc	D _e (Gy)	Mean D _e values (± s.e.)	Preheat temperature (°C)
48	72.22 ±3.9	96.8 ±3.2	300
47	81.71 ±2.7		
46	136.52 ±2.9		
45	123.3 ±4.3	103.0 ±3.8	280
44	95.55 ±4.0		
43	90.17 ±3.0		
42	128.59 ±4.1	109.7 ±3.6	260
41	114.17 ±2.9		
40	86.36 ±3.9		
39	147.41 ±3.6	98.2 ±3.3	240
38	76.18 ±3.7		
37	70.96 ±2.6		
36	129.96 ±3.6	113.7 ±3.1	220
35	117.19 ±1.9		
34	93.9 ±3.6		
33	101.12 ±2.9	110.1 ±2.8	200
32	116.26 ±2.0		
31	113.05 ±3.4		
30	133.05 ±4.0	113.0 ±3.1	180
29	92.95 ±2.2		
26	83.05 ±2.0	99.4 ±2.5	160
25	115.79 ±3.0		

Table 4-2. Equivalent dose values derived from SAR protocol for Red Lake lunette sample (98/9/3). Averaged D_e value with standard error for each of the seven groups is shown. Preheat temperatures ranged from 160 to 300°C.

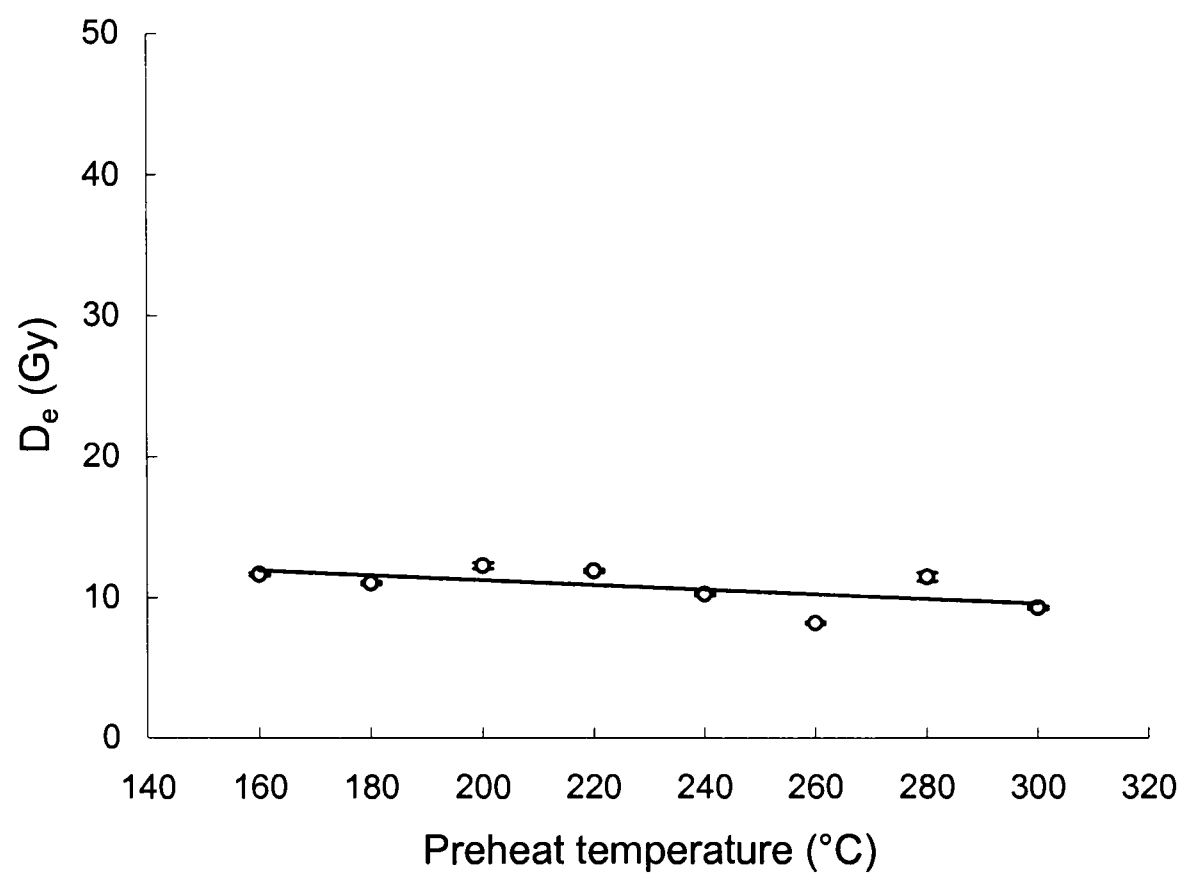


Figure 4-4. Preheat plateau for quartz extracted from a lunette sample (99/12/1A) taken at Double Lakes.

Disc	D _e (Gy)	Mean D _e values (± s.e.)	Preheat temperature (°C)
24	8.9 ±0.1	9.3 ±0.1	300
23	8.9 ±0.1		
22	10.2 ±0.1		
21	13.2 ±0.3	11.5 ±0.2	280
20	14.5 ±0.1		
19	6.9 ±0.1		
18	10 ±0.1	8.2 ±0.1	260
17	6.7 ±0.1		
16	8.0 ±0.1		
15	10.6 ±0.1	10.3 ±0.1	240
14	6.7 ±0.1		
13	13.5 ±0.1		
12	8.9 ±0.1	11.9 ±0.1	220
11	16.7 ±0.2		
10	10.2 ±0.1		
9	16.9 ±0.2	12.3 ±0.1	200
8	9.7 ±0.1		
7	10.3 ±0.1		
6	10.5 ±0.1	11.1 ±0.1	180
5	11.7 ±0.1		
4	11 ±0.1		
3	8.2 ±0.1	11.7 ±0.2	160
2	15.1 ±0.2		

Table 4-3. Equivalent dose values derived from SAR protocol for Double Lakes lunette sample (99/12/1A). Averaged D_e value with standard error for each of the seven groups is shown. Preheat temperatures ranged from 160 to 300°C.

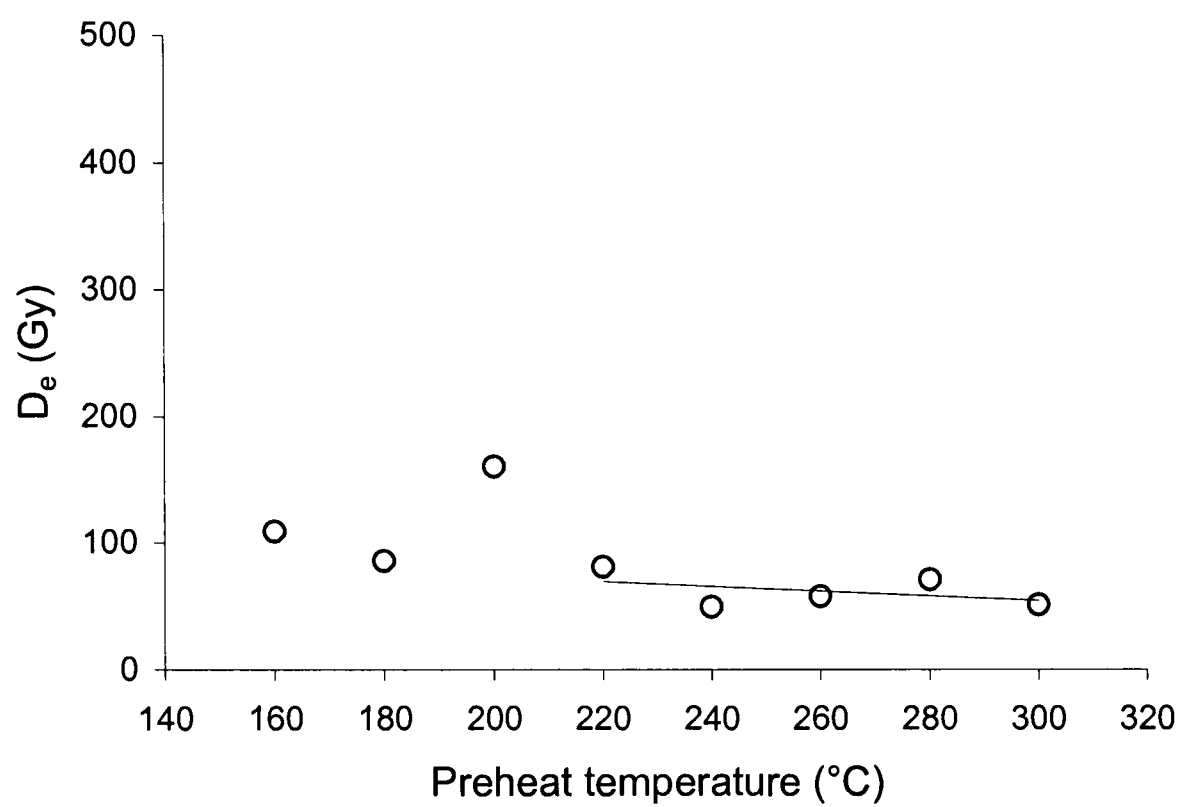


Figure 4-5. Preheat plateau for quartz extracted from a lunette sample (99/12/1B) taken at Double Lakes.

Disc	D _e (Gy)		Mean D _e values (± s.e.)	Preheat temperature (°C)
24	51.6	±0.6	51.1 ±0.7	300
23	49.8	±0.6		
22	51.8	±0.9		
21	91.9	±1.5	71.2 ±1.1	280
19	50.5	±0.7		
18	42.4	±0.6	57.7 ±0.8	260
17	42.0	±0.5		
16	88.8	±1.4		
15	34.8	±0.8	49.4 ±0.7	240
14	91.4	±0.9		
13	22.1	±0.5		
12	127.4	±2.1	81.2 ±1.3	220
11	52.5	±0.8		
10	63.5	±0.9		
9	167.5	±2.0	161.1 ±2.7	200
8	184.9	±3.9		
7	131.1	±2.2		
6	69.0	±1.1	86.0 ±1.3	180
5	82.3	±1.3		
4	106.6	±1.5		
3	109.0	±1.9	109.0 ±1.9	160

Table 4-4. Equivalent dose values derived from SAR protocol for Double Lakes lunette sample (99/12/1B). Averaged D_e value with standard error for each of the seven groups is shown. Preheat temperatures ranged from 160 to 300°C.

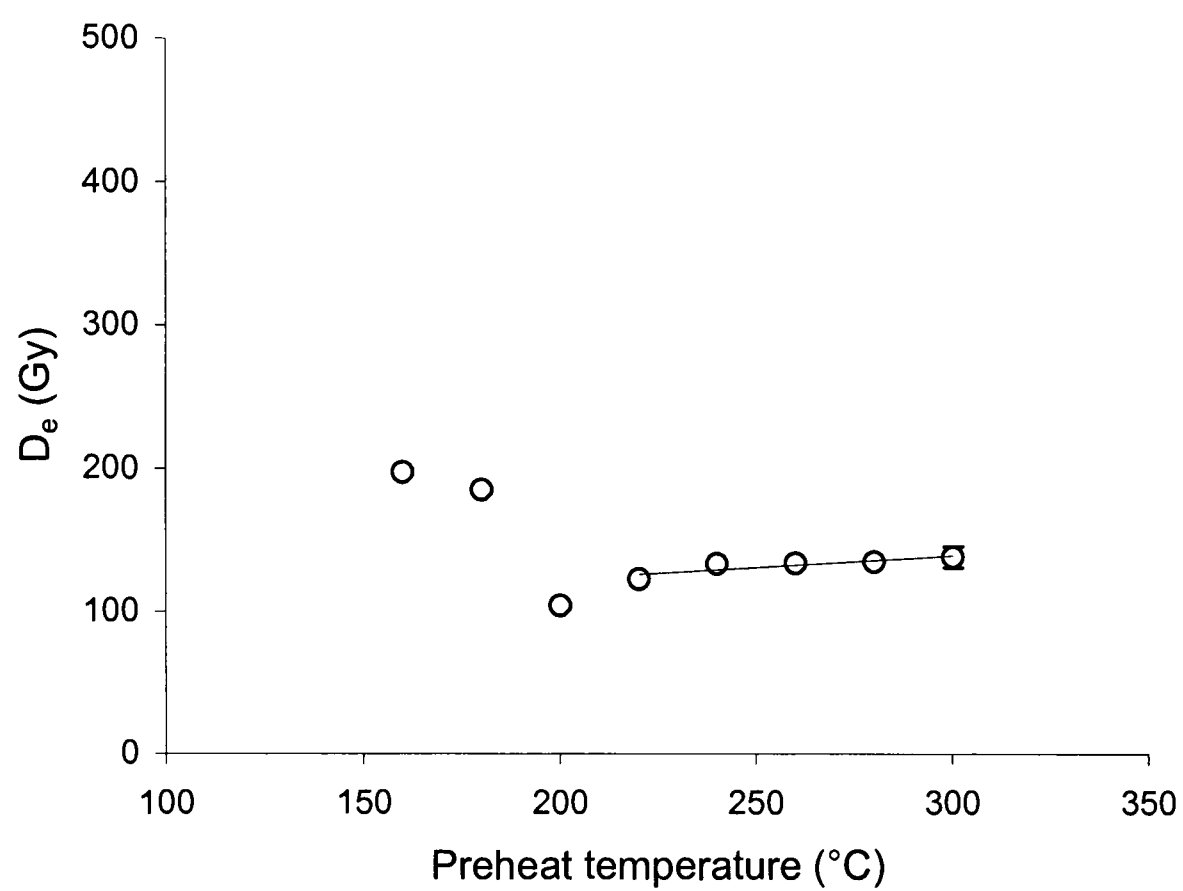


Figure 4-6. Preheat plateau for quartz extracted from a tufa sample (99/2/1) taken at Double Lakes.

Disc	D _e (Gy)	Mean D _e values (± s.e.)	Preheat temperature (°C)
24	160 ±7.57		
23	116 ±1.15	139 ±3.3	300
22	141 ±1.25		
21	129 ±1.25		
20	136 ±1.37	136 ±1.3	280
19	142 ±1.22		
18	133 ±1.32		
17	163 ±1.32	135 ±1.2	260
16	108 ±0.94		
15	153 ±1.51		
14	120 ±1.44	134 ±1.5	240
13	129 ±1.51		
12	135 ±1.17		
11	113 ±1.17	123 ±1.2	220
10	121 ±1.40		
8	96 ±0.63	104 ±1.3	200
7	112 ±1.55		
6	150 ±1.62		
5	243 ±2.55	186 ±2.0	180
4	164 ±1.78		
3	226 ±2.94	198 ±2.4	160
2	169 ±1.91		

Table 4-5. Equivalent dose values derived from SAR protocol for a tufa sample (99/2/1) taken near Double Lakes lunettes. Averaged D_e value with standard error for each of the seven groups is shown. Preheat temperatures ranged from 160 to 300°C.

4.2 Effect of varying the test dose on the D_e

The single aliquot regeneration (SAR) technique, developed by Murray and Roberts (1998) and refined by Murray and Wintle (2000b), applies a sequence of procedures to a set of aliquots for a given sample. The objective of the protocol is to build a growth curve, from which the dose equivalent (D_e) can be interpolated (see Chapter 2). This is done by measuring the natural OSL of an aliquot then irradiating the sample with regenerative doses that bracket the natural intensity (e.g. $R_1 < N \sim R_2 < R_3 \dots$) (see Chapter 2). The OSL is measured, following each regeneration, and defines the growth curve. The procedure also involves a test dose to monitor dose dependant sensitivity changes after each measurement cycle (Murray and Wintle, 2000b). It was suggested by Murray and Roberts (1998) to use a small test dose to reduce the risk of thermal transfer of charge into shallow traps.

The quartz sample used to investigate the effects of higher test dose was extracted from Muleshoe coversand (sample 99/15/2). Eighteen aliquots were divided into six groups of three. Each of the six groups had its D_e estimated using the SAR protocol (Murray and Wintle, 2000b), and each group was measured using a different test dose (ranging from 1-12 Gy) (see Figure 4-7). A preheat of 280°C was given for 10 s. The OSL was measured at 125°C for 15 s. Both preheat and OSL cycles had a heating rate of 10°C per second. All measurements were carried out on the Risø TL/OSL T1-DA-15 reader (as discussed in Chapter 3), with a source strength of 4 Gy min⁻¹. The stimulating light source was an incandescent lamp delivering approximately 20 mW cm⁻² to the sample. The luminescence signal was detected by a photomultiplier coupled with filters as described in Chapter 3.

The variation of the equivalent dose with each group of aliquots is based on the size of test dose as illustrated in Figure 4-8 and Table 4-6. The results indicate there is no significant variation in D_e over a test dose range of nearly 12 times the D_e value. Sample 99/15/2 appears to be generally insensitive to the size of test dose used in the experiment. Table 4-6 lists the disc number, test dose, D_e , and averaged D_e values for the 18 aliquots tested.

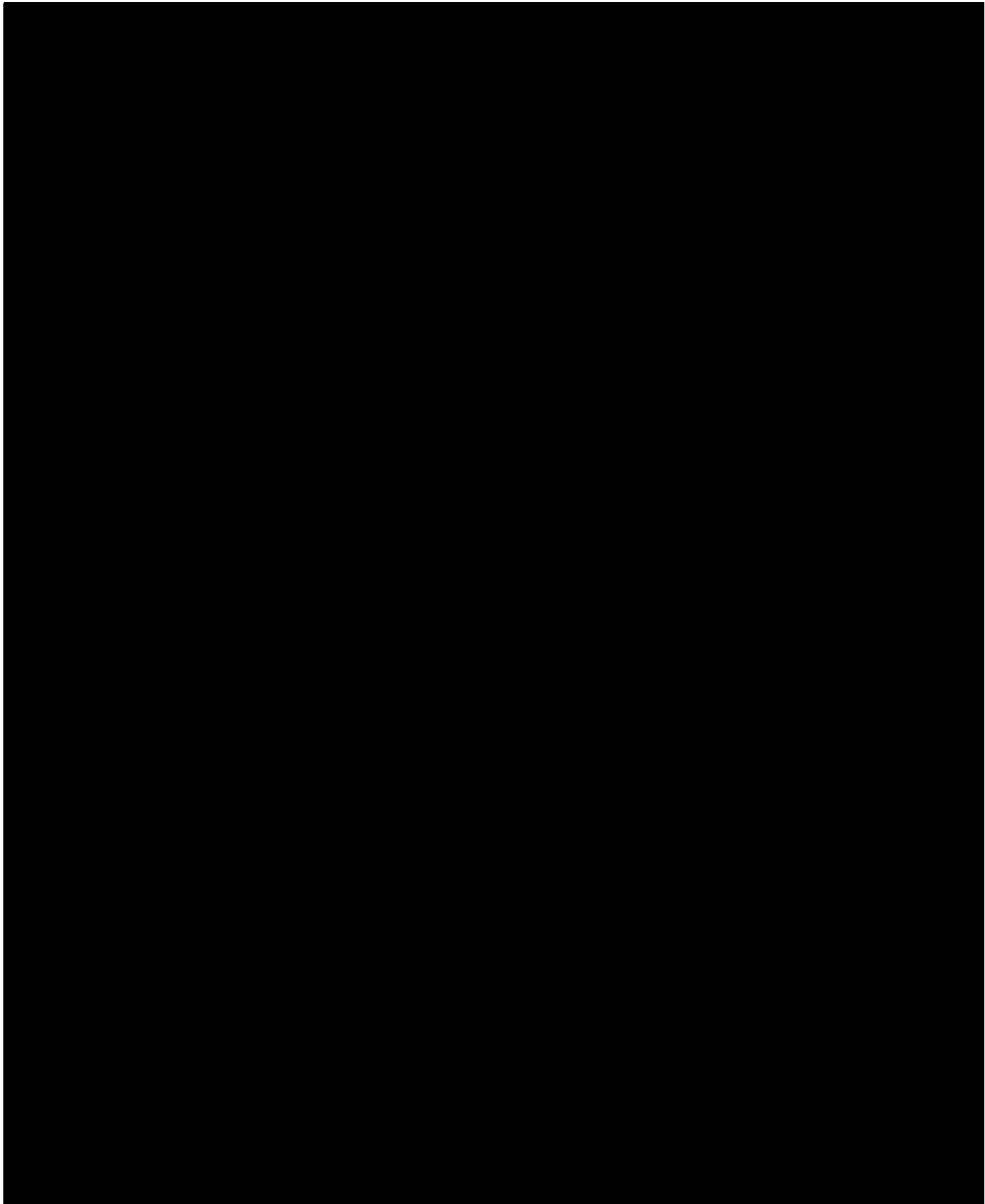


Figure 4-7. Protocol for testing the effect of higher test doses on the D_e (adapted from Murray and Wintle, 2000b).

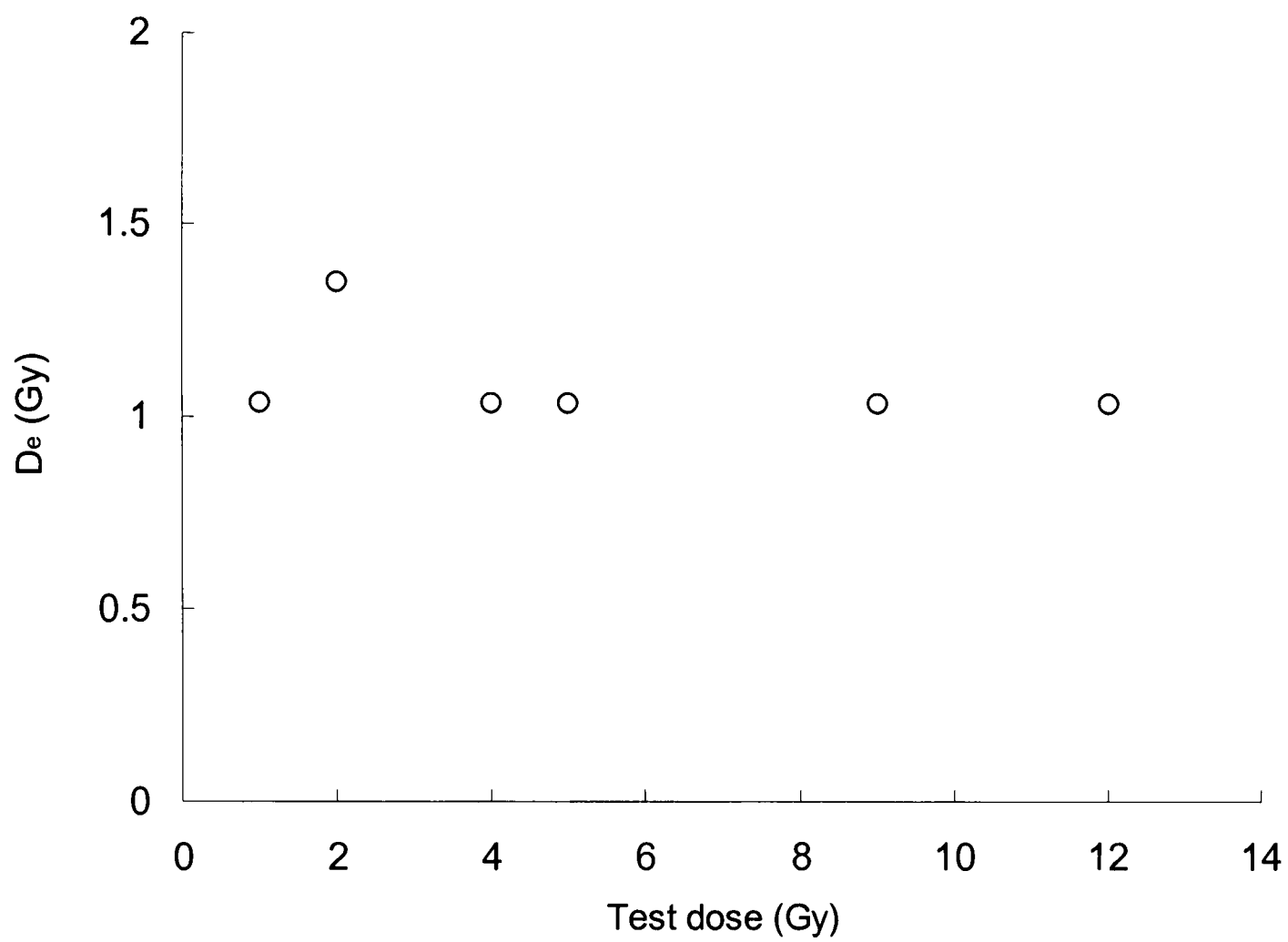


Figure 4-8. Plot of increasing test doses and dose equivalent result for sample 99/15/2. Each of the six D_e values represents an average of three aliquots.

Disc	Test dose (Gy)	D _e (Gy)	Average D _e (Gy)
1	1	0.85 ±0.02	1.04 ±0.03
2		1.19 ±0.03	
3		1.07 ±0.04	
4	2	1.61 ±0.05	1.35 ±0.06
5		1.09 ±0.06	
6		1.36 ±0.07	
7	4	0.69 ±0.08	1.04 ±0.06
8		1.52 ±0.09	
9		0.91 ±0.02	
10	5	1.43 ±0.02	1.04 ±0.02
11		1.85 ±0.02	
12		0.81 ±0.02	
13	9	1.49 ±0.01	1.04 ±0.01
14		0.71 ±0.01	
15		0.91 ±0.01	
16	12	0.82 ±0.01	1.04 ±0.01
17		1.25 ±0.02	
18		1.07 ±0.01	

Table 4-6. Sample 99/15/2 test dose, D_e, and averaged D_e values.

4.3 Recycling ratio

The dose equivalent estimate for all Southern High Plains samples was determined using the SAR protocol outlined by Murray and Wintle (2000b). As mentioned in Chapter 2, this procedure requires each aliquot to be dosed ($+β=0$ for natural), preheated (250°C for 10 s), and optically stimulated iteratively to establish the natural OSL intensity and the aliquots' sensitivity to regenerated doses. Optical stimulation for each aliquot was from 0-15 s at a measurement temperature of 125°C. Over 80% of signal depletion typically occurred during the first 2-5 seconds. Sensitivity changes were checked and corrected by a set of steps, which include a small test dose (~3-5 Gy), a 0-250°C preheat, and additional optical stimulation (Murray and Wintle, 2000b). The robustness of the SAR correction procedure for all 1189 aliquots, from 111 Southern High Plains samples, was monitored by the recycling ratio. Values varied from 0.64 to 1.33 (Figure 4-9) with aliquots within the $±10\%$ range (0.90-1.10; $n=1155$) being selected for determining the average D_e . This criteria was proposed by Murray and Wintle (2000b).

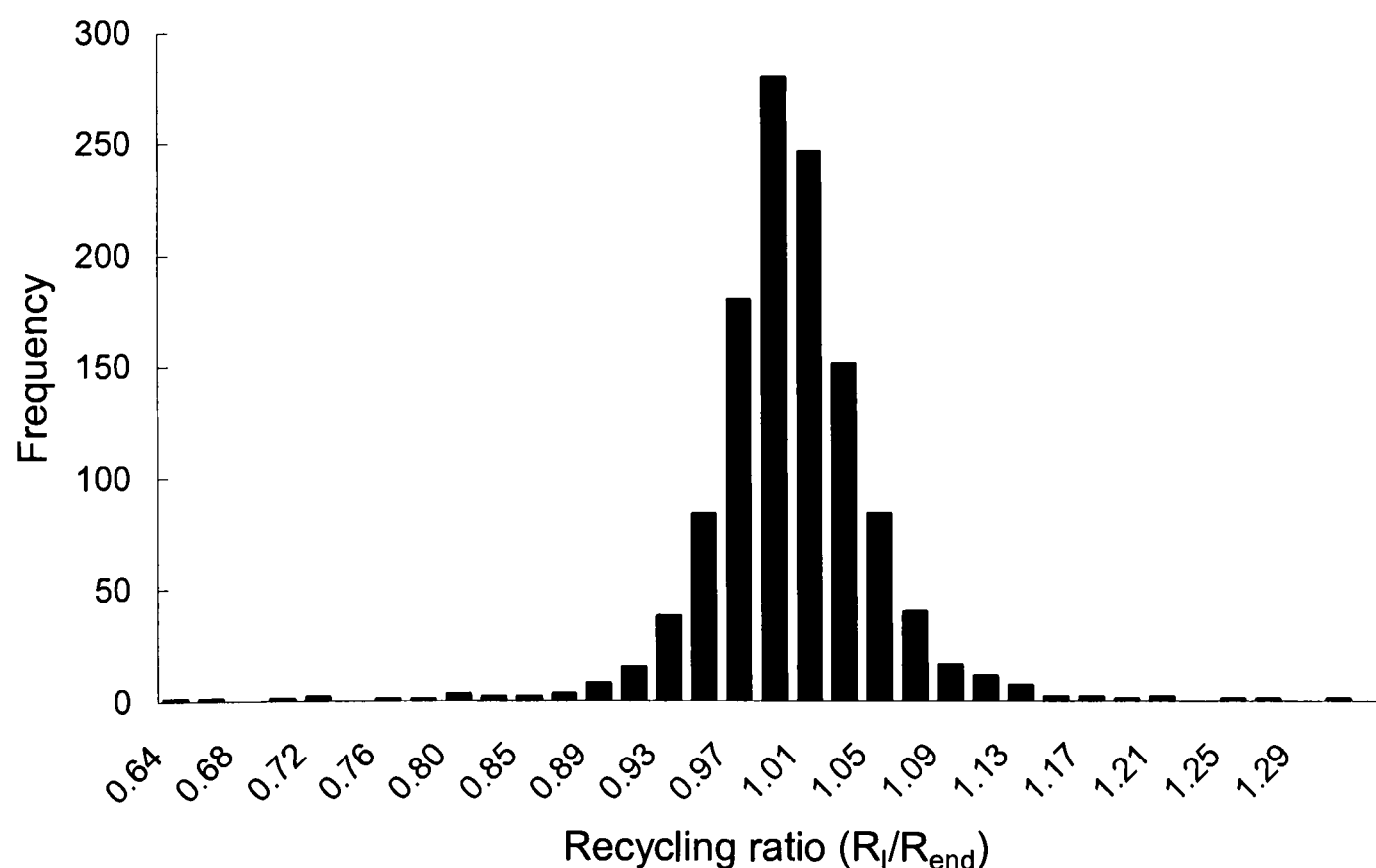


Figure 4-9. Histogram of recycling ratios for 1189 aliquots from 111 Southern High Plains samples (97% of samples are within the $±10\%$ range).

Chapter 5

ACCEPTED PAPERS AND MANUSCRIPTS PREPARED FOR SUBMISSION

Chapter overview

Chapter 5 is comprised of FOUR papers that have been accepted for publication and TWO manuscripts that have been prepared for submission. Each paper builds on the information of the previous papers and addresses the objectives of this research.

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Paper 1 - Optical dating of geoarchaeologically significant sites	135
Paper 2 - New applications of luminescence dating	147
Paper 3 - Holocene chronology for lunette dune deposition	152
Paper 4 - Optical dating of tufa	169
Paper 5 - A 200,000-year record for late Quaternary coversand.....	178
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ACCEPTED AND SUBMITTED PAPERS

5.1 List of Accepted papers

- **Paper 1** - Rich, J., and Stokes, S. (2001). Optical dating of geoarchaeologically significant sites from the Southern High Plains and South Texas, USA. *Quaternary Science Reviews* **20**, 949-959.
- **Paper 2** - Rich, J., and Stokes, S. (1999). New applications of luminescence dating to late Quaternary lunette deposits on the American Southern High Plains. *Current Research in the Pleistocene* **16**, 143-146.
- **Paper 3** - Rich, J., Stokes, S., and Wood, W. W. (1999). Holocene chronology for lunette dune deposition on the Southern High Plains, USA. *Zeitschrift für Geomorphologie Supplement-Band* **116**, 165-180.
- **Paper 4** - Rich, J., Stokes, S., Wood, W., and Bailey, R. (2003). Optical dating of tufa via in-situ aeolian sand grains: a case example from the Southern High Plains, USA. *Quaternary Science Reviews* **22**, 1145-1152.

5.2 List of Manuscripts prepared for submission

- **Paper 5** - Rich, J., Stokes, S., (prepared for submission to *Earth Science Reviews*). A 200,000-year record for late Quaternary coversand activity on the Southern High Plains and nearby Pecos River valley, USA.
- **Paper 6** - Rich, J., Stokes, S., Wood, W., (prepared for submission to *Palaeogeography, Palaeoclimatology, Palaeoecology*). Southern High Plains lunettes: A record of dune accumulation for the past 250,000-years.

PLEASE NOTE THERE ARE TWO SETS OF PAGE NUMBERS ON PAPERS. THE UPPER NUMBER IS THE JOURNAL NUMBERING SYSTEM (EXCEPT FOR SUBMITTED PAPERS), WHILE THE BOTTOM NUMBER IS THE SEQUENTIAL PAGE NUMBER FOR THE THESIS.

Objectives	Paper(s) where objective(s) discussed					
	1	2	3	4	5	6
1. Test a combination of multiple and single aliquot optical dating results on selected Southern High Plains sediments (aeolian and fluvio-lacustrine), in order to determine which approach will provide the most robust chronology.	✓					
2. Utilise optical dating methods to refine and extend existing chronologies for lunette, lacustrine material, tufa deposits, and coversands. Both aeolian and water lain sediments were chosen to provide insight on wet and dry climatic conditions.		✓	✓	✓	✓	✓
3. Investigate the possibility of using optical dating to determine age estimates on a tufa deposit adjacent to Double Lakes. This proxy record provides insight into the timing for intervals of greater effective moisture, which assists in our understanding of palaeo-climates on the Southern High Plains.				✓		
4. Determine if optical dating can correctly establish the chronology of the known 1930s drought conditions. If it is possible to date recent dune activity resulting from drought conditions, then we may be able to infer that older dune sequences may also have corresponded with earlier drought intervals.					✓	✓
5. Employ the proxy record preserved in the lunette, lacustrine material, tufa deposits, and coversands to assist in interpreting and reconstructing the region’s palaeo-environmental history.		✓	✓	✓	✓	✓
6. Compare the results from previous research on the Southern High Plains and surrounding regions (e.g., the Great Plains) to the suite of absolute age estimates derived from this study. A review of the overall results will assist in the interpretation of the regional extent of climatic fluctuations.		✓	✓	✓	✓	✓

Figure 5-1. Research objectives

Paper 1

Rich, J., and Stokes, S. (2001). Optical dating of geoarchaeologically significant sites from the Southern High Plains and South Texas, USA. *Quaternary Science Reviews* **20**, 949-959.

Paper 1 overview

Paper 1 furthers research objective 1 outlined in Chapter 1 (as indicated in Table 5-1), of testing a combination of multiple and single aliquot dating results on selected Southern High Plains sediments. This was accomplished by re-dating samples taken from geoarchaeologically significant sites, whose chronology had previously been estimated using multiple aliquot techniques. An alternative and recently developed approach to dating is the single aliquot regeneration (SAR) protocol developed by Murray and Wintle (2000b), which was applied to the samples taken from the archaeological sites. A comparison of the multiple to single aliquot methods demonstrates which of the two methodologies offers greater precision when dating sediments. Contrasting the dates obtained by SAR techniques with the archaeological record demonstrates the accuracy of the optical dates.

Results from this research presented in Paper 1, have expanded the optical dating approaches discussed in Chapter 2 by demonstrating that newer SAR methods can produce robust optical age estimates. This paper also builds upon the results of tests outlined in Chapter 4. These tests determined the amount of pre-heating Southern High Plains samples required, and offered insight on the variance of test dose and recycling ratios. Paper 1 represents a major contribution to the field of optical dating by demonstrating the accuracy and precision of the SAR technique and establishes the dating methodology that will be used in all subsequent papers (2,3,4,5,and 6).

Paper contents

1. Introduction
2. Site sampled and sampling procedures
3. Sample preparation and dosimetry
4. Multiple aliquot procedures
5. Single-aliquot regeneration (SAR) procedures
6. Independent and multiple-aliquot additive dose age control
7. Single-aliquot regeneration (SAR) D_e assessment
8. Conclusions

Paper 2

Rich, J., and Stokes, S. (1999). New applications of luminescence dating to late Quaternary lunette deposits on the American Southern High Plains. *Current Research in the Pleistocene* **16**, 143-146.

Paper 2 overview

Paper 2 furthers research objectives 1, 2, 5, and 6 outlined in Chapter 1 (detailed in Table 5-1). Together, these objectives utilise optical dating methods to refine and extend existing chronologies of the Southern High Plains, and employ the sediment proxy record to interpret and reconstruct the region's palaeo-climatic history.

The aim of this paper was to test the precision of the SAR optical dating approach on Southern High Plains lunette sediments; the robustness of the technique was established in Paper 1. Paper 2 presents preliminary results on the application of SAR protocol to lunette samples, which are developed in Paper 3. Paper 2 demonstrates that precise equivalent dose estimates can be achieved on these sediments, thus providing more robust optical age estimates. This paper represents the first published attempt to date lunette samples on the Southern High Plains using the SAR optical dating approach.

Paper Contents

The format style of the journal keeps the article as a single document and does not divide the paper into sections; therefore contents are not listed.

Paper 3

Rich, J., Stokes, S., and Wood, W. W. (1999). Holocene chronology for lunette dune deposition on the Southern High Plains, USA. *Zeitschrift für Geomorphologie Supplement-Band 116*, 165-180.

Paper 3 overview

Paper 3 furthers research objectives 2 and 6 as outlined in Chapter 1 (summarised in Table 5-1). Paper 3 represents a natural progression from Paper 2 and substantially extends the interpretation of the results presented in the previous paper. Whilst Papers 2 and 3 are based on the same data set they make different contributions to the literature. The role of Paper 2 is to test the applicability of the SAR dating technique to lunette sediments, and its primary concern is methodological. Paper 3 uses the chronology established in Paper 2 to interpret landscape response to climate change during the Holocene, based on the data obtained from the lunette sediments.

Paper 3 compares the chronology developed from the optical dating of lunette sediments in Paper 2, to the results of dating programs supplied by previous research on the Southern High Plains and surrounding regions (e.g., the Great Plains). Specifically, the optical age estimates for the study on Double, Mound, and Rich Lake lunettes are used to interpret dune activity during the Holocene.

Paper 3 makes a significant contribution to the literature by broadening the interpretation of the regional extent of climatic fluctuations. This forms an important foundation for the work presented in Paper 4, which provides optical dating results from a tufa deposit associated with the lunette sediments also found at the Double Lakes location.

Paper contents

1. Introduction
2. Lunettes and playa basins on the Southern High Plains
3. Methodology
4. Results
5. Conclusions

Paper 4

Rich, J., Stokes, S., Wood, W., and Bailey, R. (2003). Optical dating of tufa via in-situ aeolian sand grains: a case example from the Southern High Plains, USA. *Quaternary Science Reviews* **22**, 1145-1152.

Paper 4 overview

Paper 4 furthers research objective 3 outlined in Chapter 1 (summarised in Table 1-1). Paper 4 investigates the possibility of using SAR optical dating techniques to determine age estimates on tufa deposits, which have been described as important environmental archives. This dating technique offers an alternative approach to establishing chronologies on tufas. Standard approaches to dating these deposits have been radiocarbon or uranium-series, but have been hampered by the open system behaviour of tufas.

Paper 4 presents the results of a first attempt to use optical dating to establish a chronology on Southern High Plains tufa material. This is important in the context of reconstructing the region's palaeo-environmental history of the Southern High Plains because tufas correspond with periods of regional groundwater recharge resulting from greater effective moisture. Tufa chronology established in Paper 4 will be contrasted with the timing of lunette and coversand deposition that is presented in Papers 5 and 6.

Paper contents

1. Introduction
2. Sample collection and preparation
3. Equivalent dose (D_e) determination
4. Dose rate assessment
5. Results and discussion
6. Conclusions

Paper 5

Rich, J., Stokes, S., (prepared for submission to *Earth Science Reviews*) A 200,000-year record for late Quaternary coversand activity on the Southern High Plains and nearby Pecos River valley, USA.

Paper 5 overview

Paper 5 meets research objectives 2 and 4-6, outlined in Chapter 1 and summarised in Table 5-1, by utilising SAR optical dating techniques to establish the depositional timing on the Southern High Plains coversands. This technique has proven successful in generating age estimates on wind deposited lunette sediments (see Papers 1-3), and can also provide robust optical ages for the aeolian derived coversands. Paper 5 refines and extends the existing coversand chronologies on the Southern High Plains.

The coversand chronology presented in Paper 5 provides insight into the timing for depositional events, which will be compared to periods lunette accretion intervals discussed in Papers 3 and 6. The employment of coversand and lunette proxy records will facilitate interpretation of the palaeo-environment of the Southern High Plains. Significant contributions of Paper 5 are the detection of recent coversand deposition that corresponds with the 1930s North American “Dust Bowl” event, and the insight that is provided into the dynamics of coversands during glacial/interglacial and stadial/interstadial periods.

Paper contents

1. Introduction
2. Study site
3. Previous research
4. Methodology
5. Results
6. Discussion
7. Conclusions

Paper 6

Rich, J., Stokes, S., Wood, W., (prepared for submission to *Palaeogeography, Palaeoclimatology, Palaeoecology*). Southern High Plains lunettes: A record of dune accumulation for the past 250,000-years.

Paper 6 overview

Paper 6 fulfils research objectives 2 and 4-7 as previously outlined in Chapter 1 (Table 5-1) and applies optical dating techniques to a suite of lunette samples from various lake and playa basins across the Southern High Plains. Paper 6 demonstrates that optical dating can establish the timing of recent (1930s) lunette accretion, which deposition corresponds to the “Dust Bowl” event that extended into the Southern High Plains. Information is also provided in Paper 6 on the timing of lacustrine sedimentation. This provides insight into the dynamic relationship between lunettes and their adjacent playa/lake basin.

Paper 6 is the last document in a series of manuscripts and is a culmination of the results obtained from this study. The primary goal of Paper 6 is to interpret and reconstruct the Southern High Plains palaeo-environmental history. This is achieved by synthesising information derived from tufa and coversands, plus incorporating research by others which present interpretations on past environmental conditions for the Southern High Plains and surrounding areas. Paper 6 represents an important contribution to our understanding of the response of lunettes, lacustrine material, tufa, and coversands to changing climatic conditions on the Southern High Plains.

Paper contents

1. Introduction
2. Southern High Plains study area
3. Previous Southern High Plains research
4. Approaches to sampling
5. Sampling localities
6. Optical dating
7. Sample preparation
8. Equivalent dose (D_e) determination
9. Dose rate determination
10. Results
11. Discussion
12. Environmental history of the Southern High Plains
13. Conclusions

CONCLUSIONS

Chapter overview

This final chapter presents a synthesis of the findings and ideas presented in this thesis. **Chapter 6** begins with an outline of the aim and objectives of this research, and demonstrates how they were accomplished. This is followed by a section that details the specific conclusions drawn from each of the key depositional features on the Southern High Plains; namely lunettes, lacustrine material, tufas and coversands. The chapter ends with a brief summary, which draws together all of the research and provides a history of depositional events across the Southern High Plains. This is then followed by suggestions for further research.

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CONCLUSIONS

6.1 Overview of research aim and achievement of objectives

The Southern High Plains is an important area due to the sensitivity of its landscape to climate change, and the variety of sediments that provide insight into changing environmental conditions. This region may be one of the more sensitive areas to climate alterations on the North American continent, and possibly be one of the first regions to reactivate given present global warming scenarios.

The aim of this study was to investigate the landscape response to late Quaternary climatic change on the Southern High Plains in order to reconstruct the environmental history of the region. This was achieved through six research objectives previously outlined in Chapter 1, which are listed below (*italicised text*). A discussion follows each objective summarising how it was achieved (normal text).

The research objectives were to:

- 1) *Test a combination of multiple and single aliquot optical dating results on selected Southern High Plains sediments (aeolian and fluvio-lacustrine), in order to determine which approach will provide the most robust chronology.* This aim was achieved by contrasting multiple and single aliquot approaches to optical ages determined on selected Southern High Plains sediments, then comparing the results to independent dates for the same sediment sequences. This study demonstrates that the single aliquot regeneration (SAR) technique can provide accurate and precise age estimates, when compared to multiple aliquot approaches, and therefore can offer a robust chronology for sediment samples (see Paper 1).
- 2) *Utilise optical dating methods to refine and extend existing chronologies for lunette, lacustrine material, tufa, and coversands.* This aim was achieved by using the single aliquot regeneration (SAR) technique that previously was shown to greatly improve the accuracy and precision of optical dating.

Application of this technique to 111 samples from the four key Southern High Plains surficial features refined and extended their chronologies. The newer chronologies established for the key depositinal features allowed historic periods of accretion to be detected, and extended the timing for the aeolian sediments into the late-middle Pleistocene. The timing of deposition for the Southern High Plains sediments encompasses two glacial and two interglacial periods, which provided insight into how the dunes and fluvio-lacustrine material respond during these times (see Papers 2-6).

- 3) *Investigate the possibility of using optical dating to determine age estimates on a tufa adjacent to Double Lakes. This proxy record provides insight into the timing for intervals of greater effective moisture, which assists in our understanding of palaeo-climates on the Southern High Plains.* This aim was achieved by applying single aliquot regeneration (SAR) techniques to Southern High Plains tufa. The approach provided stratigraphically sensible optical ages, which are consistent with existing palaeo-environmental models of regional recharge (see Paper 4).
- 4) *Determine if optical dating can correctly establish the chronology of the known 1930s North American drought conditions. If it is possible to date recent dune activity resulting from drought conditions, then we may be able to infer that older dune sequences may also have corresponded with earlier drought intervals.* This aim was accomplished by utilising single aliquot regeneration (SAR) optical dating techniques to establish the timing of deposition for both coversands (see Paper 5) and lunettes (see paper 6). The precision and demonstrated accuracy of the SAR technique (see Paper 1) permitted the detection of a recent depositional event that corresponded with the well-documented North American “Dust Bowl” event. This historical event was recognised in both sets of proxy records (coversands and lunettes) and provides evidence for the robustness of the technique in age dating recent depositional events which aided in the reconstruction of the environmental history of the region (refer to discussion section in Papers 5 and 6).

- 5) *Employ the proxy record preserved in lunette, lacustrine, tufa, and coversand deposits on the Southern High Plains to assist in interpreting and reconstructing the region's palaeo-environmental history.* This aim was achieved by synthesizing the results from Papers 2-6. Each consecutive paper provided new chronologies and palaeo-environmental information that was incorporated in the final manuscript (Paper 6). Paper 6 is a culmination of the optical dating results obtained from the four key depositional environments and synthesises the results of this thesis in its discussion section. The chronologies established for this research were used to determine intervals of deposition, which assisted in the interpretation of landscape response to changing climatic conditions over the past 250,000 years.
- 6) *Compare results from previous research on the Southern High Plains and the Great Plains to the optical age estimates derived from this study. A further understanding into the regional extent of climatic fluctuations is offered.* This aim was achieved by reviewing earlier literature on the Southern High Plains and surrounding areas (e.g., the Great Plains), then contrasting the conclusions from these works to the depositional patterns that were detected in the lunettes, lacustrine material, tufa, and coversands. The results obtained from Papers 2-6, coupled with information derived from previous work, provide important insights into the Southern High Plains palaeo-environmental history, and include a further understanding of the regional extent of dune deposition resulting from periods of aridity.

6.2 Conclusions for key depositional features

The following section provides an overview of the significant conclusions drawn from the results of the optical dating programme for each of the key depositional features, as outlined below:

6.2.1 Lunettes

The Southern High Plains lunette sediments preserve within their stratigraphy information regarding the dynamics of the adjacent lake basin and can provide proxy evidence of fluctuating groundwater levels. The following are specific conclusions distilled from Papers 2, 3, and 6.

- 1) Lunettes were accreting during the penultimate glaciation (early to late Illinoian). The error estimates derived on these older samples introduces difficulties when attempting to determine whether the lunettes were deposited during stadial or interstadial events. Nonetheless, these optical ages are the first presented, which indicate lunette accretion on the Southern High Plains during the late-middle Pleistocene. The construction of these dunes during this time period further demonstrates that the adjacent large lake or small playa must be at least as old. The results generally support Sanford and Wood's (1995) age estimate for the large lakes, but are in contrast with Holliday's (1997) late Pleistocene (25-15 ka) timing for small playa basin formation.
- 2) Concurrent with the cessation of lunette construction on large lake playas was dune accretion for the small playa lunettes. Evidence from this thesis suggests that even under conditions of greater effective moisture for the Southern high Plains, accretion on small playa lunettes is not uncommon, and may be tied to short term or other local, playa-specific factors. Hence, small playa lunettes may provide insight into localised, or short-term precipitation changes, whereas the large lake lunettes present evidence of lower regional water tables, possibly resulting from prolonged, region-wide reduction in moisture.
- 3) A significant period of lunette construction took place during the mid-Holocene when ~12 m of material was accreted on the Double Lakes inner lunette, indicating a young temporal framework for this dune. This demonstrates a marked shift to drier climatic conditions on the Southern High Plains, which reduced the water table and allowed a substantial amount of sediment to be deflated from the lake basin, and provides supporting evidence for a dynamic relationship between large lake basins and lunettes. This model is corroborated by mid-Holocene well digging at Archaic occupation sites near the Southern High Plains-Edward's Plateau border, and their subsequent abandonment due to a later dramatic drop in the water table, resulting from prolonged arid conditions. This dry period also corresponds with a phase of dune activation that extended across much of the Great Plains (e.g., Forman *et al.*, 1995; Forman, 2001; Stokes and Gaylord, 1993; Stokes and Swinehart, 1997; see also Appendix I and J).

- 4) In the historical period, this research demonstrates that the Southern High Plains lunettes were active during various drought intervals that occurred between AD 1300 and 1700. These times of drought were identified in tree-ring records from nearby regions and broadly correlate with the timing of the Little Ice Age.
- 5) The Southern High Plains lunettes and coversands reactivated during the recent 1930s “Dust Bowl” drought event, which demonstrates the sensitivity of the Southern High Plains landscape to reductions in effective moisture.

6.2.2 Lacustrine material

Southern High Plains lacustrine sediments are important archives that provide insight into the dynamics of lake basin hydro-geological processes and can be used in concert with the record of basin deflation and lunette deposition that is preserved within the dune stratigraphy. The following represent specific conclusions drawn from the lacustrine data set as discussed in Paper 6:

- 1) Optical age estimates demonstrate that large lake lacustrine sediments were deposited across the Southern High Plains during the early to late glacial interval, at approximately 78-69, 57-56, 40-39, and 35-17 ka. These time intervals generally correspond to periods of marked ice increase, (*e.g.*, Wisconsin glacial substages), including the last glacial maximum. This suggests that during glacial periods, the Southern High Plains had greater effective moisture that resulted in regional recharge.
- 2) During the time when the Southern High Plains was experiencing regional recharge, between approximately 78-17 ka, the lunettes associated with large lake basins were stable (Figure 6-1). This provides important evidence that a dynamic relationship exists between large lake basins and their associated lunettes, and higher ground water levels that fill the lake basin will result in lunette stability.
- 3) A lacustrine layer at Rich Lake was deposited during the pleniglacial (middle Wisconsin) approximately 57 ka, which corresponds with the timing of tufa formation at Double Lakes (see Paper 4, on the optical dating of tufa). This significant information confirms the above statement that the Southern High Plains was experiencing regional recharge during the glacial period (middle

Wisconsin). This also demonstrates the robustness of the optical dating technique to successfully date diverse sediment types whose deposition was coeval with a period of greater effective moisture on the Southern High Plains.

6.2.3 Tufa deposits

This study presents the first attempt to directly date palaeo-spring discharge events on the Southern High Plains using quartz grains entrained in tufas. Chronologies of Southern High Plains tufas, established by this thesis, refine the interpretation of late Pleistocene environmental conditions for this region. The following represent specific conclusions are drawn from the tufa data. Methodologies and approaches to dating the tufa are found in paper 4:

- 1) This study has provided encouraging results, and has successfully demonstrated that entrained quartz grains from the Double Lakes tufa can provide reliable optical age estimates. This is a significant contribution to the utilisation of optical dating, and is important for future research on inactive tufa sites in arid regions.
- 2) Single aliquot regeneration (SAR) techniques were employed for D_e evaluation of entrained quartz deposited within the Double Lakes tufa-forming environment. SAR methodology in this case proved to be a robust approach for determining dose equivalent values.
- 3) The data set for the tufa deposit is stratigraphically sensible and indicates Southern High Plains regional palaeo-recharge was occurring during the glacial period (early and middle Wisconsin) as shown in Figure 6-1.

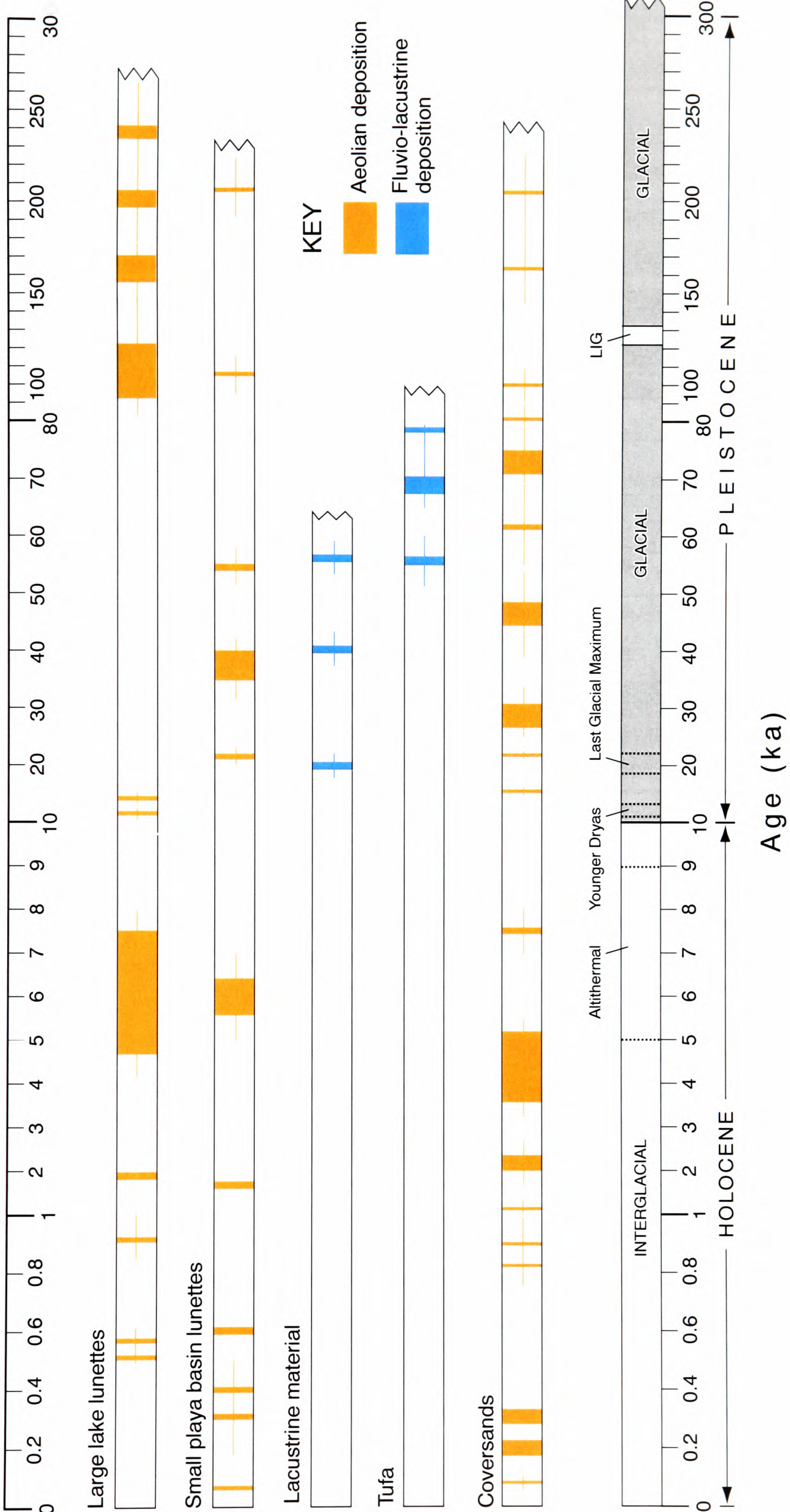
6.2.4 Coversands

The Quaternary aeolian deposits mantling the Southern High Plains have proven to be an important component of the surficial material of this region, and a rich archive of past climatic change. The following represent general conclusions drawn from the coversand data. For specific conclusions on the coversands see Paper 5:

- 1) New chronologies of coversand deposition provided by this research have refined and extended the timing of deposition and indicate multiple reactivation

of these dunes during the late-middle Pleistocene through the Holocene and historic periods.

- 2) Optical age estimates indicate coversand activity on the Southern High Plains in the 1890s, 1910s, 1920s, and 1930s. These depositional periods correspond to historic drought intervals that were detected in tree-ring data collected from nearby regions, and represent times of contracted moisture and/or greater evaporation for this region. The correspondence between historically recorded climatic events and dune deposition demonstrate the precision of the dating technique used for this study.
- 3) The Blackwater Draw Formation, an aeolian mantle underlying younger coversand material, is known to have accumulated during an extended duration of the Quaternary, and thought to have accrued in a cyclical manner. Optical age estimates potentially support this cyclical theory of Blackwater Draw sedimentation. Optical age estimates demonstrate that two of these cycles occurred during the late-middle Pleistocene (*c.* 165 ka) and late Pleistocene (*c.* 73-62 ka). This timing of deposition represents important new information on earlier periods of accretion for this mantle of aeolian material.
- 4) Coversand sediments on the Southern High Plains may have aggraded during four depositional Intervals (1-4) (the division between Intervals 1 and 2 is not as clear due to large errors on the older dates). Each interval is characterised by periods of dune intensification followed by a period of landscape stability or non-deposition. These intervals are based on the timing of sediment accretion, plus the recognition of distinct contacts or palaeosols at the sample sites and throughout the coversands. Detailed results for the timing of these Intervals are found in Paper 5.



6.3 Brief summary of depositional history

This study set out to simultaneously demonstrate the applicability of optical dating procedures as applied to sand-sized quartz grains from well-bleached sedimentary environments and to establish a chronology on lunette, lacustrine, tufa, and coversand deposits from selected sites on the Southern High Plains. The data set considerably expands evidence for the timing of construction for Southern High Plains lunette, lacustrine material, tufa, and coversand deposits from the late-middle Pleistocene (penultimate glaciation) through the historic period and provides an important basis from which to examine landscape response to regional and climatic changes. The record of climate change preserved in the lunettes, lacustrine material, tufa, and coversands has provided an insight into the response of this dynamic landscape to climatic fluctuations. This information has been employed for the reconstruction of the palaeo-environmental history of the Southern High Plains. An understanding of landscape response is important in light of the future of the Southern High Plains environment as global temperatures continue to increase and is also critical to a complete evaluation of continental response to climatic change.

The following is a synthesis the Southern High Plains environmental history, which has been drawn from the empirical research for this thesis and from the discussion section in Paper 6 (also see Figure 9 in Paper 6). The general patterns are summarised below:

- 1) The large lake lunettes of the Southern High Plains generally accreted during the pleniglacial (Illinoian) period, yet were clearly stable during the early, middle, and late Wisconsin glacial time (up to the last glacial maximum) (Figure 6-1).
- 2) Evidence from this study suggests that between 80 and 10 ka (Wisconsin glacial), on the Southern High Plains, the large lake basins experienced high water levels, which effectively shut down basin excavation and lunette accretion. During the Wisconsin period alternating deposition/non-deposition was evident between the small playa lunettes and coversands (aeolian material) and the lacustrine and tufa material (Figure 6-1). The depositional timing of

the fluvio-lacustrine material generally corresponds with the advancing North American mountain glaciers.

- 3) During the Younger Dryas period, the Southern High Plains was undergoing a contraction of effective precipitation, which resulted in a drop of the regional water table and subsequent lunette deposition (Figure 6-1).
- 4) Depositional patterns and timing for the lunettes and coversands provide strong evidence for significant dune accretion on the Southern High Plains during the middle Holocene (Altithermal). This period of aeolian activity has also been identified in regions adjacent to the Southern High Plains.
- 5) Deposition for the lunettes and coversands correlate with historic drought events (Figure 6-1). This response indicates their susceptibility to alterations in the moisture receipt for the region and proves their usefulness as proxy records in reconstructing past environmental histories.
- 6) Overall, the broad depositional patterns for the lunettes, lacustrine material, tufa, and coversands show accretion during both glacial and interglacial periods. These deposits may be responding to slight climate fluctuations caused by a reduction in effective moisture. This pattern of response during glacials and interglacials suggests that the Southern High Plains landscape was as sensitive to past climate changes as it has been during recent historical time. As such, the Southern High Plains may be particularly sensitive to climate alterations on the North American continent, and be one of the first regions to reactivate given present global warming scenarios.

6.4 Future research

From the research carried out in this thesis, a number of potential areas for future work can be identified. The Blackwater Draw Formation, for instance, is a rich archive of palaeo-environmental information that extends back 1.6 Ma. Identification of specific depositional events for the Blackwater Draw Formation remains to be completed. This could be accomplished with new red luminescence dating techniques; optical age estimates extending beyond a million years have been published by Fattahi and Stokes (2001) and Krbetschek and Gonser (2001).

A refined and extended chronology for the Blackwater Draw Formation may permit the detection of millennial-scale oscillations such as Heinrich events, in this low latitude continental sediment record. It is worth noting that coversand depositional episodes interpreted from optical dating chronologies for this research showed very broad agreement with Heinrich events (H6-H5, H3-H1, and the Younger Dryas). These have been described by Broecker (1994), Broecker *et al.* (1992) and Bond *et al.* (1992). General patterns recognised for coversand deposition during the Holocene roughly correspond to millennial-scale ice discharge events identified in two North Atlantic cores (Bond *et al.*, 1997). These tentative observations of the sensitivity of coversands to millennial-scale climate fluctuations may be validated by age-dating the Blackwater Draw Formation.

Further investigation into the Southern High Plains tufa deposit is needed in order to extend and enhance the data set. This would require the tufa outcrop at Double Lakes to be sampled at closer intervals. Additional relict spring vent sites also need to be located and optically dated to determine the extent of regional recharge across the Southern High Plains. An extended tufa chronology would allow cycles of increased moisture for this region to be identified. These approaches to dating and sampling would provide a more robust tufa chronology for this palaeo-environmental archive.

The Southern High Plains is a region with a variety of proxy records that can provide insight into the continental response to climatic changes which alter either the moisture receipt or evaporation rate of this region. Additional investigations and chronologies are necessary for this climatically sensitive area in order to further our understanding into the relationship between climate change and landscape response.