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GEOMORPHIC, SEDIMENTOLOGIC AND CHRONOLOGIC ANALYSIS OF THE OPAL DUNE FIELD, LINCOLN COUNTY, WYOMING

By

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GEOMORPHIC, SEDIMENTOLOGIC AND CHRONOLOGIC ANALYSIS OF THE OPAL DUNE FIELD, LINCOLN COUNTY, WYOMING

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INTRODUCTION

Eolian deposits are very common in the Rocky Mountain Basins and on the Great Plains as described by Ahlbrandt and others (1983), but detailed investigations of the internal structures and chronology of these eolian sequences are relatively uncommon. Many of these eolian terrains are dormant but susceptible to reactivation when disturbed due to the relatively high wind energy as measured in many regions of the Rocky Mountain and Great Plains. This report summarizes the investigations of a previously unrecognized dune field, here named the Opal Dune Field, that occurs in an active area of hydrocarbon exploration in the Green River Basin, Wyoming. The dune field and associated sand sheets are now stabilized by grasses and low shrubs. Many aspects of the Opal Dune Field are distinctly different from the nearby Killpecker Dune Field located 40 miles east of the Opal Dune Field (fig. 1A). The Killpecker Dunes have been studied by Ahlbrandt, (1974a, 1974b, 1974c, and 1975) and later by Kolm (1982). The only other dune fields that have been studied relatively recently but are geographically removed, about 100 to 200 miles east, from the Opal Dunes are the Casper Dunes, studied by Albanese (1974), the Ferris Dunes, studied by Gaylord (1990) and Stokes and Gaylord (1993), and the nearby Seminoe dunes studied by Kolm (1982) and Miller (1986). The Opal study was conducted to evaluate the environmental impact resulting from the construction of a natural gas processing plant, the Exxon LaBarge Project Plant Site, (also known as the Shute Creek Site), among the eolian deposits of the Opal dunes, most of which contain numerous Indian artifacts (figs. 1B and 1C). The Shute Creek facility is a natural gas processing plant designed to improve the quality of natural gas piped to it from gas fields in the Wyoming Overthrust Belt. The original Opal dune research was conducted over several years, mostly in 1983 and 1984 and consisted of geomorphic, sedimentologic and geoarcheologic investigations in support of a significant archeologic investigation at the site. The archeologic results, which in part incorporate the geologic studies, are summarized in a report prepared by Western Cultural Resource Management, Inc. (WCRM, 1984) which is on file with the Bureau of Land Management at Rock Springs, Wyoming, as is an earlier version of this report. Exxon Company, U.S.A. supported these environmental impact studies preparatory to the building of the Shute Creek facility, which was completed in the middle 1980's and is currently in use. The Shute Creek facility was built over a subsurface structure known as the Moxa Arch. Since the plant was constructed, the area along much of the Moxa Arch has been designated as a tight gas reservoir area thereby allowing tax incentives of Section 29 Federal Energy Regulatory Commission statutes facilitating hydrocarbon development there. This tax incentive was terminated for new wells

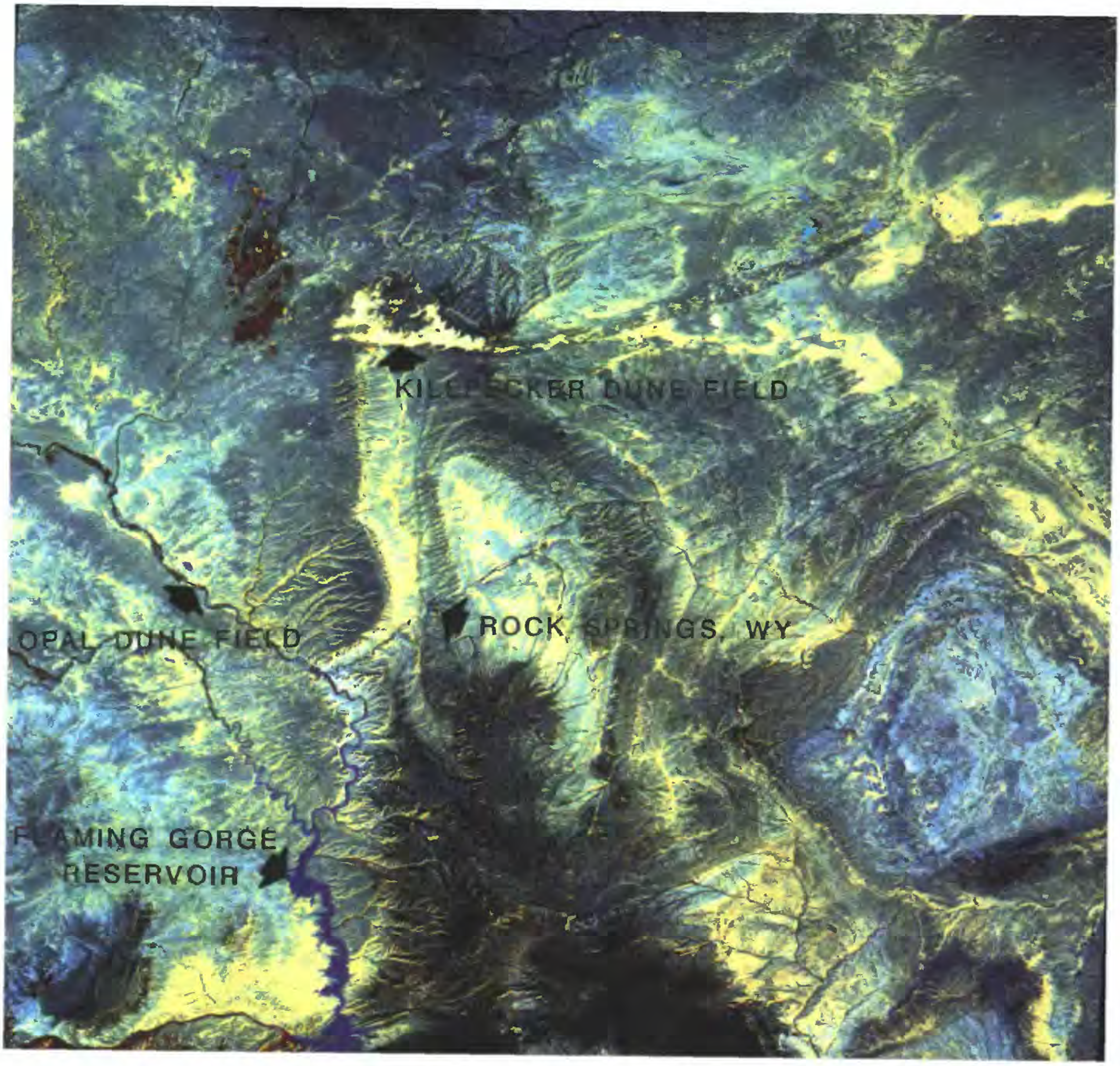
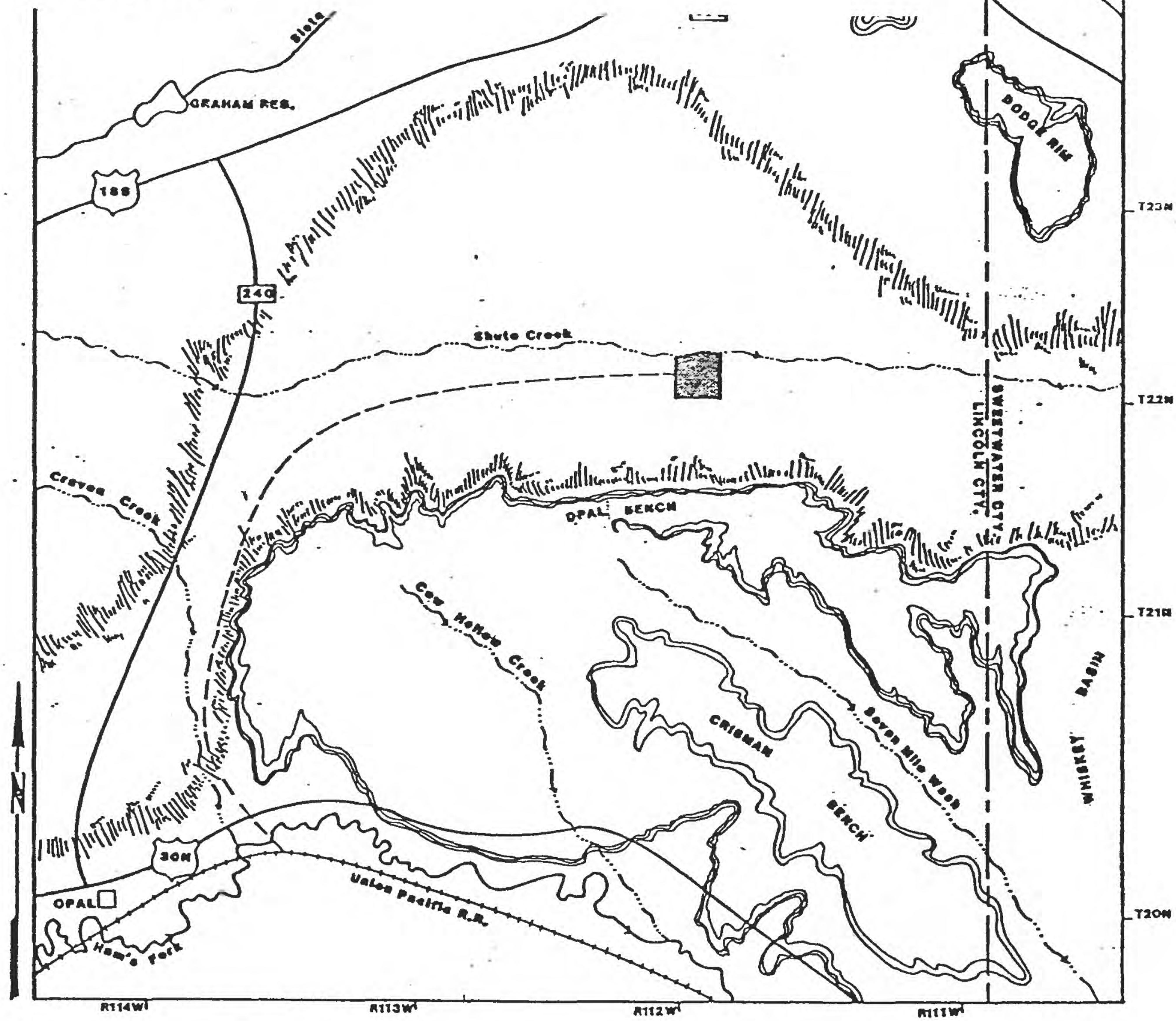


Figure 1A LANDSAT Multispectral Scanner image (1:1,000,000) of southwestern Wyoming processed in near infrared showing the Opal Dune Field, Killpecker Dune Field and presumed surficial eolian sediments in yellow regionally distributed across the area. The model used to generate the yellow color incorporates percent of vegetative cover and soil types. Areas shown in yellow reflect the combination of very low vegetation density with soils that have high reflectance (Pat Chavez, written commun., 1993). Areas shown in various shades of blue do not have these two conditions present and variations in shades of yellow indicate different levels of low vegetation density and reflectance brightness as can be seen contrasting the Killpecker Dunes where sand is partially active in contrast to the Opal Dunes which are stabilized.

Figure 1B General Location of the Shute Creek Plant Site, north of the Opal Bench. Note the town of Opal in the lower left portion of the map for which the Opal Dune Field is named and is generally shown withing the hachures west and north of the Opal Bench. The Ham's Fork River, which is a tributary to the Green River, is the southern boundary of the Opal Dune Field. The Shute Creek area refers to the region in the immediate vicinity of the Shute Creek Plant Site whereas the Craven Creek area refers to to region northeast of Opal in the vicinity of the confluence of Craven Creek and Ham's Fork drainages southwest of the Opal Bench.



Geologic Features in the Vicinity of the Shute Creek Project

Proposed Plant Site

Proposed Railroad Corridor

Well Developed Dune Field

Not to Scale

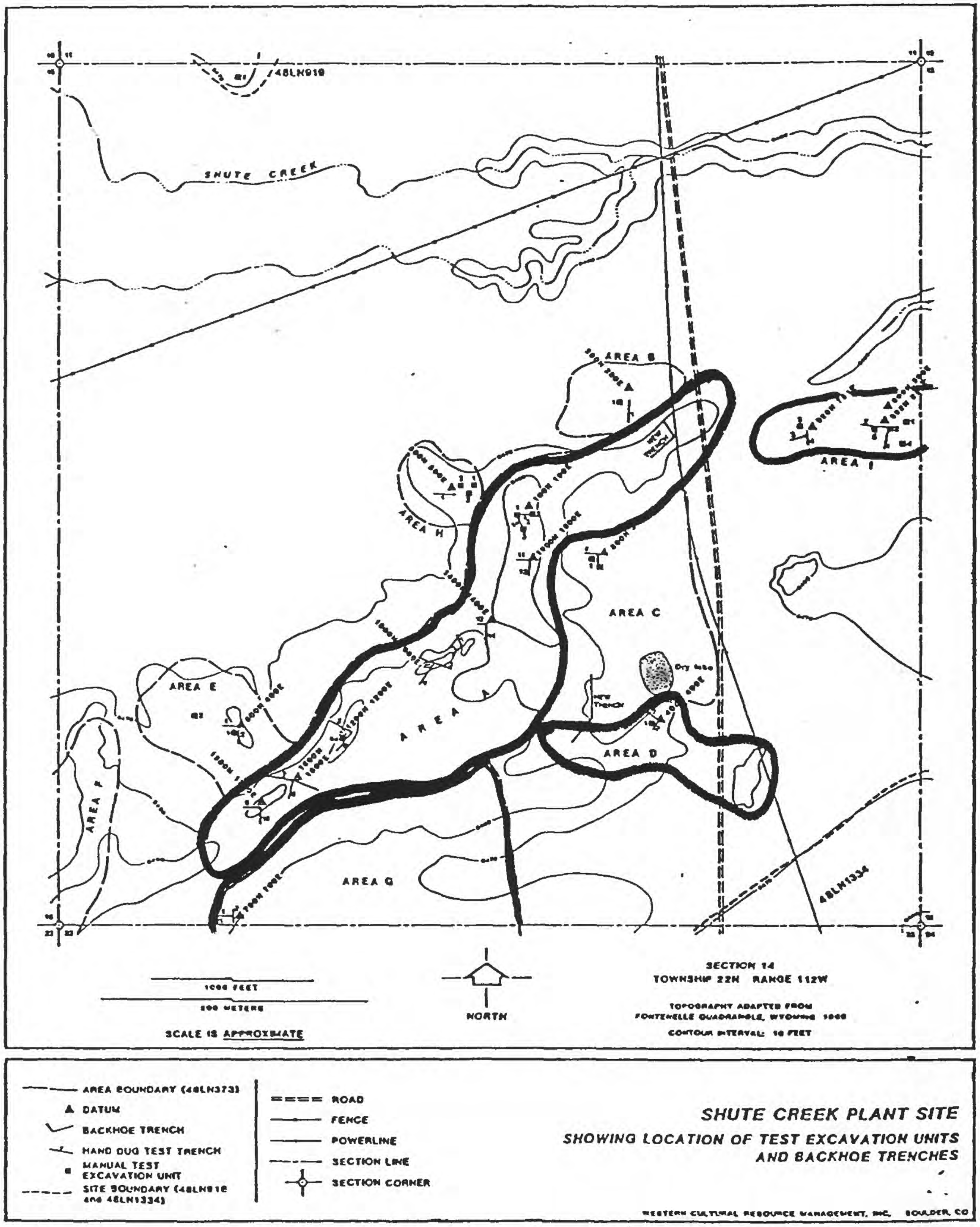


Figure 1C Locations of trench excavation units and backhoe trenches in the Shute Creek area as illustrated by WCRM (1983).

drilled after December 31, 1993. However, drilling prior to this deadline demonstrated significant natural gas resources along the Moxa Arch so that the Shute Creek facility is now placed within an exploration and development fairway leading to increased development of resources in and among the surficial eolian deposits described in this report.

New processing of LANDSAT imagery (Pat Chavez, written commun., 1993, USGS, Flagstaff) in the thermal infrared and infrared bands compared to older processing of MSS bands 4-5-6, identify potential eolian terrains previously not observed or mapped in southwestern Wyoming (fig. 1A). This study in part confirms that much of the surficial material shown in yellow on figure 1A is of eolian origin. Our reconnaissance field work in this area demonstrated that there are extensive eolian deposits, particularly sand sheets, across much of southwestern Wyoming, but although identifiable on figure 1A, they remain essentially unmapped on published geologic maps such as the Wyoming Geologic State map (Love and Christiansen, 1985). The recognition of significant surficial eolian deposits and numerous archeologic sites in a highly prospective hydrocarbon area necessitates an understanding the consequences of extensive development of natural gas in a susceptible eolian terrain.

This synopsis is a report of our detailed investigations of a 54 square mile segment of the Opal Dune Field as geomorphically mapped in Plate l using 1980 1:24,000 scale aerial photographs. The Opal Dune Field by our rough aerial photograph and field reconnaissance probably nearly is twice the size (approximately 100 square miles) of the region of detailed investigations. This study focuses on two areas of construction, the site of the Exxon LaBarge Project Plant Site (referred to in the text as the Shute Creek area) and the general area of the north-south railroad spur to be built by Exxon from the former location of the town of Opal (referred to as the Craven Creek area) north to the Shute Creek plant (fig. 1B). An understanding of the geomorphology, dynamics, sedimentary petrography, and chronology of this dune field is essential both for interpretation of archeologic sites within the dune field as well as assessment of impacts during construction and operation of the railroad spur, roads and facilities built within the dune field. We also dug trenches near Opal in the Craven Creek area that are pertinent to the Exxon railroad spur and conducted site investigations northwest of this area extending northward to the Fontenelle Reservoir. The Craven Creek trenches were excavated by a separate archeological contracting group (Mr. Scot McKern) under the overall guidance of Mr. Nick Hakiel of Archaeological Rescue, Inc.

METHODS

Fifty-four sediment samples were collected on a grid shown in figure 3A and from the archeological investigation trenches in both the Shute Creek and Craven Creek areas. All samples were taken from pits dug beneath the soil profile at depths greater than one foot below the surface. Samples were sieved by Western Research Archeology on full phi intervals. We subsequently calculated textural parameters of mean grain size, graphic standard deviation, graphic skewness and graphic kurtosis (table 2) as described by Folk (1968). Fifteen samples along a north-south traverse (A-A', fig. 3A)

Table 1--C^{14} radiocarbon dates from samples in the Opal Dune Field

Feature No.	Elevation (meters)	Radiocarbon Dates*	Grid and Test Trench Location in Area A
5	99.30-99.05	1030 ± 80 B.P.	Unit 2, 91.5N/96.5E, 90.5N/97
15	99.26-99.22	N/A	Trench 2, 80.5N/85.SE
2	99.155-99.03	1170± 60 B.P. (SC-3)	Unit 3, 75N/102E
5	99.03-98.96	N/A	Trench 1, 75N/100E
1/3	98.85-98.70	2960 ± 60 B.P. (SC-4)	Unit 1, 77N, 83E 78N/83E, 79N/83E 79N/83E, 78N/84E 77N/84E, 77N/85E 78N/85E, 79N/85E
12	98.68-98.61	N/A	Trench 1, 75N/100E
10	98.63-98.5	N/A	Trench 2, 83N/88E, 84N89E
20	98.56-97.76	N/A	Trench 1, 75N99E
14	98.43-98.29	1860 ± 100 B.P. (SC-6)	Trench 1, 75N/100E
13	98.41	N/A	Trench 1, 75N/99E
11	98.31-98.09	4000 ± 70 B.P. (SC-1)	Trench 2, 82N/87E
22	98.17-98.06	N/A	Trench 1, 75N/99E, 75N/100E
21	98.16-98.05	N/A	Trench 1, 75N/99E
16	97.71-97.62	3800 ± 100 B.P. (SC-5)	Unit 1, 77N/84E
17	97.55-97.52	N/A	Trench 2, 81N/86E
18	97.35-97.30	N/A	Trench 2, 82N/87E
19	97.30-97.23	5530 ± 100 B.P. (SC-36)	Trench 2, 81N/86E

* SC numbers refer to the Shute Creek Laboratory's master catalogue list.

Table 2. Textural Parameters of Opal Dune Field Samples

Sample		Mean grain Size ø (mz)	Graphic Standard Deviation	Graphic Skewness	Graphic Kurtosis
A3		2.00	.85	.18	1.02
A41	(Zone 1)	2.33	.63	-.04	1.00
A42	(Zone 2)	2.37	.80	.13	1.09
A43	(CS 1)	1.90	.80	.26	1.31
A112	(Zone 1)	2.58	.73	.17	1.46
A113	(Zone 2)	2.55	.80	.19	1.23
G1	(Zone 1)	2.40	.70	0	1.02
G2	(CS 1)	2.00	.85	.18	1.45
I1	(Zone 2)	2.58	.88	.14	1.19
I2	(Zone 3)	2.63	.83	.15	1.23
7A4	(Gravel)	.33	2.15	.16	.73
7A5		2.23	.60	.33	1.30
7E1	(Zone 1)	2.73	.80	.25	1.27
7E2	(Wedge)	2.80	.78	.10	.78
7F1	(CS 1)	2.23	.65	.08	.84
7F2	(Zone 1)	2.70	.75	.20	1.32
7F3	(Zone 2)	2.87	.95	.26	1.07
8CC1	(CS1)	2.03	.60	.33	1.23
8CC3	(Zone 2)	2.12	.60	.42	1.00
11WW1	(CS 1)	2.48	.93	.30	1.19
11WW2	(Zone 2)	2.68	.95	.21	1.10
1		1.97	.43	.06	1.23
2		2.53	.83	.15	1.25
4		1.88	.65	.31	1.29
6		2.71	.77	.23	1.31
7		2.33	.78	.16	1.17
9		1.90	.65	.23	1.51
12		2.68	.95	.21	1.10
13		2.08	.55	.36	.89
14		2.15	.58	.39	.87
18		2.12	.60	.42	1.13
20		2.32	.68	.04	1.09
29		2.93	1.00	-.10	1.02
29A		2.30	.75	.20	1.11
30		2.43	.90	.22	1.19
34		1.73	.80	.25	2.15
36		2.02	.85	.29	1.64
40		2.25	.63	.12	.96
41		2.50	.50	0	1.15
47		2.07	.60	.42	1.10
48		1.82	.73	.24	1.37
49		2.00	.58	.37	1.07
50		2.23	.58	.22	.87
51		2.60	1.20	0	1.58

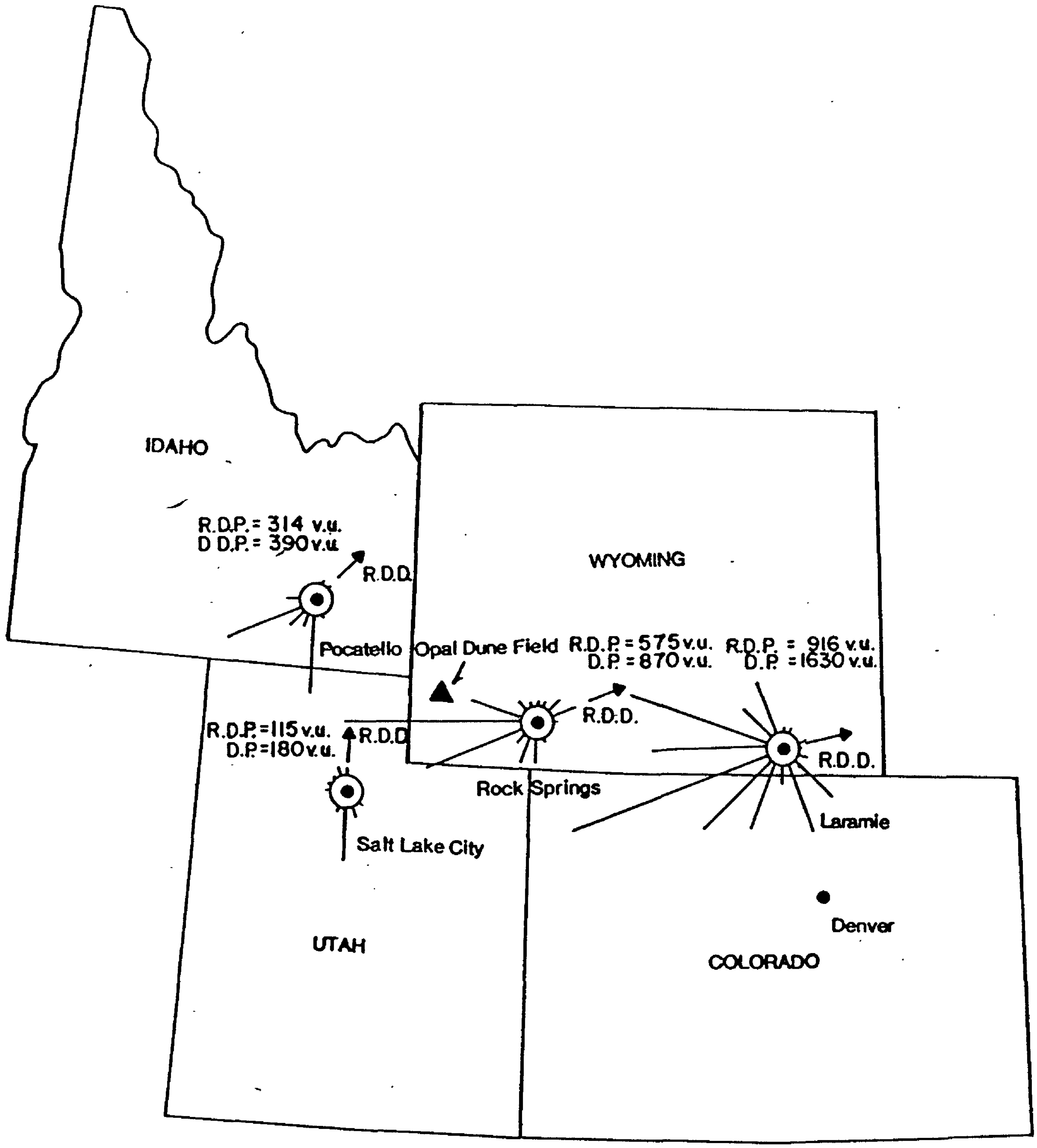
and an east-west traverse (B-B', fig. 3A) were analyzed for both total composition and separately for heavy minerals. The fifteen bulk sediment samples were thin-sectioned, impregnated with blue epoxy and 300 points per slide counted. An additional fifteen slides, impregnated with clear epoxy, were prepared from heavy mineral splits of these same samples.

A total of 29 backhoe trenches were excavated in 10 areas, i.e. areas A, B, C, D, E, F, G, H, and I in the Shute Creek area and Sites 48LN373 and 48LN919 in the Craven Creek area as shown in figures 4-25. Detailed archeologic discussions of the various areas of excavation are given in WCRM (1984) and projectile points discovered during WCRM investigations are shown in figure 26. The total area investigated in detail was 194 acres, 2,583,000 square meters and 798 square meters of excavation. Chronologic determinations were made by C^{14} dating of 9 charcoal and bones samples; 7 C^{14} ages in area A and one C^{14} date each from areas E and G (fig. 1C, table 1) and by numerous artifacts which were identifiable as to their cultural component. C^{14} ages were determined by Beta Analytic, Inc. in Coral Gables, Florida.

DUNE MORPHOLOGY

The Opal Dune Field is a topographically controlled dune field produced by the downwind topographic obstacle of the Opal Bench and Dodge Rim shown as the stippled pattern on plate 1 blocking the predominantly easterly sand transport across the region (fig. 2A, pl. 1). The Opal Dune Field is now stabilized by grasses, sage, rabbit bushes and a variety of low (< 3 feet high) vegetation. Although most of the dormant dunes recognizable in the Opal Dune Field are small (< 50 feet high), their morphology is well preserved. Barchan and barchanoid ridge dunes are the dominant forms with lesser numbers of dome, parabolic and transverse dunes (pl. 1). The dune field was a sediment-limited system when active which is reflected in the small size of the dunes, the wide spacing of dunes with large deflated interdune corridors, and the dominance of barchan-type dunes which are known to occur in areas of reduced sand supply. As discussed by McKee (1979), transverse dunes would be more prevalent and dunes would be closely spaced together if sand supply were more abundant.

The now stabilized Opal dune forms were produced by paleo-winds blowing almost directly from the west-southwest (fig. 2A, pl. 1). Although the dunes date to at least 5,500 years B.P., paleo-sand transport as deduced from 770 slipface measurements (as shown in fig. 2A) are consistent with the present day winds which blow dominantly from the west-southwest (fig. 2B). Wind data from four recording stations, Pocatello, Idaho; Salt Lake City, Utah; Rock Springs, Wyoming and Laramie, Wyoming, were evaluated for this report using the sand rose technique. As demonstrated by Fryberger and Dean (1979), wind energy has much greater sand transporting ability at higher speeds; thus, a weighted equation is needed to properly evaluate sand transport potential for a given set of wind records. We will not discuss the mathematics of sand rose construction; however, Fryberger and Dean (1979) quantify the total energy available at a given site as drift potential (DP). Observations of numerous desert wind records indicate that low energy deserts have vector unit values of drift potential (DP) (a measure of sand



SAND ROSE PLOTS IN THE REGION OF THE

OPAL DUNE FIELD

FIGURE 2 A

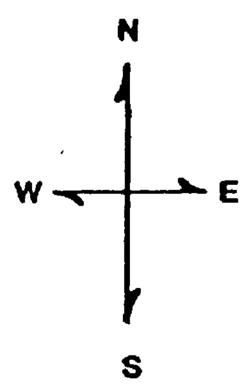
LEGEND

R.D.P. RESULTANT DRIFT POTENTIAL

D.P. DRIFT POTENTIAL

R.D.D. RESULTANT DRIFT DIRECTION

J. VECTOR UNITS



0 100 200

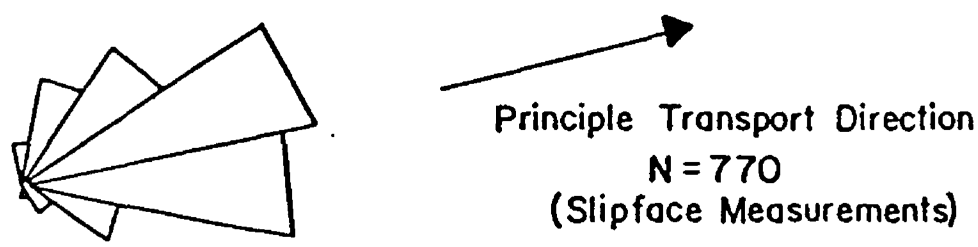
VECTOR UNITS

0 50 100

MILES

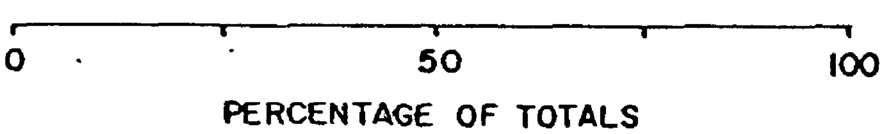
Paleosand Transport Determined From
Slipface Strike and Dip Data

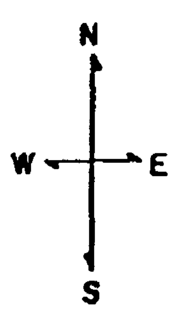
FIGURE 2 B



Opal Dune Field

Lincoln County, Wyoming





transport potential in cubic meters of sand per meter width per year) of less than 200 vector units (VU), moderate energy deserts have values of 201 to 400 VU and high energy deserts have values more than 400 VU.

However, it is the resultant direction of drift of sand (RDD) and the resultant drift potential (RDP) which determine the direction and amount of sand drift. As shown on figure 2B, drift potential and resultant drift potential for the Rock Springs wind data are very high (DP = 870 VU, RDP = 575 VU) and this is the closest wind station to the Opal Dune Field. The Laramie data reflect similar strong sand transporting capability and both Laramie and Rock Springs have strong resultant drift directions to the east-northeast (fig. 2B), consistent with the dune forms seen both at the Opal Dunes (figs. 1A and 2B; pl. 1) and in the Killpecker Dune Field which occurs about 40 miles north of Rock Springs (Ahlbrandt, 1974, 1975). D.R. Muhs (written commun., 1993) provided monthly and annual sand roses for Rawlins, Wyoming which is about 100 miles east of Rock Springs, Wyoming. His annual summary for the sand rose at Rawlins shows very high wind energy (DP= 824 VU) and the resultant drift direction is strongly to the east-northeast (RDP= 705 VU) consistent with the Rock Springs and Laramie sand rose data.

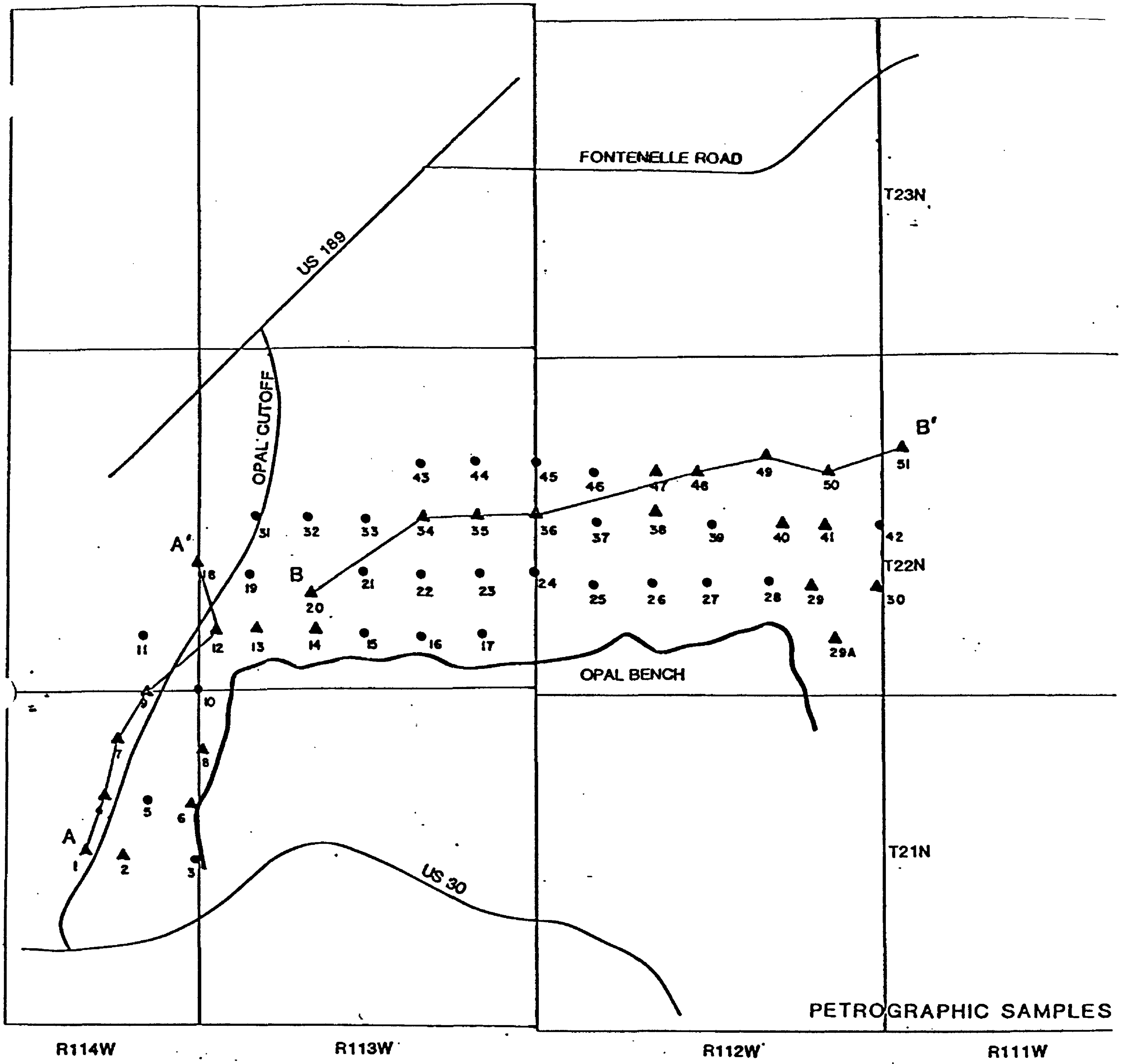
Reactivation of the Opal dunes after surface disruption is a potential hazard based on the very high DP values for this region. Small barchan dunes (<20 feet high) are documented to migrate from 30 to 150 feet per year under high wind energy conditions (Finkel, 1959; Haynes, 1989) which can pose a hazard to both the refinery and maintenance efforts. The cold climate in the region is a mitigating factor due to freezing in the winters, which is known to reduce sand transport during those months in Rocky Mountain dune fields (Ahlbrandt and Andrews, 1978).

SEDIMENTARY PETROLOGY

We will first discuss the textural parameters, then petrographic analyses of the sand samples, and finally the potential sand source for the fifty four samples from the Opal dunes (fig. 3A).

The isopleth map of mean grain size values (fig. 3B) demonstrates that most (78.5 percent) of the sand samples are fine sand (2-3 phi) and occur along the downwind margins of the dune field; i.e. in the Craven Creek area close to the Opal Bench and in the Shute Creek area in the easternmost group of samples. Fine-grained sand is the dominant grain size of many dune sands in the deserts of the world (Ahlbrandt, 1979). The remaining 21.5 percent of the Opal dune samples are medium sand (1-2 phi) and occur along the upwind margins of the field; i.e. western side of Craven Creek area, and the northwest portion of Shute Creek area.

The Opal dune sands are generally only moderately well sorted as shown by the graphic standard deviation isopleth (fig. 3C). Only two samples are well sorted (values < .50); most are moderately sorted (.50-.70) and some are moderately sorted (.71-1.00). The general poor sorting of the Opal dune sand is in part due to its immature composition, as will be discussed, and apparent proximity to its source, because grains are generally subangular to subrounded in hand specimen and thin section.



SCALE

0 1 2 3

MILES

LEGEND

GRID NUMBER 1

SAMPLE LOCATION △

SAMPLING GRID OF THE OPAL DUNE FIELD

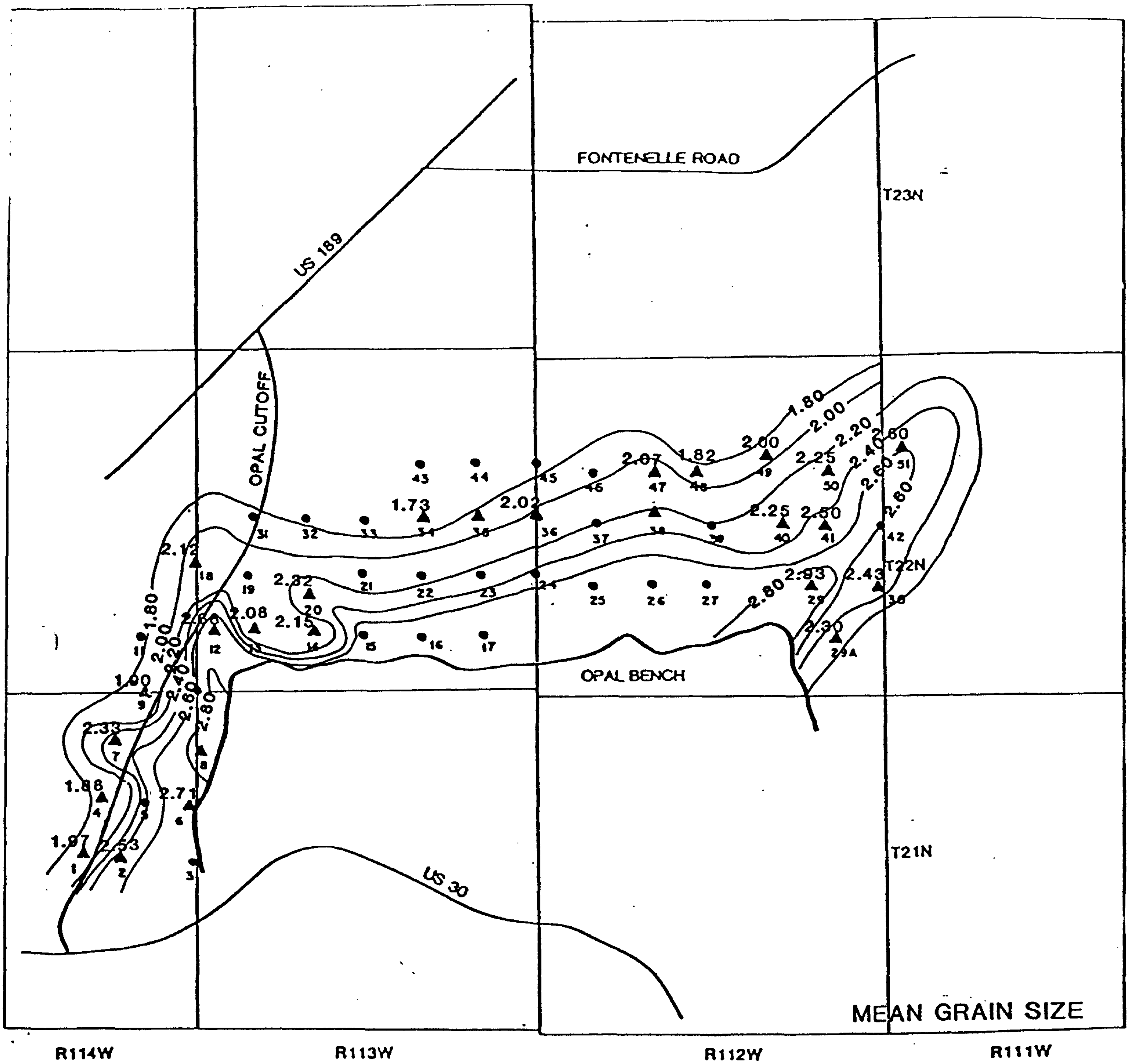
LINCOLN COUNTY, WYOMING

FIGURE 3 A

N

W E

S



SAMPLING GRID OF THE OPAL DUNE FIELD

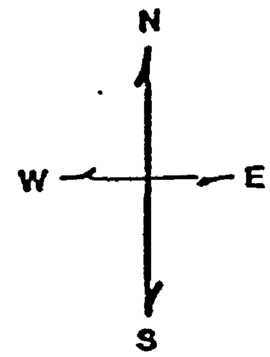
LINCOLN COUNTY, WYOMING

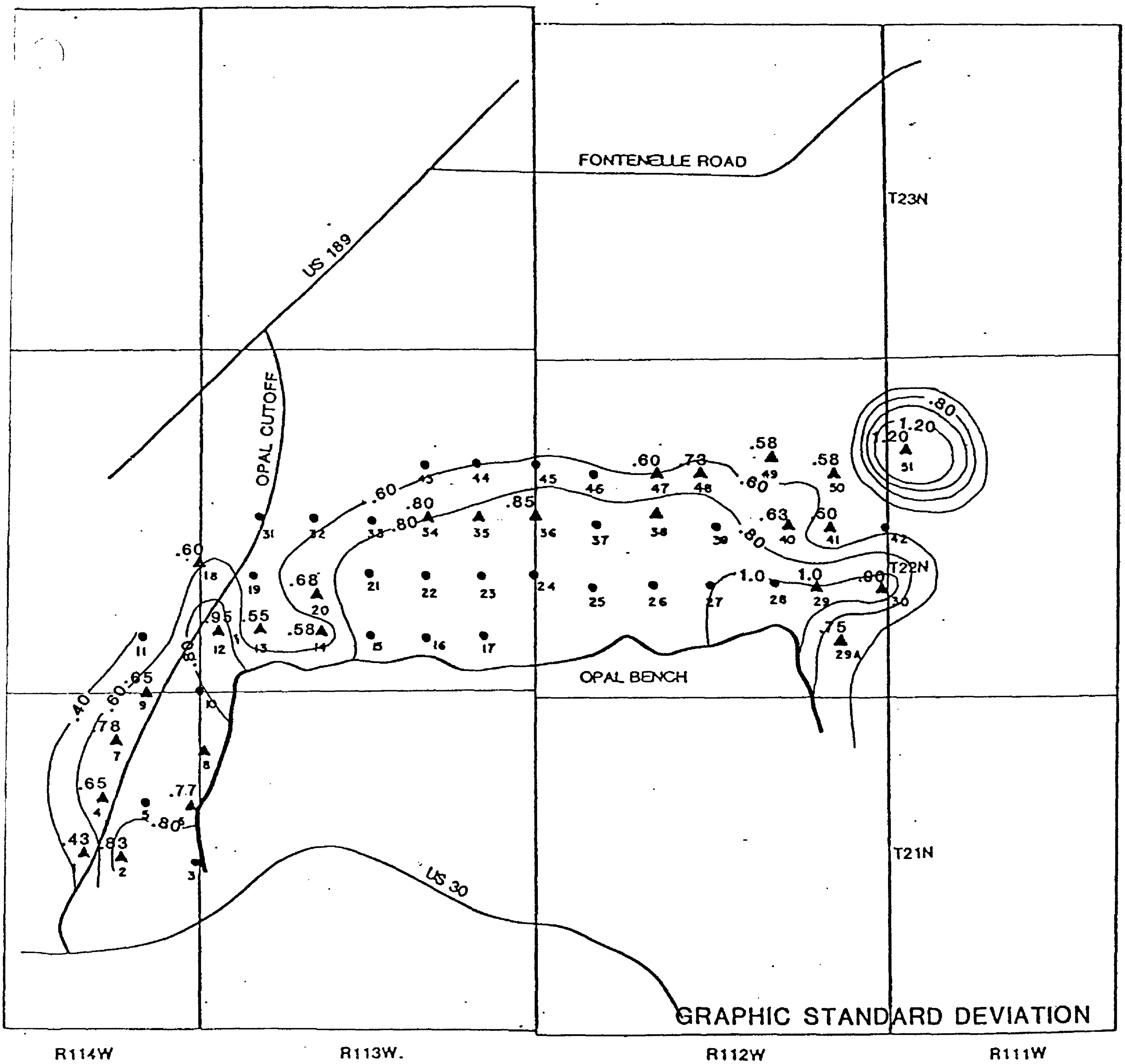
FIGURE 3 B

LEGEND

GRID NUMBER 1

SAMPLE LOCATION Δ





SAMPLING GRID OF THE OPAL DUNE FIELD

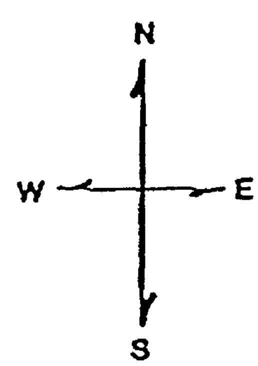
LINCOLN COUNTY, WYOMING

FIGURE 3 C

LEGEND

GRID NUMBER 1

SAMPLE LOCATION △



The graphic skewness isopleth (fig. 3D) shows only one sample to be nearly symmetrical (- .10 to +. 10 values), the remainder of samples are fine skewed (+ .30 to + .10 values) to strongly fine skewed (+ 1.0 to +.30 values). Thus, the Opal sand samples are generally asymmetrically distributed to the finer grained fractions. Positive skewness is very common in dune sands as discussed by Ahlbrandt (1979); however, skewness is known to be dependent on mean grain size; the finer the grain size the closer to negative skewness. Thus, the only negatively skewed sample of the grid set (#29) is also the finest grained sample (2.93 phi) which is consistent with the interdependence of these two parameters.

The graphic kurtosis isopleth (fig. 3E) shows the Opal dune sands are generally leptokurtic (1.11-1.50) to very leptokurtic (1.51-3.0) with a few mesokurtic samples (.9-1.1). Leptokurtic curves generally reflect poorer sorting in the tails of the cumulative frequency curve, and relatively better sorting in the central portion of the curve. Generally, inland dune sands are mesokurtic to platykurtic Ahlbrandt (1979). Thus, the generally leptokurtic values of the Opal dunes are somewhat unusual, perhaps related to the complex lithology of the dune sands.

The Opal dune sands compositionally are lithic sandstones (litharenites ranging to feldspathic litharenites of Folk, 1968) with large components of both volcanic rock fragments and other, non-volcanic rock fragments (table 2; figs. 3F, 3G, and 3H). The highest quartz component in the samples studied was 39 percent in Sample 1, which is relatively low for eolian sands. Plagioclase feldspar is considerably more common than K-feldspar in the samples. The plagioclase grains are relatively fresh with little alteration even along cleavage planes. The K-feldspar grains show considerably more alteration to clay (mostly montmorillonite as determined by reflective petrographic analysis). The volcanic rock fragments contain numerous relatively unaltered plagioclase laths.

Clay coatings (mostly montmorillonite, with perhaps some mixed layer illite-montmorillonite) are common on grains of all composition. The sand grains are not well rounded; most are subangular to subrounded. Quartz, non-volcanic rock fragments, and feldspar grains are generally subangular where as volcanic rock fragments are somewhat more rounded.

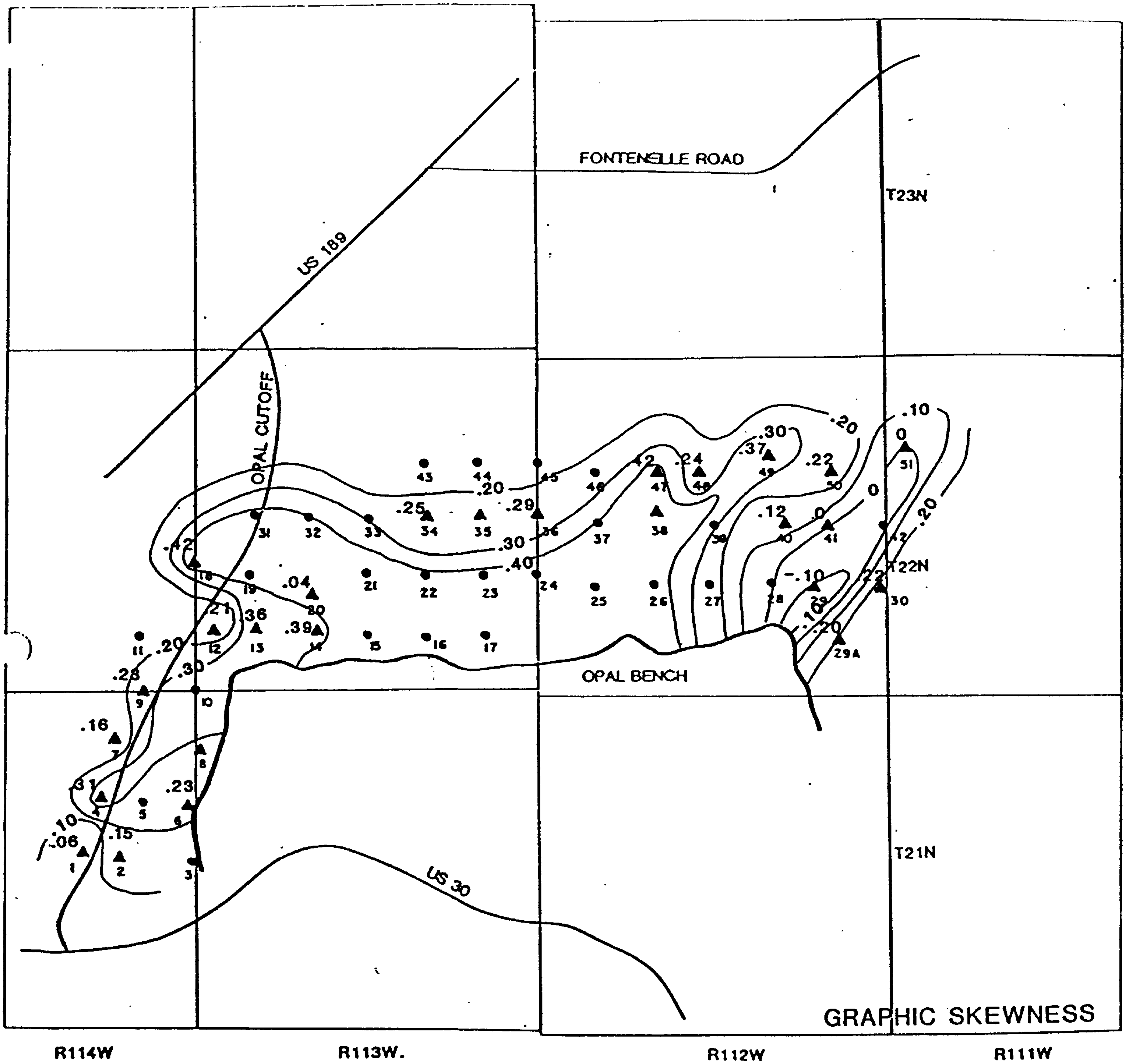
The heavy mineral assemblage of the samples is dominated by brown hornblende and biotite, with lesser amounts of augite and stable minerals such as zircon, tourmaline and rutile (table 3).

The presence of abundant volcanic rock fragments and a significant component of brown hornblende and biotite suggest a volcanic (not plutonic) sandstone source. As discussed by Denson and Pipiringos (1969) and Denson and Sato (1967), there is a marked change from plutonic assemblages in Lower Eocene rocks such as the Green River Formation versus volcanic assemblages in Middle and Upper Eocene rocks such as the Bridger Formation. The composition of the Opal dune sand, both in the light and heavy mineral fractions, is considerably different from assemblages in the Killpecker

Table 3.--Petrographic Summaries of Opal Dune Field Sand Samples In Percent (300 points/slide)

	A-A' TRAVERSE (SOUTH-NORTH) Sample Number					
	#1	#4	#7	#9	#12	#18
Quartz	39%	26%	26%	25%	34%	33%
K-Feldspar	1%	1%	1%	2%		1%
Plagioclase	10%	6%	7%	7%	2%	5%
Chert	5%	1%	.5%	3%	1%	
Rock Fragments	25%	28%	31%	27%	17%	25%
Volconic Rock Fragments	14%	28%	23%	26%	30%	21%
Detrital Carbonates			2%		1%	
Heavy Minerals:						
Biotite	2%	4%	4%	3%	3%	3%
Muscovite		.5%			1%	
Epidote		1%		1%	1%	
Augite					1%	
Rutile						
Hornblende	4%	5%	4%	6%	9%	7%
Zircon			1%	2%	2%	
Tourmaline		1%				

	B-B" TRAVERSE (WEST-EAST) Sample Number						
	#20	#34	#36	#48	#49	#50	#51
Quartz	33%	10%	3%	15%	21%	29%	17%
K-Feldspar		1%		2%	1%		
Plagioclase	6%	2%	1%	5%	5%	6%	4%
Chert							1%
Rock Fragments	19%	20%	5%	22%	19%	18%	18%
Volcanic Rock Fragments	21%	60%	85%	44%	37%	36%	43%
Detrital Carbonates		1%	1%		1%	1%	2%
Heavy Minerals:							
Biotite	4%		1%	2%	2%		2%
Muscovite	2%			1%			
Epidote	1%	1%		2%	1%	1%	
Augite	1%			1%	1%		
Rutile				1%			
Hornblende	9%	4%	2%	4%	8%	6%	5%
Zircon	3%	1%	2%	1%	2%	3%	6%
Tourmaline	1%				2%		1



SAMPLING GRID OF THE OPAL DUNE FIELD

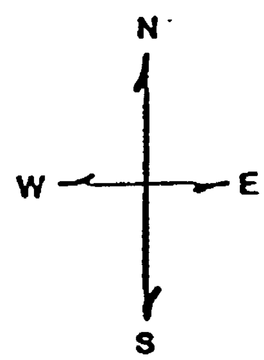
LINCOLN COUNTY,WYOMING

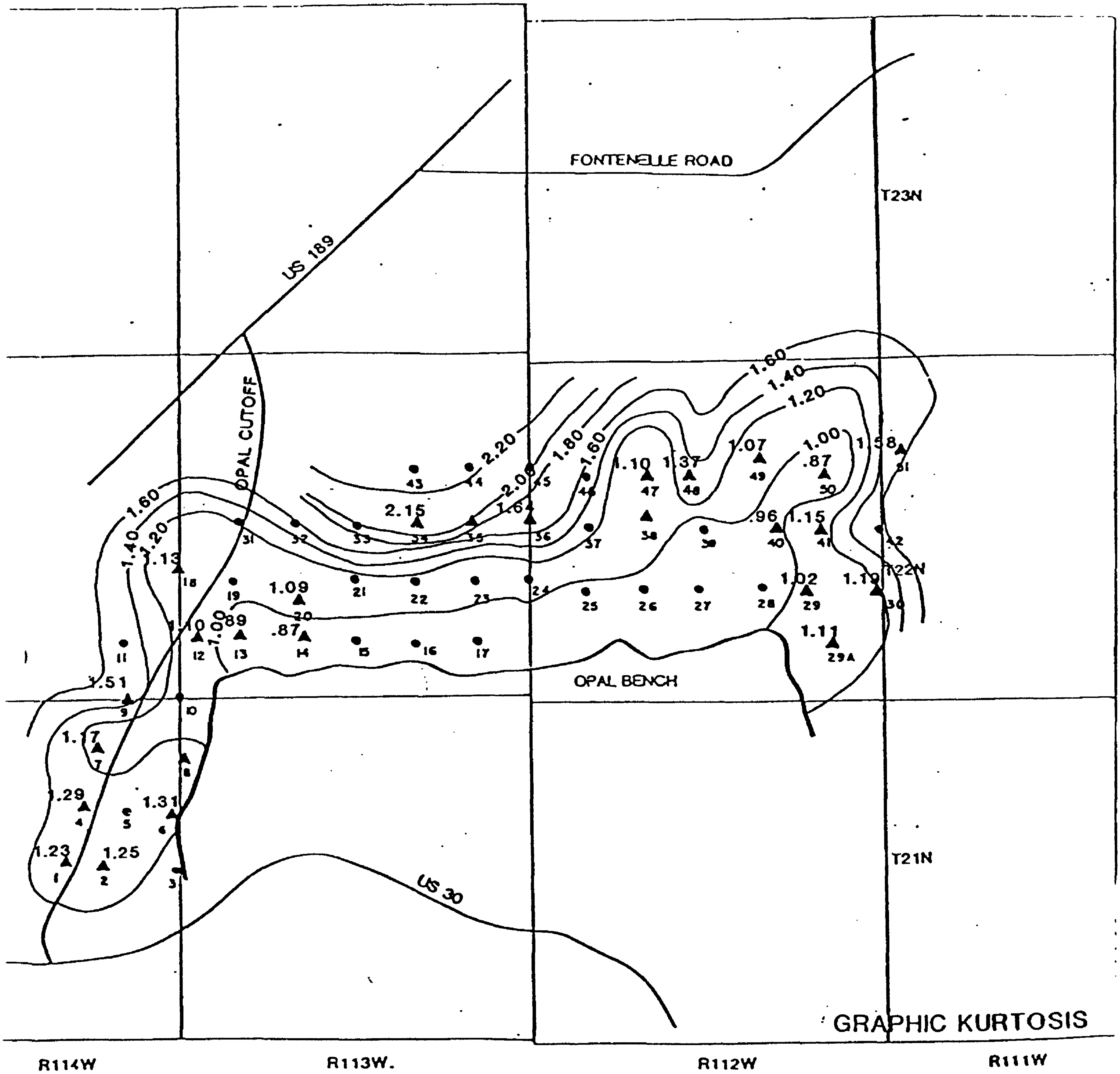
FIGURE 3 D

LEGEND

GRID NUMBER 1

SAMPLE LOCATION △





SAMPLING GRID OF THE OPAL DUNE FIELD

LINCOLN COUNTY, WYOMING

FIGURE 3 E

LEGEND

GRID NUMBER 1

SAMPLE LOCATION △

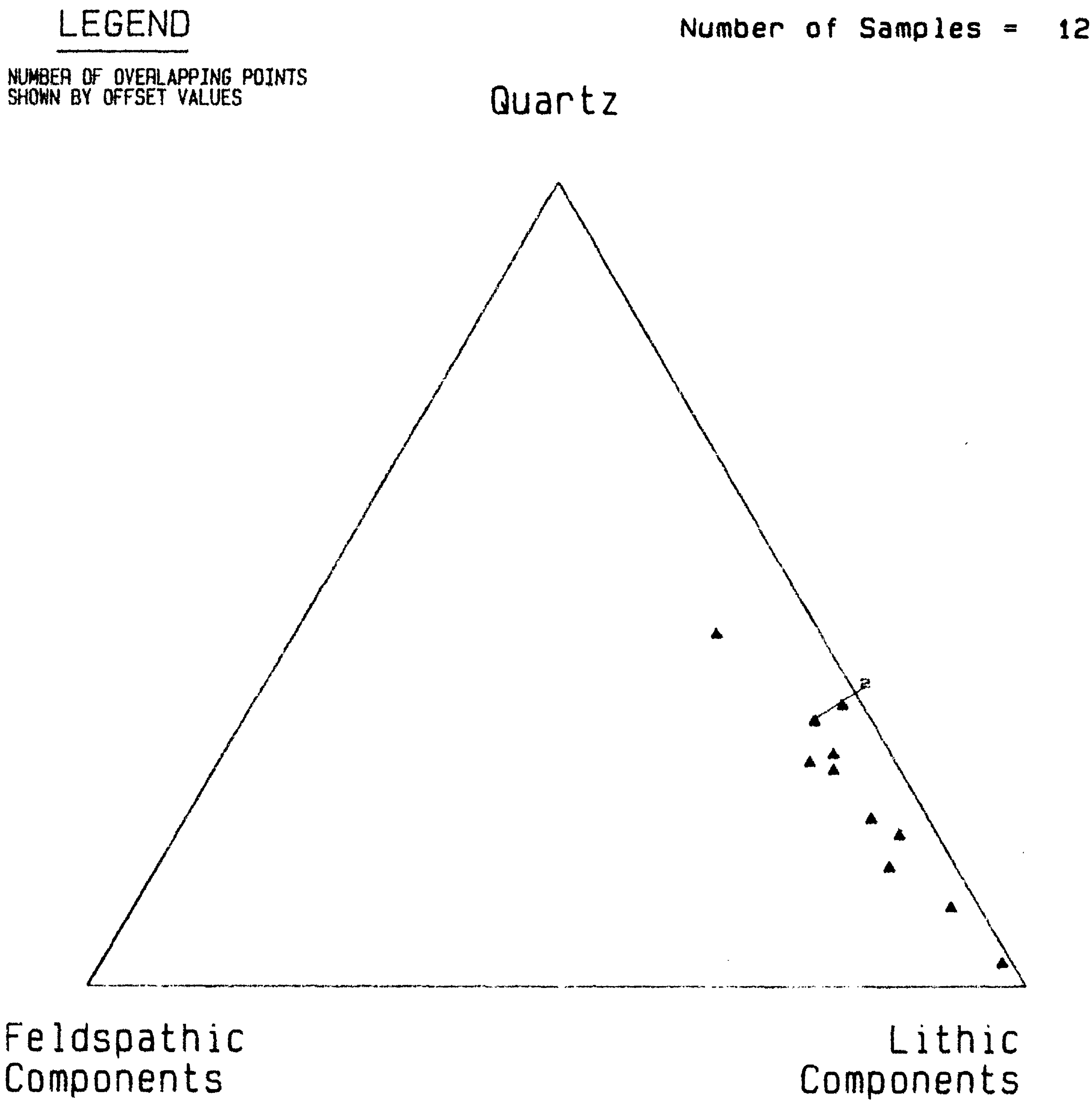


Figure 3F: Ternary compositional plots (quartz/feldspar/lithics) of 13 dune sands samples (2 samples had the same composition) from the Opal Dune Field includes data from Transects A-A' and B-B' shown on Figure 3. Detailed percentages of sand composition (as well as heavy mineral assemblages) are shown in Table 3.

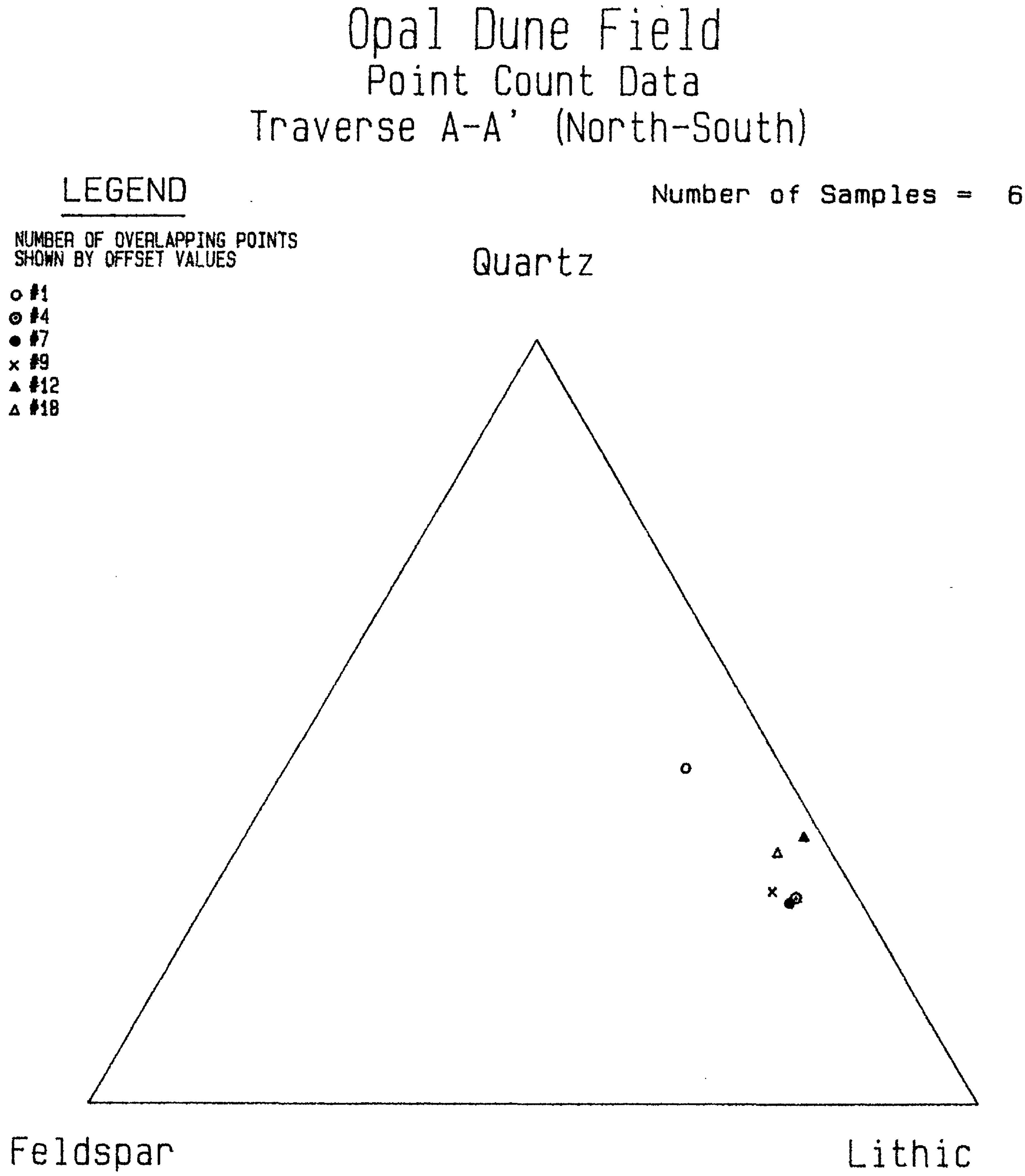


Figure 3G Ternary plot (QFL) of 7 dune sands along a north-south transect A-A'. The southernmost sample (31) contains the greatest amount of quartz (39%) of any of the sand samples perhaps reflecting proximity to the Ham's Fork and Craven Creek drainages. Details of percentages shown in Table 3.

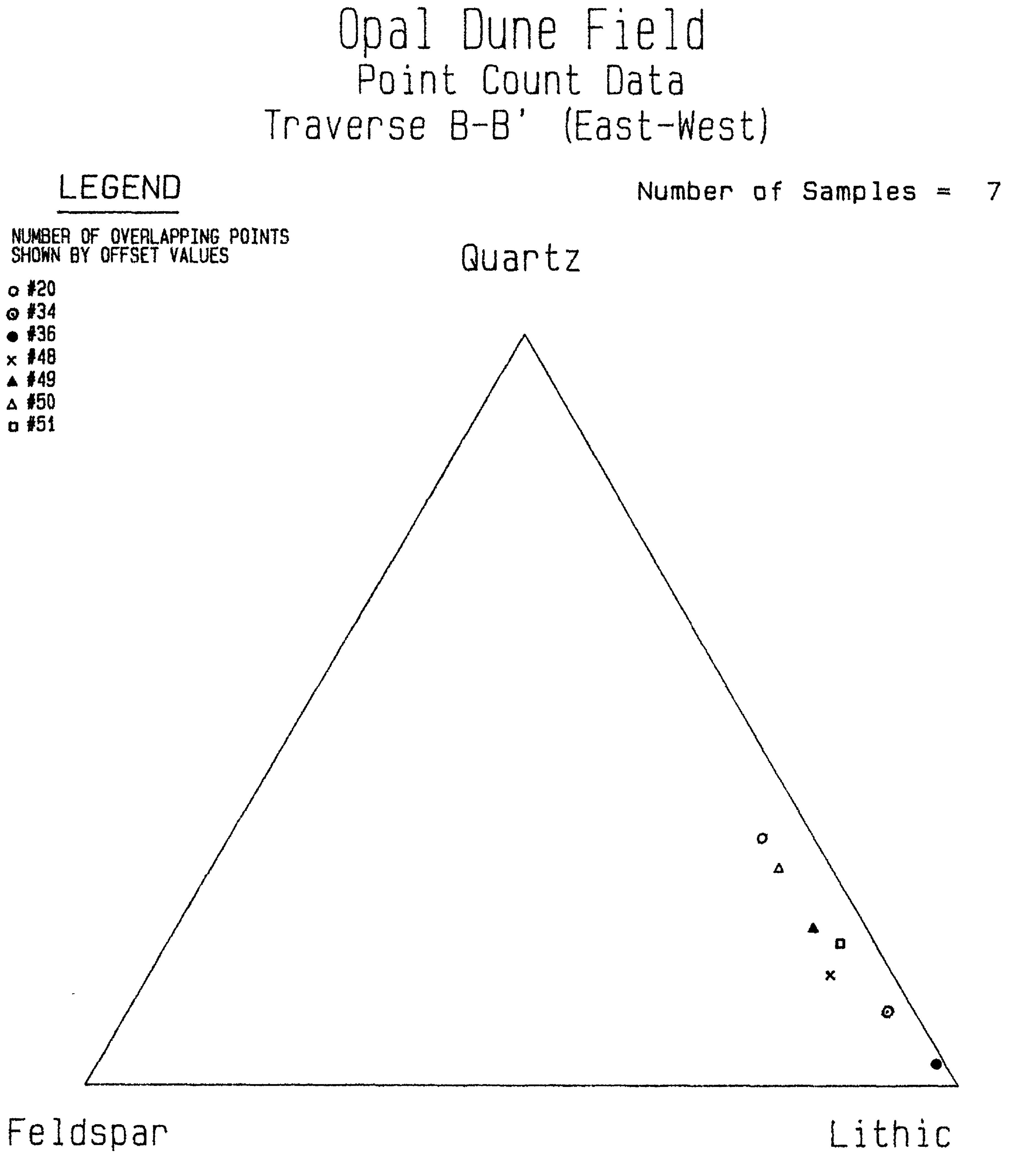


Figure 3H Ternary plot (QFL) of 6 dune sands along an east-west transect B-B'. The westernmost sample is the most quartz rich (33%) along this transect; however the sand is dominated by lithic fragments as detailed in Table 3.

dune sands. The Killpecker dunes, which occur about thirty miles east of the Opal dunes, were determined by Ahlbrandt (1974) to have been derived from sandstones in the Laney Member of the Green River Formation. The light fraction of dune sand in the Killpecker samples was dominated by quartz and feldspar with an associated plutonic heavy mineral assemblage dominated by epidote, blue-green hornblende, green brown hornblende and virtually no augite. The Bridger Formation is known to contain a volcanic heavy mineral assemblage; this is consistent with independent evidence of increased volcanism in the Middle and Upper Eocene as discussed by Denson and Sato (1967).

We conclude, based upon our present data, that the most likely source of sand for the Opal dunes is disaggregated sand derived from sandstones of the Bridger Formation. The Bridger is the likely source because it underlies the Opal Dune Field, and it has a volcanic light and heavy mineral assemblage consistent with that observed in the dune samples. The limited amount of sand available from the Bridger may be reflected in the small size of the Opal dunes, and their wide spacing with deflated, interdune corridors.

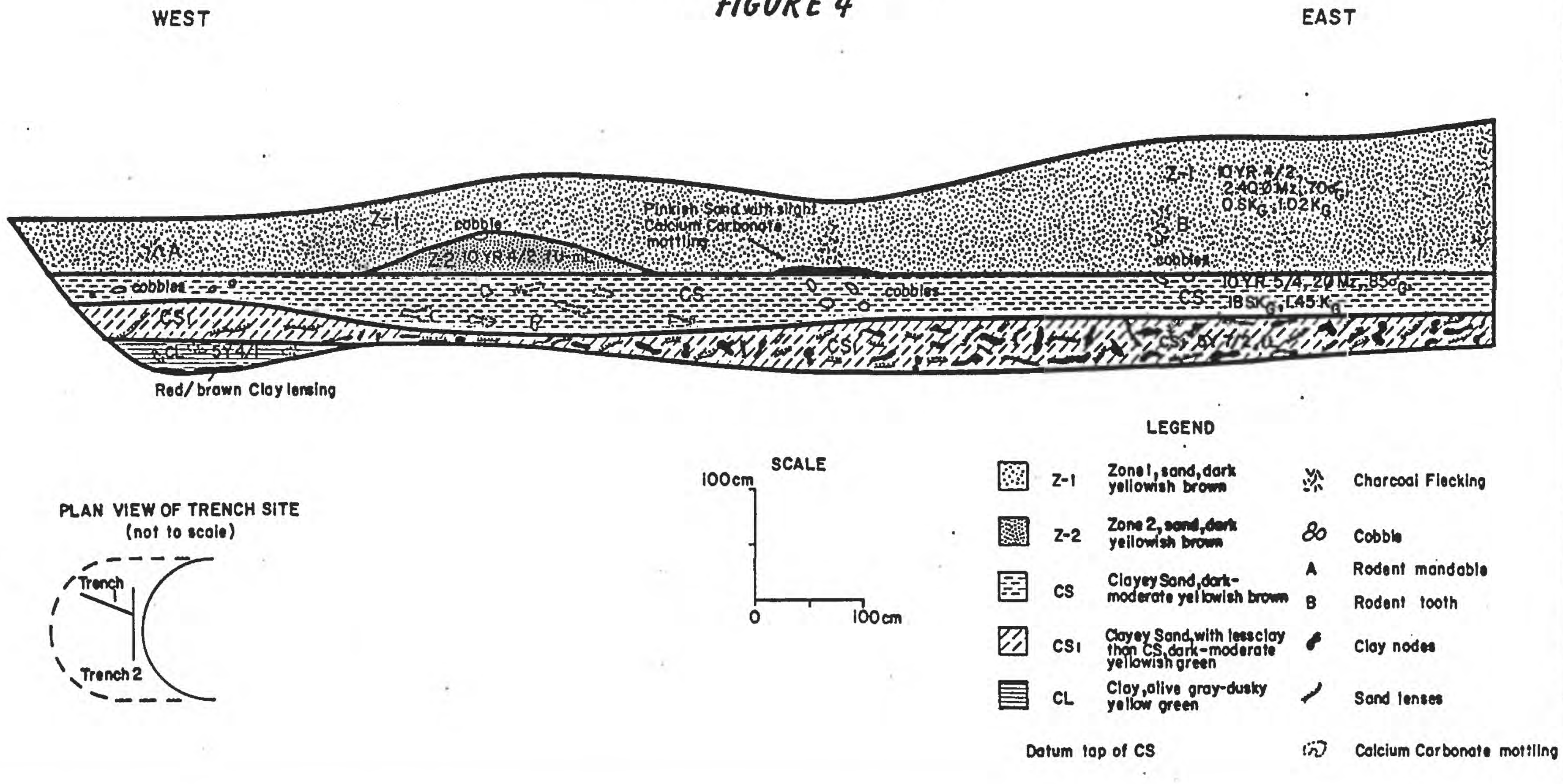
There are no significant textural and compositional differences between the Opal dunes in the Craven Creek area versus the Shute Creek area other than the observation that the Shute Creek samples are somewhat finer grained. The petrologic data would suggest that both parts of the Opal Dune Field had a common provenance, most likely sandstones of the Bridger Formation eroded along various tributary drainages to the Green River particularly along the Ham's Fork River, Shute Creek and Craven Creek (fig. 1B; pl. 1).

STRATIGRAPHY AND CHRONOLOGY

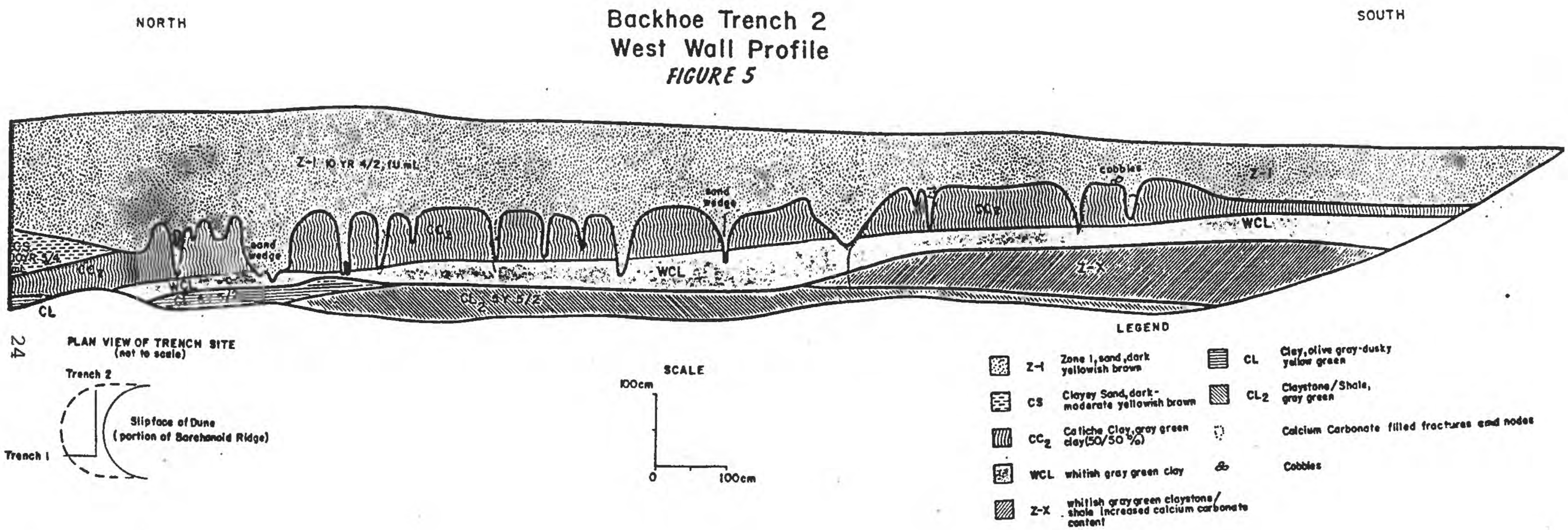
The stratigraphic successions revealed in a series of trenches in both the Shute Creek area (figs. 4-12) and the Craven Creek area (figs. 13-16) are generally comparable. The few differences will be noted as we discuss each unit. The eolian sands are highly disrupted by plant and animal bioturbation and by various cultural occupations. Several features of particular interest were: (1) sand wedges and patterned ground which may have considerable paleoclimatic significance (figs. 5-9, 14, 17, 18, and 20-24), (2) the presence of cultural material limited to the uppermost sand horizons (figs. 4-18 and 25), and (3) terrace development about 10 feet above the Shute Creek drainage; the Shute Creek area dunes occurred on this "Shute Creek Terrace." The general stratigraphic succession includes a basal gray-green clay, overlain by a yellowish-brown clayey sand, or a white colored carbonate-rich clay and sand horizon, followed by upper artifact-bearing eolian sands (commonly there are two horizons or zones).

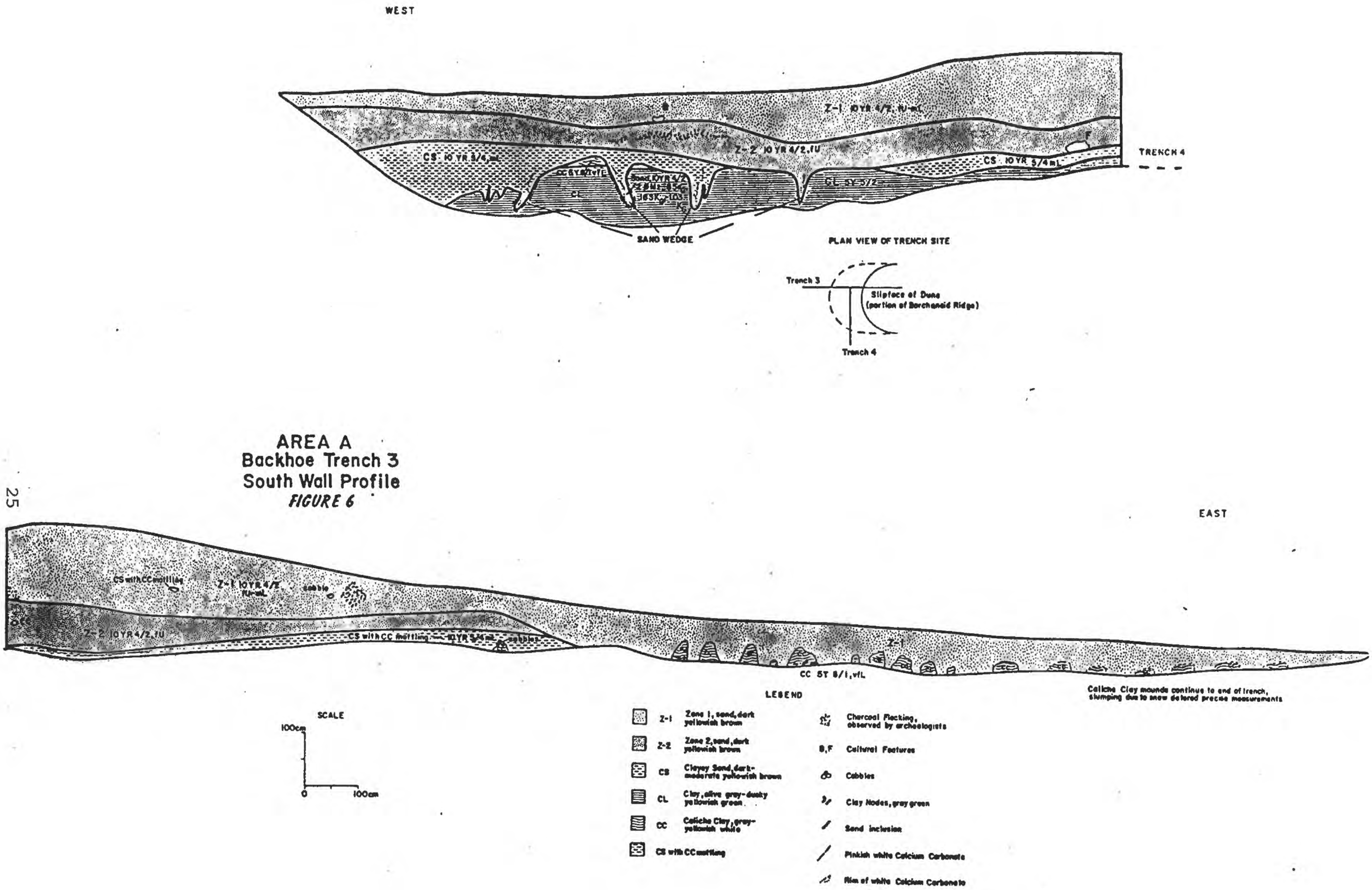
The basal unit exposed in the backhoe trenches is an olive gray to dusky yellow green (5Y4/1-5Y5/2) well sorted clay. This unit (CL) was common to the entire dune field. In some areas, this unit has a shale-like composition and in others more of a claystone texture. Sand wedges that were observed in several of the trenches extended downward from overlying horizons into this unit.

AREA A
Backhoe Trench I
North Wall Profile
FIGURE 4



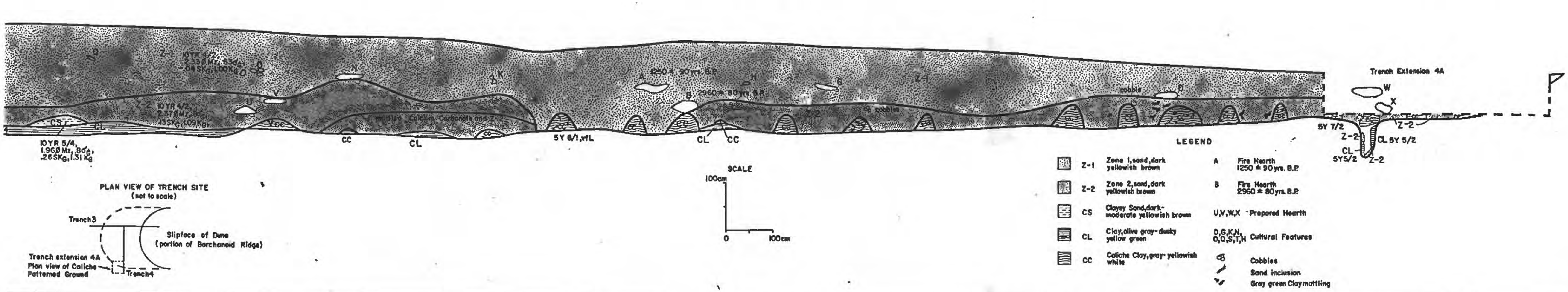
AREA A
Backhoe Trench 2
West Wall Profile
FIGURE 5





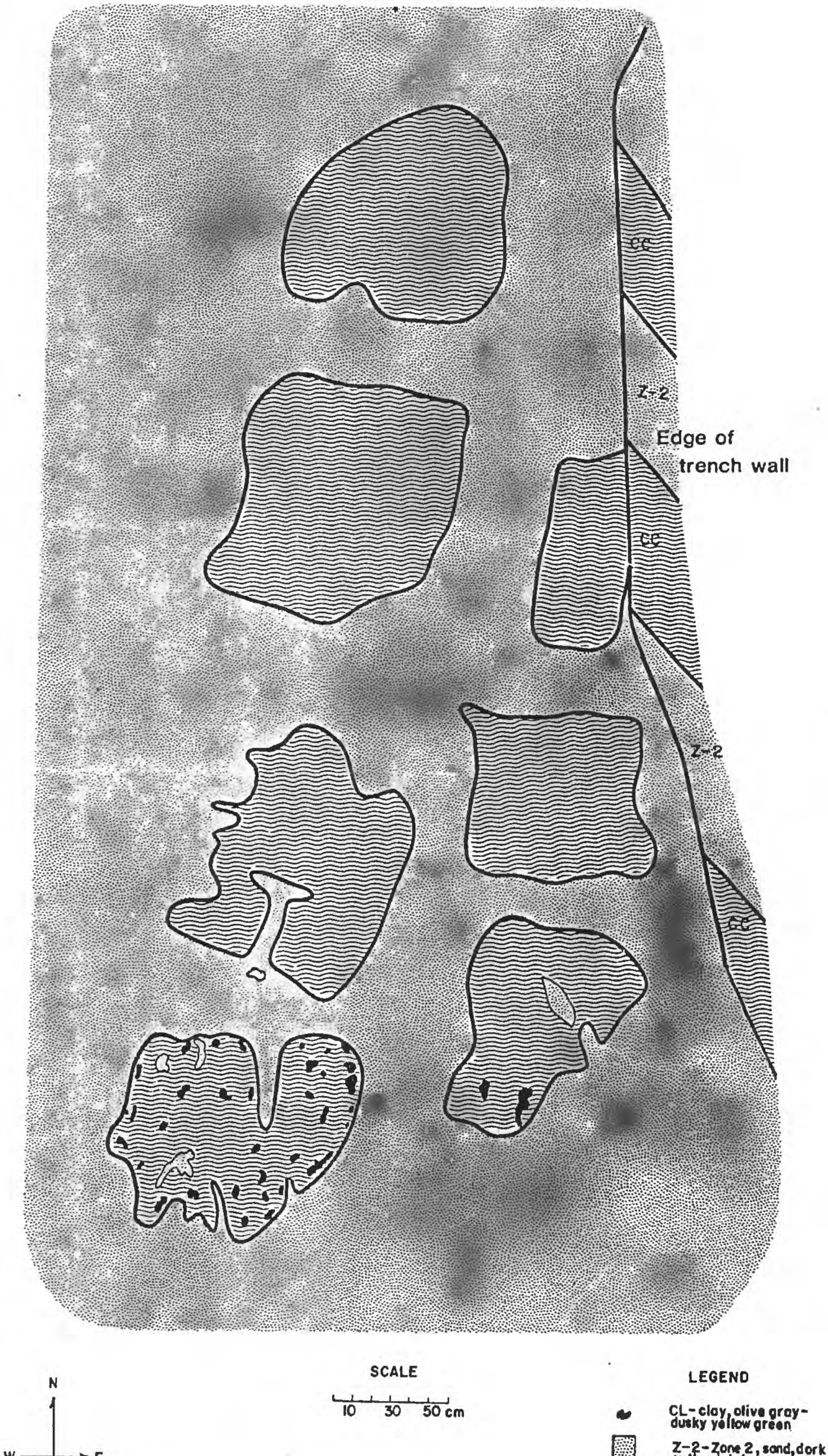
AREA A
Backhoe Trench 3
South Wall Profile
FIGURE 6

AREA A
Backhoe Trench 4
West Wall Profile
FIGURE 7



26

AREA A
Trench 4A
Patterned Ground

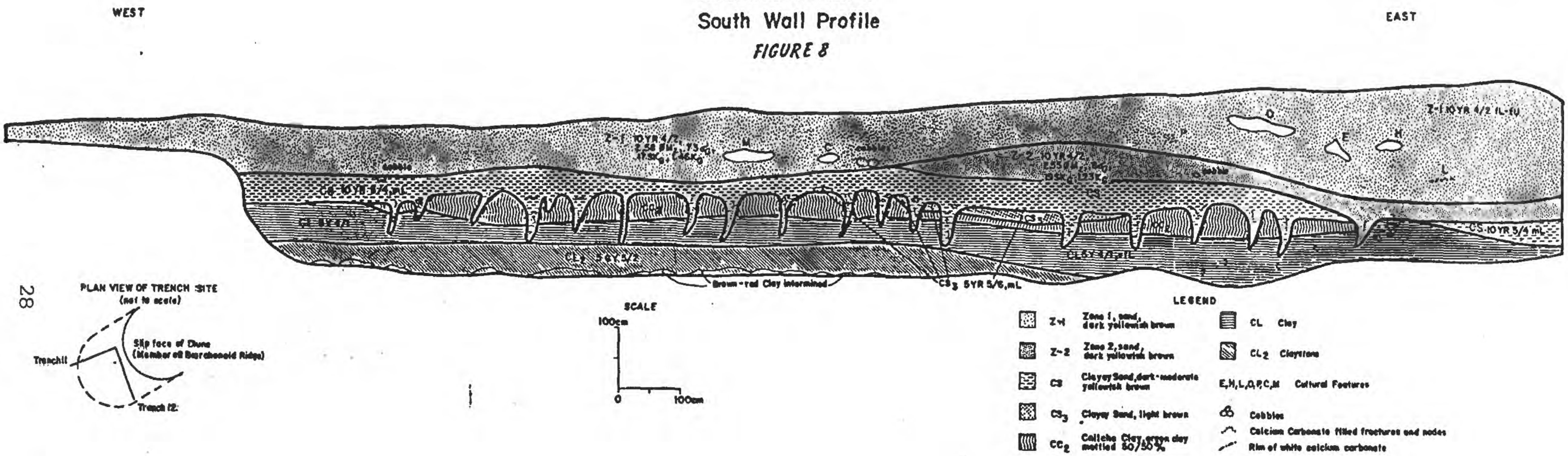


Plan View Area 20'x11', patterned ground extended throughout the trench.

Southwest corner drawn with detail, see photographs for more details.

FIGURE 7A

AREA A
Backhoe Trench II
South Wall Profile
FIGURE 8

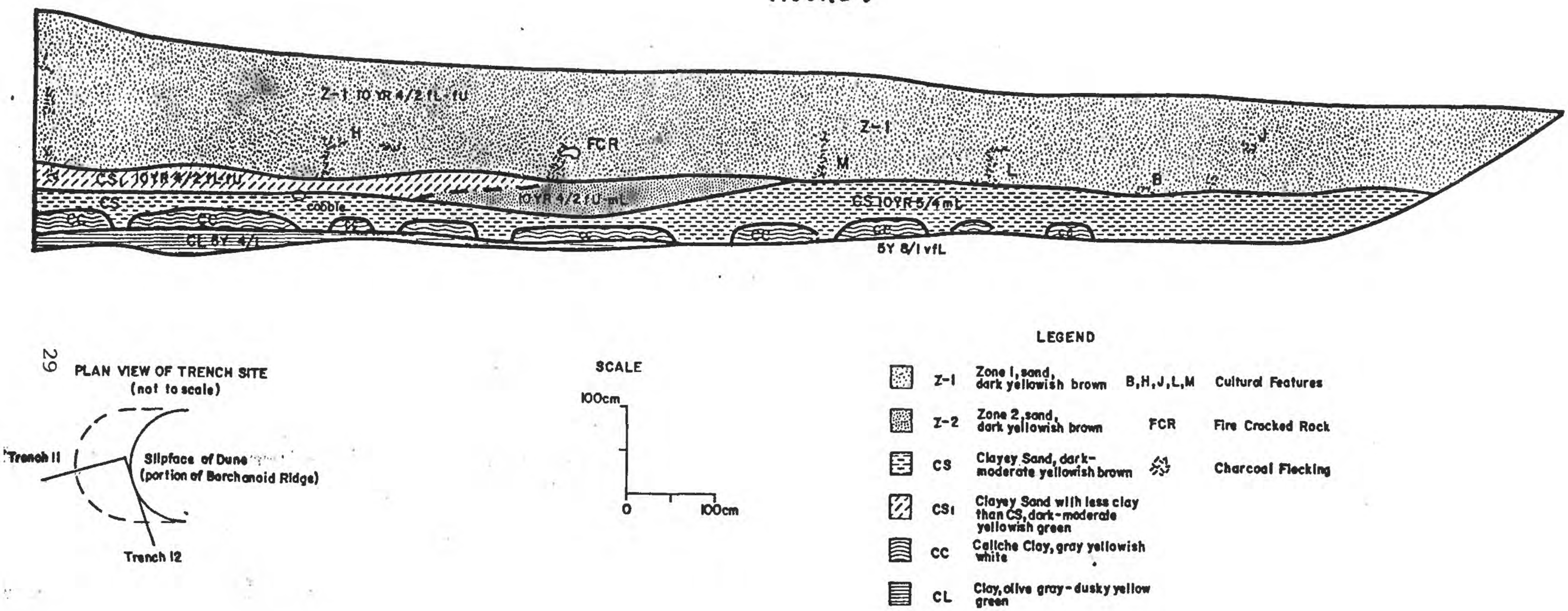


AREA A

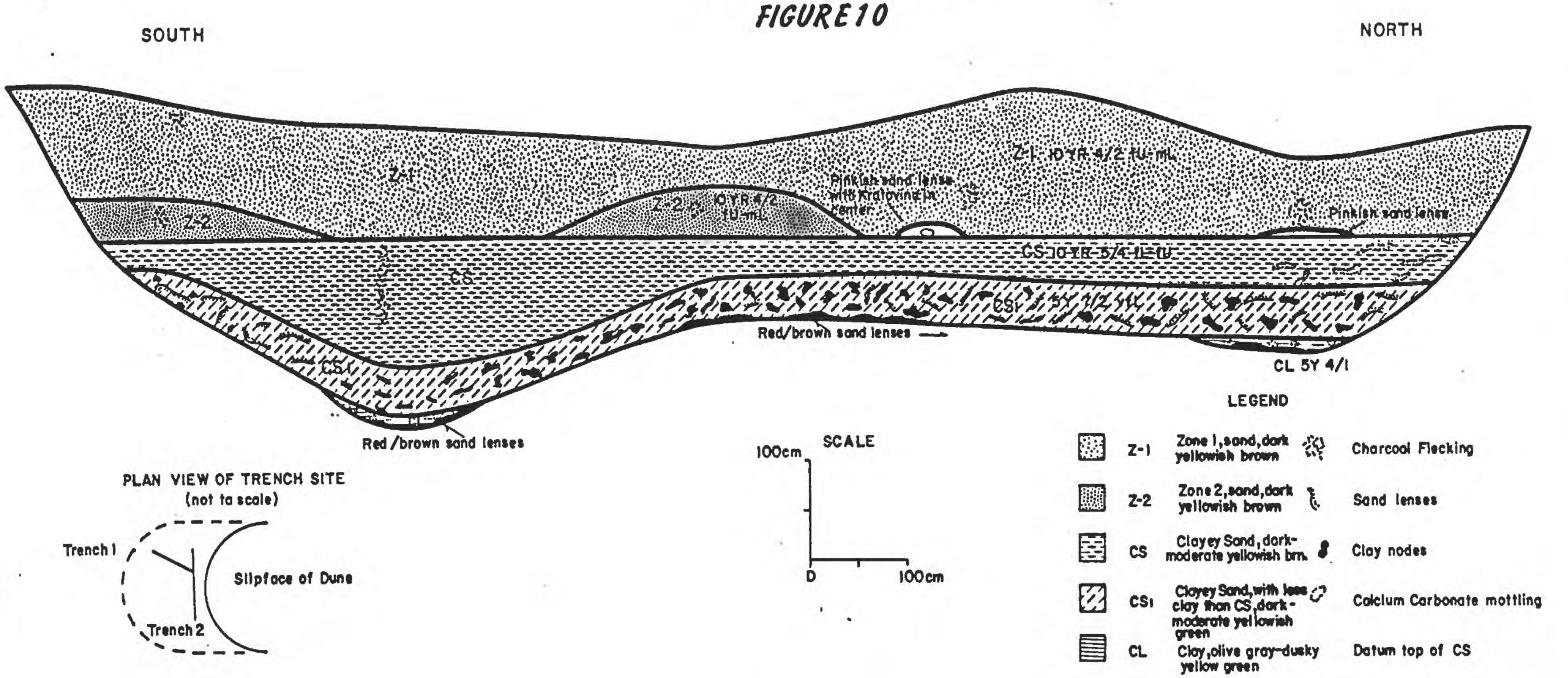
Backhoe Trench 12

East Wall Profile

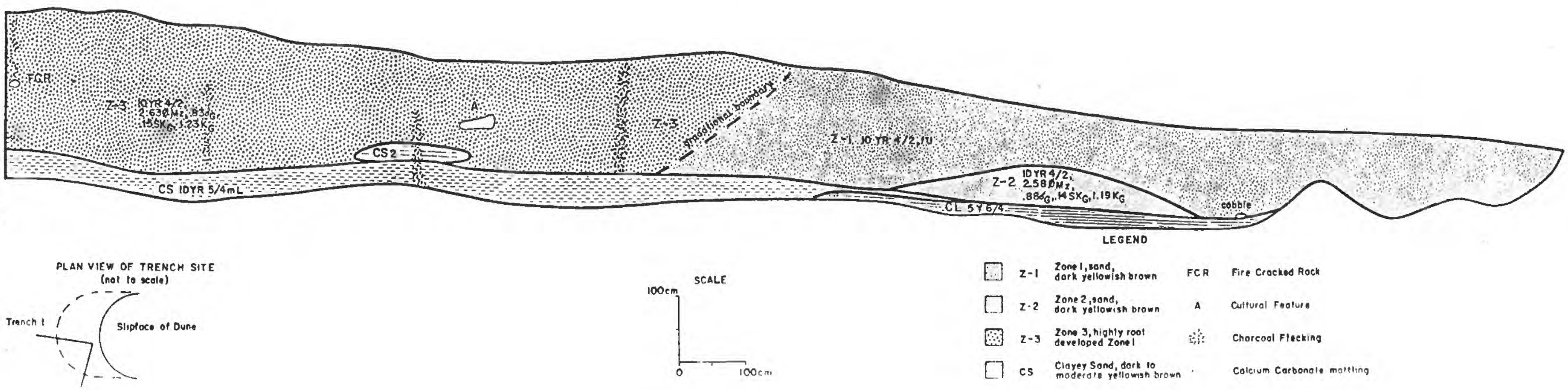
FIGURE 9



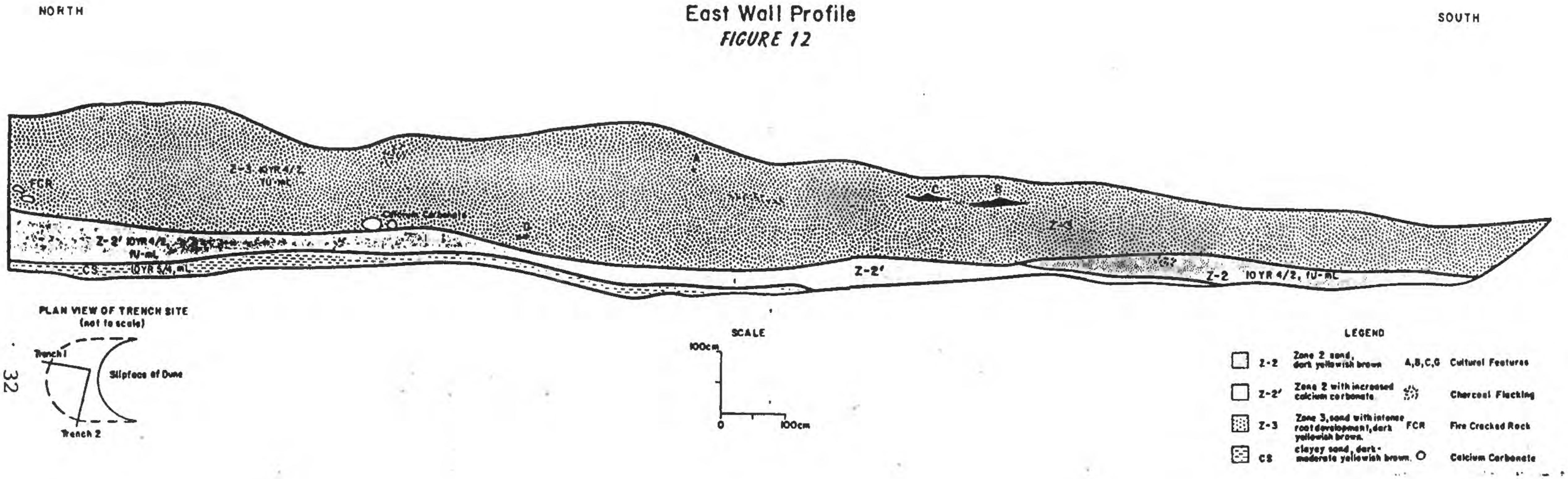
AREA G
Backhoe Trench 2
West Wall Profile
FIGURE 10



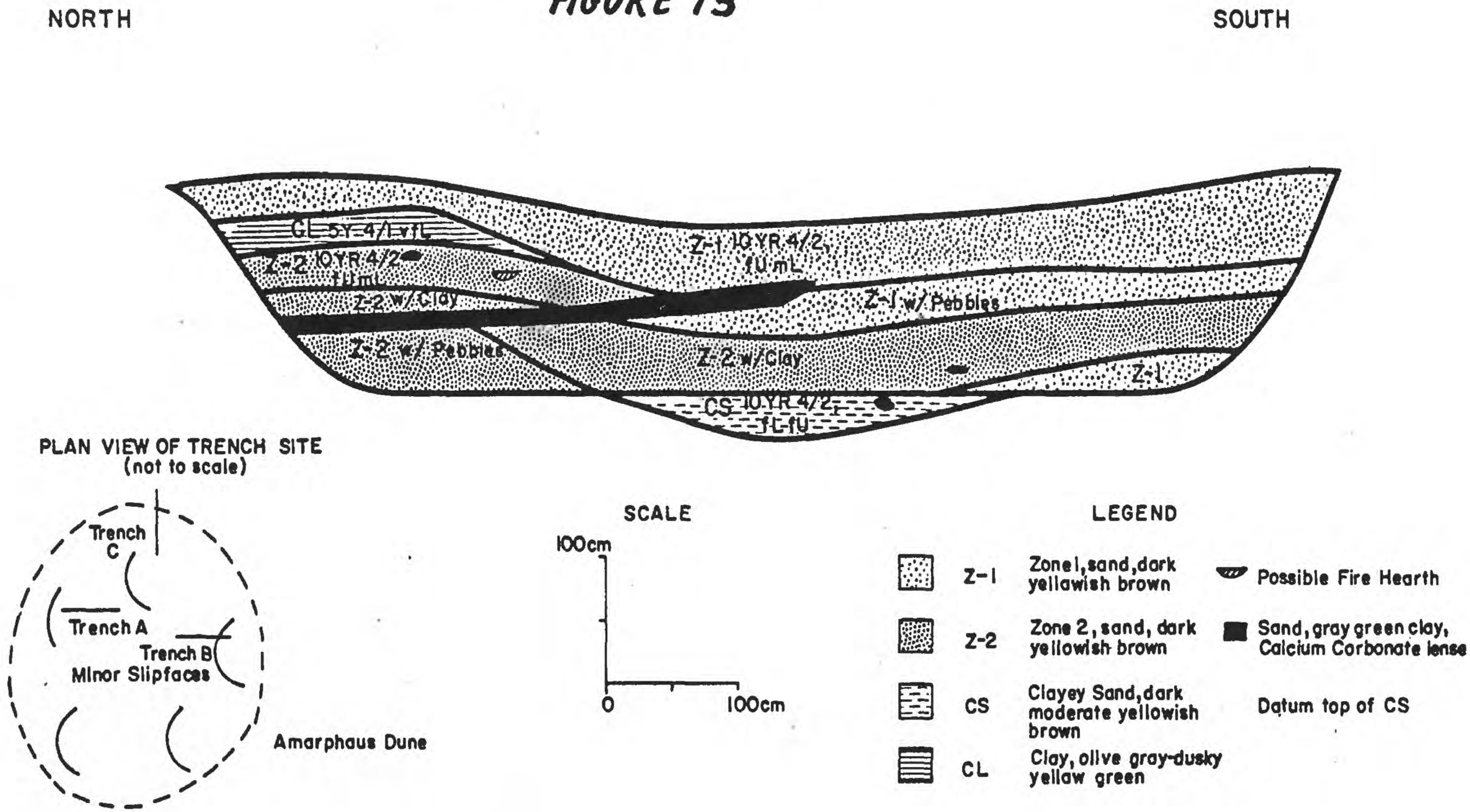
AREA I
Backhoe Trench I
South Wall Profile
FIGURE 11



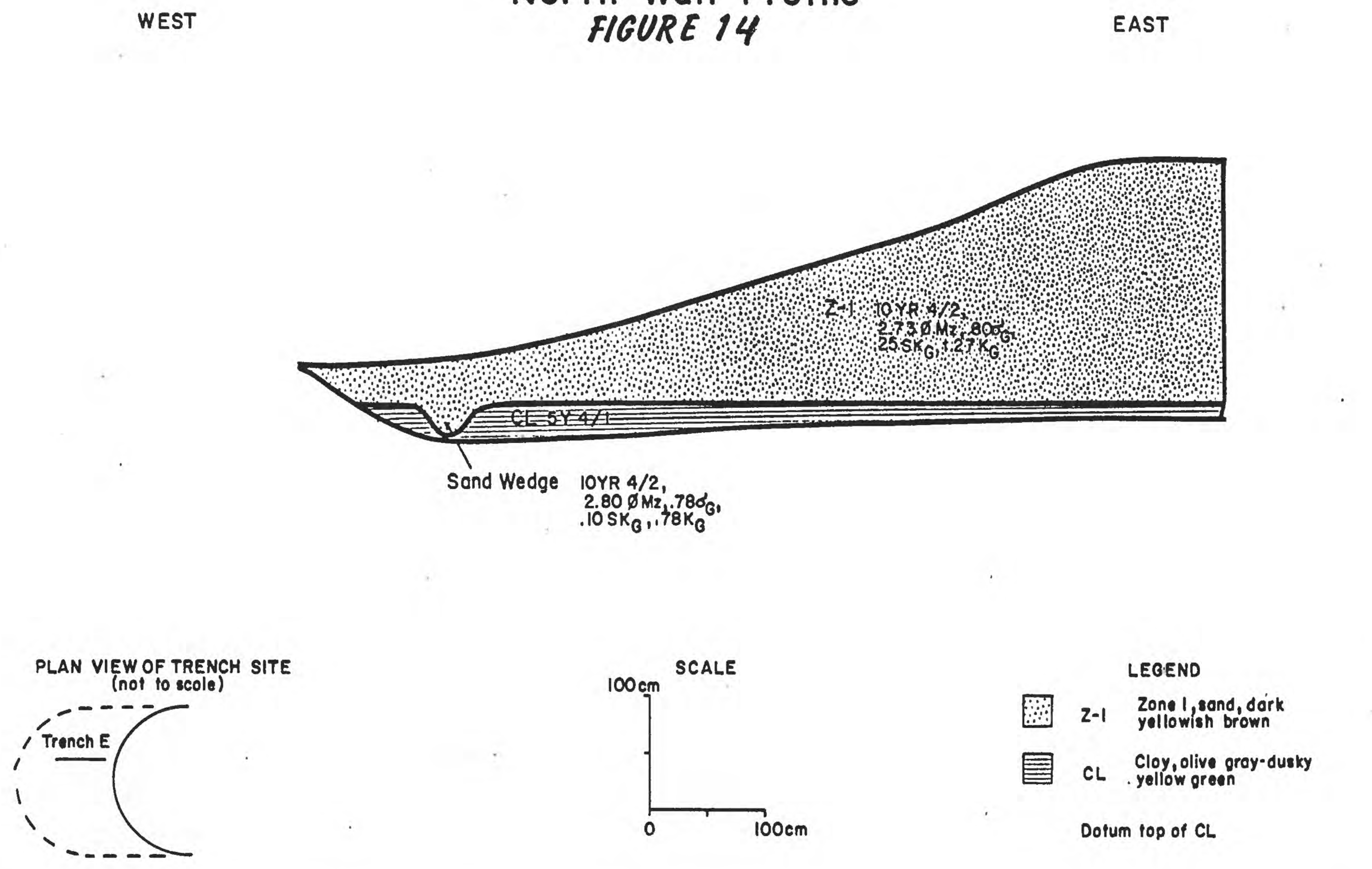
AREA I
Backhoe Trench 2
East Wall Profile
FIGURE 12



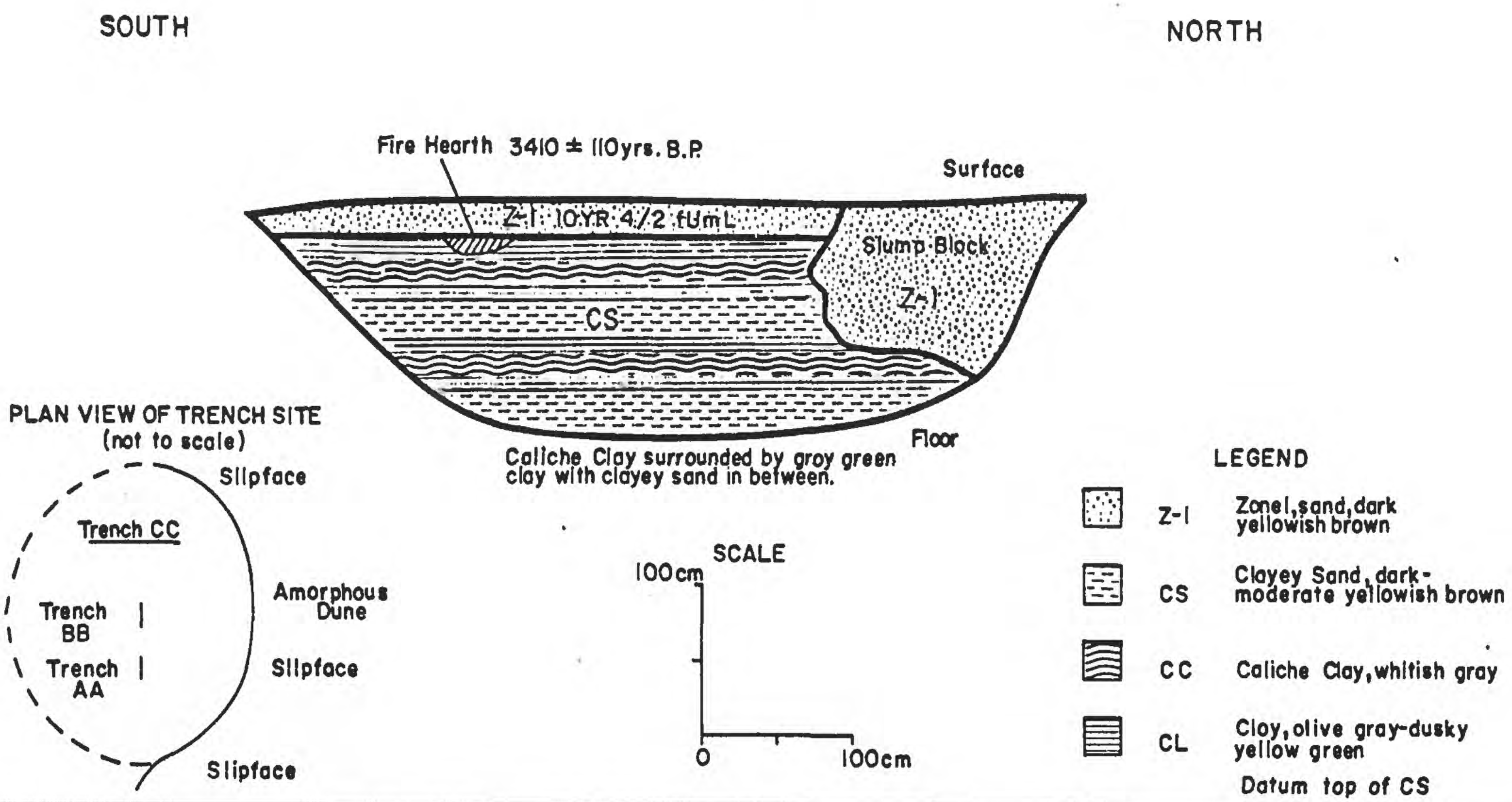
AREA 7
Backhoe Trench C
East Wall Profile
FIGURE 13



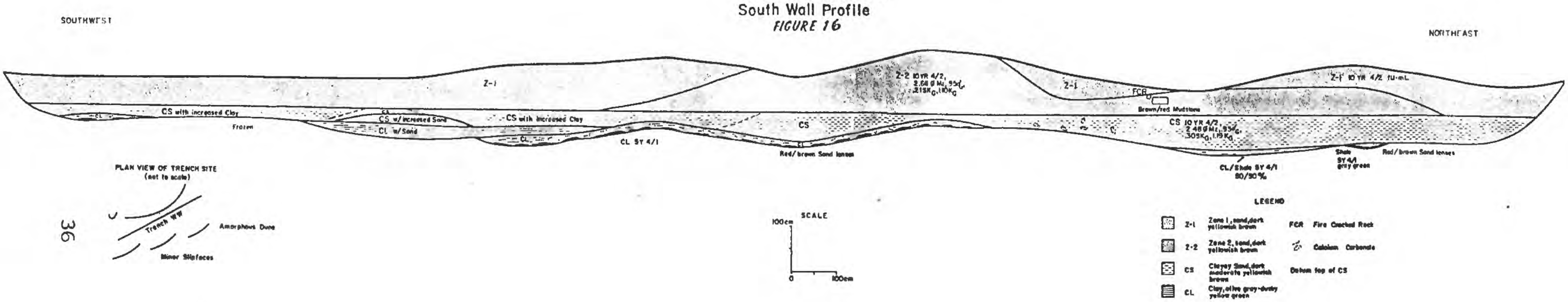
AREA 7
Backhoe Trench E
North Wall Profile
FIGURE 14



AREA 8
Backhoe Trench AAA
West Wall Profile
FIGURE 15



AREA II
Backhoe Trench WW
South Wall Profile
FIGURE 16



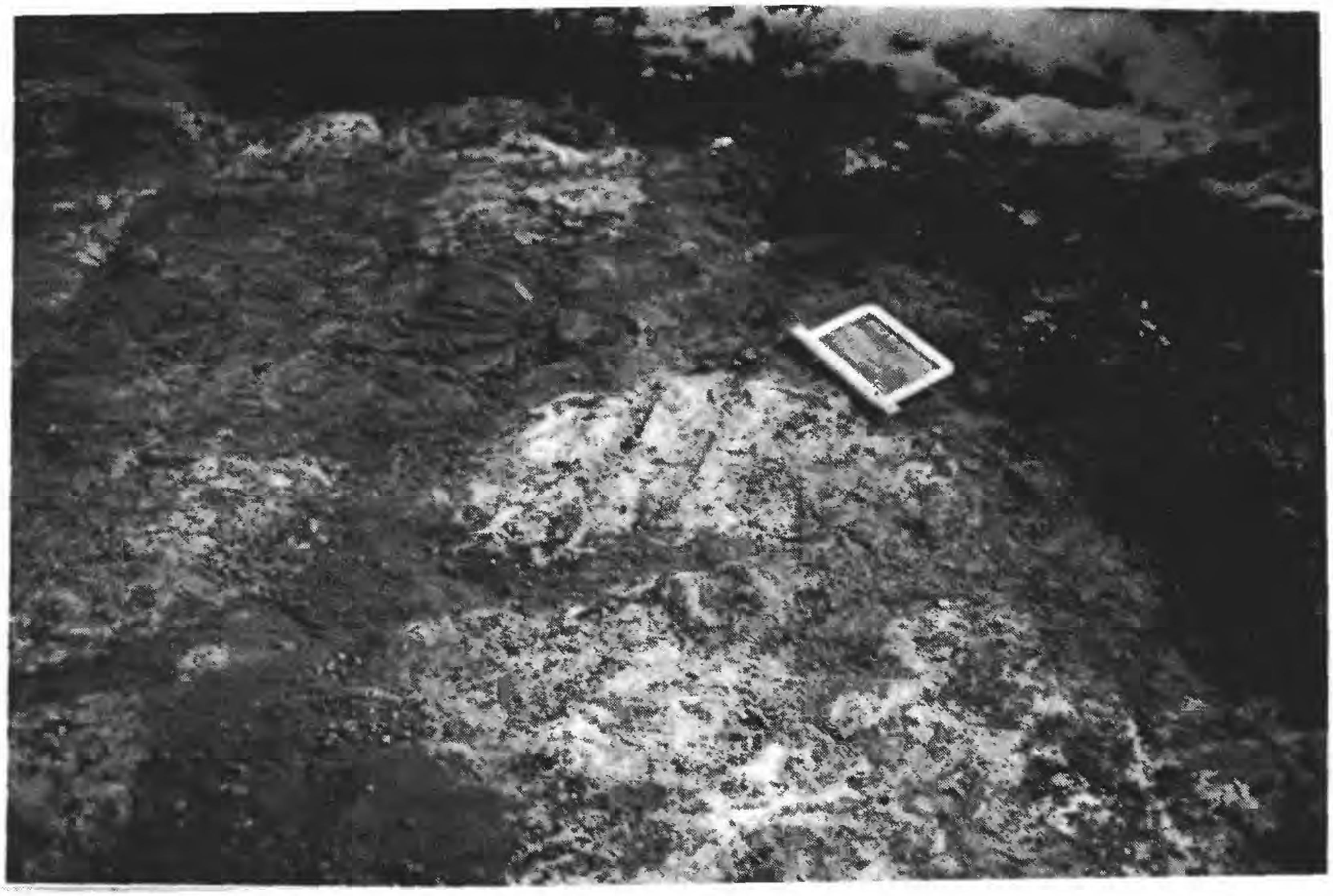


Figure 17 Plan view of patterned ground with sand wedges surrounding white caliche clay mounds. Exposed horizon is contact between the caliche clay layer and Zone 2 sand, Area A, Trench 4A, Shute Creek. Scale is 12 inches (30 cm) long.

Figure 18 Caliche clay mounds containing gray green clay nodules and sand inclusions possibly reflecting frost action. This is a closer view of the patterned ground shown in the previous figure, Area A, Trench 4A, Shute Creek.

Figure 19 Fluvial gravel lenses intercalated with eolian sand in dunes west of Opal Bench, Area 7, Trench C ,Craven Creek. Note scale in inches.

Figure 20 The lower termination, toe, of a sand wedge which is penetrating the basal gray green clay unit. The sand wedge is bordered by a calcium carbonate cemented rim., Area A, Trench 3, Shute Creek.

Figure 21 Multiple terminations, toes, of sand wedges are common. The locality shown is in Area A, Trench 11, Shute Creek.

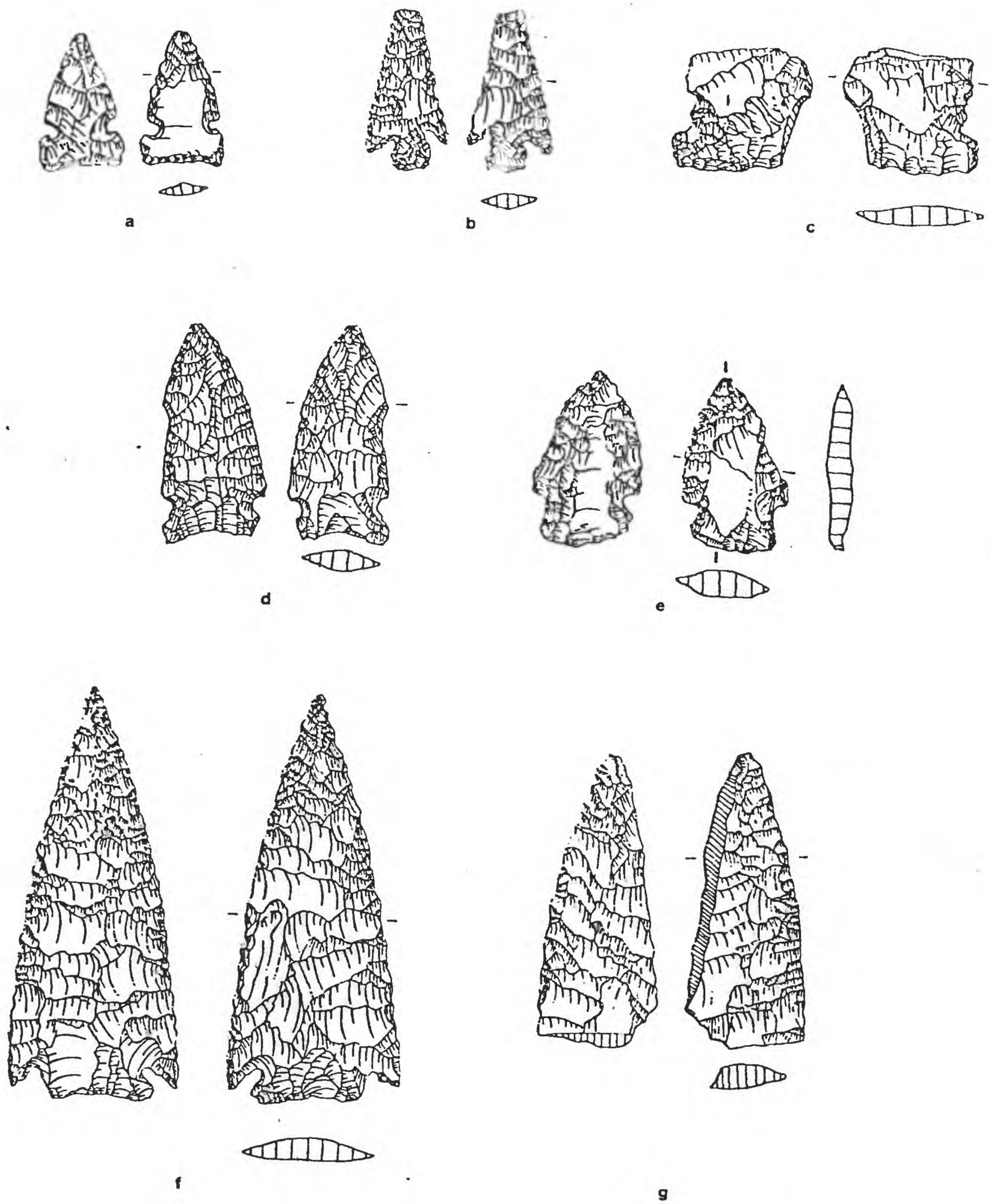
Figure 22 Distinct horizontal and vertical fractures enhanced by calcium carbonate cement are present in some sand wedges as shown in this trench of Area A, Trench 3, Shute Creek.

Figure 23 Reopening of fractures adjacent to sand wedges along a clay/sand contact after exposure to subfreezing temperatures in trenches in Area 7, Trench E, Craven Creek.

Figure 24 Reopening of fractures adjacent to sand wedges along a clay/sand contact after exposure to subfreezing temperatures in Area A, Trench 1, Shute Creek.

Figure 25 Remains of a fire hearth that was removed for radiocarbon dating. The hearth occurred above a sand wedge and caliche clay mound in Area A, Trench 4, Shute Creek. Charcoal from the hearth was C14 dated to 2,960± 80 years B.P.

Figure 26 Projectile points from archeologic investigation sites, Opal Dune Field (from WCRM, 1984).



a. Desert side notch - Late Prehistoric
b. Rose Springs - Late Prehistoric
c. Large side notch - Early Archaic
d. Oxbow - Early to Middle Archaic
e. Medium-sized corner notch - Late Archaic
f. Large corner notch - Pelican Lake or Elko
g. James Allen - Late paleo-Indian

Overlying the basal clay is a dark to moderate yellowish brown (10YR4/2-10YR5/4) sand. This sand unit (CS) was composed of fine-grained, rounded, well sorted sand which ranges in thickness from an inch to nearly 2 ft. This unit is highly bioturbated with no distinct primary structures remaining. Roots and root remnants are common, although dense root development in this unit is uncommon. Calcium carbonate and probable evaporite cementation is very common which, when present, gives this unit a mottled appearance.

Mounds of carbonate-cemented clay (CC) commonly occurring in areas between sand wedges were also found above the gray green clay layer. These mounds are yellowish gray to gray (5Y8/1) depending upon the amount of calcium carbonate present. Sand inclusions and nodes of the gray green clay were commonly present within the mounds. Contact with the overlying sand is predominantly gradational, and the overlying sand separated the mounds. A horizontal trench marginal to the distribution of the mounds displayed a patterned character in plan view (fig. 20). This horizontal trench displayed the polygonal pattern of the mounds and the varying types of sand/caliche contacts. Several of the mounds, as seen in plan view, had very distinct contacts with the sand surrounding them, whereas others demonstrated a gradational character. All of the mounds contained nodes of gray green clay within the caliche clay as well as sand lenses, some of which were up to 10-15 percent of the total area of the mound itself (fig. 21). The inclusion of green clay nodules derived from the basal green clay layer suggests a frost churning mechanism associated with the patterned ground and sand wedge development. The patterning of the mounds within the sand is not regular but was distinctly polygonal; the carbonate-cemented patterns ranging in diameter from 30 to 60 inches (2-1/2 to 5 ft, fig. 20).

Overlying these units is a dark yellowish brown (10YR4/2) well sorted, upper fine to lower medium grained, rounded sand (Zone 2). This sand unit is also highly bioturbated with root development and krotovina commonly present. No primary structures were preserved. Flecks of calcium carbonate are present throughout this unit.

A slightly less consolidated unit of dark yellowish brown (10YR4/2) sand with a gradational basal contact overlies the Zone 2 sand. This sand unit (Zone 1) is also well sorted, upper fine to lower medium grained, rounded sand, although it does not contain the discrete calcium carbonate flecks present in the unit below it. Again, this sand was highly bioturbated with no primary structures preserved. Root development and krotovina are common. This unit generally extended to the surface of the trench.

A unique unit (Zone 3) of dark yellowish brown (10YR4/2) sand characterized by extremely dense root development was observed only in Area I of the plant site (figs. 11 and 12). This zone was considered to be equivalent to a highly bioturbated Zone 1 sand. The majority of the unit consists of roots with the sand acting as a matrix. The sand is well sorted, upper fine to lower medium grained, and well rounded. The unit commonly extends to the surface and has a gradational basal contact with underlying units.

In the Craven Creek area, along the west side of the Opal Bench, the stratigraphy is very similar to that observed at the Shute Creek plant site area. The major difference is the presence of occasional lenses of gravel and inclusions of calcium carbonate that were observed only at Craven Creek sites (figs. 13, 19, and 23). These features represent erosional talus derived from the Opal Bench and adjacent buttes. Fluvial gravels may be represented in some of these lenses, and the remnants of interdunal ponds may be the contributing factor to the increased clay content in others.

Sand wedges were observed in trenches throughout the study area (figs. 5-9, 14, 17, and 20-24). These wedges extend into the gray green clay unit from the overlying sand. The sand wedges are up to 24 inches deep and ranged from inch to more than three feet in width. Smaller wedges extending beyond the main body of the wedge are common as are small wedges developing marginal to the main wedge (fig. 21). The major wedges are regularly spaced along the trench walls in the eolian sand where they are present, at an average of 3 to 5 feet. In only one instance was one sand wedge found to have developed by itself with no apparent patterning (figs. 14 and 23). In only one dune were sand wedges found in both trenches parallel and perpendicular to the slipface (fig. 6). In all other instances, only one trench in the dune contained sand wedges. The sand within these wedges appears to be uniform and is not differentiable from the overlying sand, as determined by petrographic analysis of thin sections from the sand within the wedge and sand overlying it. Faint banding is occasionally observed within the sand of some wedges. The contact between the clay and sand wedges is very sharp. Calcium carbonate rims are present around several of the wedges (fig. 20). These rims only developed within the clay unit rather than developing within the sand wedge itself. Vertical and horizontal fractures occurred within the wedges, and the fractures are filled with pinkish white material which appears to be calcium carbonate (fig. 22). Rims of this same carbonate material are also present on some of the wedges, again, being developed in the clay layer rather than within the sand (fig. 22). The backhoe that was used for the trenching was not able to penetrate through the caliche clay layer so it is not known whether sand wedges would be found beneath the caliche clay mounds. A hand-dug hole beneath the caliche clay unit went through gray green clay and sand, bottoming in gray green clay at a depth of 60 cm below the caliche mound. However, it must be stressed that the extent of the hand dug hole was not sufficient to demonstrate the continuity of a sand wedge penetrating both through the caliche clay and continuing into the lower gray green clay.

After the trenches had been exposed to subfreezing temperatures, reopening of the fractures occurred along the clay/sand contact as well as along fractures within the sand of the wedge (figs. 11 and 23). The reopenings were generally several millimeters wide and extended into the face of the clay unit as much as several centimeters. In addition, the openings extended the length of the preexisting fracture. The fractures within the sand portion of the wedge were not as predominant as those along the clay/sand contact but were distinct and demonstrated the same characteristics.

Small scale patterned ground was observed on one of the trench floors, further suggesting churning by paleo-frost action. The patterned ground involved the gray green clay and the overlying sand unit (Zone 2). A distinct polygonal pattern was present ranging in diameter from 3 to 10 centimeters. The contact between the clay and sand is distinct. Similar patterning may be present throughout the study area; however, the trench floors were not routinely faced, thus, the extent of this type of patterning is not known.

The lack of primary structures within the eolian sand throughout the Opal Dune Field may be the result of several factors. The length of time they have been stabilized, and therefore the extent to which they have been exposed to bioturbation, are major contributors to the absence of structures. The extensive amount of cultural material over the entire study area would suggest that some disruption of the primary stratigraphy also took place due to human occupation as the dunes were developing.

The cultural material, including a variety of points, hearths, bones (see table 4) generally observed in the trenches, was present in every sand unit (Zones 1, 2, and 3), but was not found in the lower non-sandy units; i.e CL, CS or CC horizons (figs. 4, 7-9, 11, 12, 13, 15, and 16). No cultural material was present within the sand wedges extending through the clay or the between caliche clay (CC) mounds. Several fire hearths as well as other cultural materials occurred directly above the caliche clay mounds, but, again, no cultural material was found within the mounds or wedges, or within the sand (CS) between the mounds (fig. 25). In the Craven Creek area, cultural material was observed in sand units beneath clay lenses, but further study is needed to understand the relation between the two.

The vast majority of cultural material throughout the field was observed in the trenches that were dug parallel to the slipfaces of the dunes. This would seem to indicate a preference for cultural occupation in the lee of the dune. The trenches that were dug along the Opal Bench in the Craven Creek area were not positioned in the same manner as those at the plant site. Many of the trenches were excavated perpendicular to the slipface of the dune and none of them were dug with both parallel and perpendicular trenches to the slipface. For this reason, not as much cultural material was observed within the Craven Creek trenches although the amount of surface cultural material was similar to that found on the plant site. The distribution and amount of cultural material found throughout the Opal Dune Field would suggest that similar types and levels of occupation occurred throughout the entire area of study.

The larger dunes within the Opal Dune Field were not trenched and those on the downwind and upwind edges of the field were also not trenched, as these areas were not within the specific areas of interest to this investigation. Varying types of cultural material may be present in these larger dunes as they may have been used and occupied in a significantly different manner than the smaller dunes which have been extensively studied. The larger dunes migrate more slowly than the smaller dunes and have a greater probability of preserving cultural material. Similar preservation of dune form and possible cultural material may also be found in falling dunes, as they are also less susceptible to erosion than small, migrating dunes.

Table 4.--Comments on Opal Dunes geologic and archaeological sites and area investigations

AREA INVESTIGATIONS

A	20 BARCHAN/BARCHANOID RIDGE DUNES (1-6M HIGH); 904,000 sq. mi; 14 trenches in seven dunes; 200 cultural features; interdune/desert pavement; up to 4 cultural components in a trench; 7 - C^{14} dates ranging from 1,030 to 5,530 yrs. BP, correlable stratigraphy of 5 units, sand wedges are common
B	3 SAND SHEETS; 224,000 sq. mi; up to 1.5 m thick; 2 trenches; 40 cultural features; abundant cultural material--mano, bones, fire-cracked rocks, cores
C	2 BARCHAN DUNES, BLOWOUT DUNES, INTERDUNAL POND; 311,000 sq. mi, 1 trench (11 manual excavations); 2 cultural components; numerous artifacts and bone fragments; tool manufacturing site
D	3 BARCHAN DUNES, BLOWOUT DUNES AND DRY/WET INTERDUNE; 267,000 sq. mi; 2 trenches; Rose Springs component; C^{14} date--1,400 yrs. BP; numerous bones-rabbit, prairie dog, bison, deer, antelope, projectile points
E	1 LARGE BARCHAN DUNE, 2 DOME DUNES, DESERT PAVEMENT; 151,000 sq. mi; 2 trenches; high concentration of lithic debitage, mano, fire rock
F	5 BARCHAN DUNES; Minor cultural activity
G	2 ISOLATED BARCHAN DUNES; 320,000 sq. mi; 2 trenches; numerous artifacts-rose springs; C^{14} date 2,055 yrs. BP
H	3 DOME DUNES; 68,000 sq. mi; 1 trench; numerous cultural remains; lithic procurement and tool manufacturing site
I	2 BARCHAN DUNES ON DESERT PAVEMENT; 135,000 sq. mi; 2 trenches; numerous mammal remains, charred seeds

SITE 48LN919 NW OF SHUTE CREEK; BARCHAN, BARCHANOID RIDGE, DOME AND SAND SHEETS; numerous artifacts; Rose Springs and reworked Agate Basin artifacts

SITE 48LN1334 FALLING DUNES; campsite and extensivwe tool manufacturing and debitage

Total area studied in detail: 194 acres, 2,583,000 sq. mi; 798 sq. mi excavated

Briefly, the cultural components found include possible Early Archaic extending back to about 5,500 years. BP, demonstrating an abundant Middle Archaic occupation (Pinto, McKean, Yonkee, Oxbow and Humboldt/Black Rock projectile points); Rose Springs points (reflecting the transition from dart to arrow points from A.D. 400 to A.D. 1100) and uncertain correlation to the Fremont peoples. The Opal dunes appear to have been occupied by Fremont people during a time when they were absent from the Great Basin. Two radiocarbon dates from Site 48LN373 (1860 and 2055 yrs. BP) occur from this supposed absence and suggest continuous occupation from Archaic population to Fremont lifeways (WCRM, 1984, p.93). The position of the Opal dunes between the Great Basin and the Plains cultures suggest possible cultural exchange or population migrations to and from the Great Basin across this area. The Numic or Shoshonean groups also occupied the Opal Dunes after about AD1400, and it is suggested that southwestern Wyoming was the locus for indigenous development of the Dismal River Apache, prior to AD 1400 and pressured to migrate eastward into their ethnographically known home in Nebraska (WCRM, 1984, p.95). It is significant to note that the artifacts of the Dismal River culture are well known in the Nebraska Sand Hills (Ahlbrandt and others, 1983).

The stratigraphy exposed within the trenches combined with the radiocarbon dates (table 1) and cultural components determined from WCRM (1984) samples indicate a tentative chronology. The lower green clay (CL) may represent either an early phase of eolian deposition (interdune) or a portion of the underlying bedrock, the Eocene Bridger Formation. The yellowish clayey sand (CS) above the green clay may reflect a poorly developed paleosol.

The overlying caliche clay (CC) which is likely a paleosol possibly a Bt (argillic) horizon engulfed by secondary $CaCO_3$ (D. R. Muhs, written commun., 1993) and sand horizon with associated patterned ground is suggestive either of Late Pleistocene sand and ice wedges or of desiccation polygons. The latter situation could reflect the remnants of a xeric period (perhaps the mid-Holocene Altithermal) of evaporation followed by cementation and then erosion of the upper surface of this horizon which was subsequently buried in post Altithermal time by sands of Zones 1, 2 and 3. The presence of mid and/or late-Holocene cultural material in only the upper sands (Zones 1, 2, and 3) and the presence of only upper sand within sand wedges that penetrate either the caliche horizon and the stratigraphically lower green clay horizon has potentially significant climatic implications.

If we incorporate the sequence of events observed in the Opal dunes with those seen at Killpecker and in other dune fields of the Rocky Mountain basins and Great Plains, both similarities and differences are seen. The Opal Dune Field suggests a depositional history extending back more than 5,500 years B.P. where dated cultural material overlies the as yet undated caliche layer and green clay layer. There is neither cultural material nor radiocarbon dates to establish the age of these older sediments. If we assume that the caliche layer represents remnants of Altithermal sand deposits and that the overlying Zones 1, 2, and 3 sands represent post-Altithermal deposition, then we can compare Opal dune deposition with other dune fields. If the caliche horizon is Altithermal, then the remaining sediments in the horizon would correspond to Ahlbrandt's (and others, 1983) Phase II of eolian deposition from 7,500 to 4,000 years B.P.) and the overlying dune sand (Zones 1, 2, and 3) would represent multiple periods of deposition during Phase III deposition (< 4,000 to 500 years B.P.).

If the hypothesized chronology suggested above for the Opal dunes is correct, then the Opal dunes reflect a significantly different occupational history, cultural usage and eolian activity compared to the Killpecker dunes or the Ferris dunes; the downwind extension of the Killpecker dunes. The larger dunes, up to 150 feet high, at Killpecker (relative to the Opal dunes) were used as natural corrals and were effective kill sites (Ahlbrandt, 1974). The Opal dunes are too small, too widely scattered and apparently not in existence in the early Holocene to be used for trapping purposes of these early Holocene fauna. Our interpretation of the WCRM (1984) archeologic investigations suggest that the dunes were essentially used as campsites with rather intense occupation since the Altithermal. The apparent minor amount of dune migration since 5,500 years B.P. to present suggests a favorable site to camp, dunes being more comfortable to camp on than the adjacent desert pavement in the interdune areas.

The absence of Paleo-Indian artifacts in all trenches excavated is markedly different from cultural occupation observed at Killpecker, specifically at the Finley site (Ahlbrandt, 1974b). This absence of artifacts at the Opal dunes during the early Holocene, Phase 1 of Ahlbrandt (and others, 1983) may be the result of either a difference in age of the dunes, differences in the times of occupation, or lack of preservation due to migration of small bedforms. The Ferris dunes demonstrate two relatively short phases of eolian activity from 8,800-8,100 and 4,300 to 4,000 years B.P. with numerous wetter periods, at least nine interdune pluvial periods as recently demonstrated by Stokes and Gaylord (1993). The Opal dunes demonstrate a quite different chronology. Referring to the active eolian phases of Ahlbrandt (and others, 1983), the Opal dunes were active in late Phases II and III, but were essentially continuously occupied. The Killpecker dunes were active in all four phases with intermittent cultural occupation. The Ferris dunes seem to have more and longer wet phases and were active in early Phase II and late Phase III. The numerous interdunes, i.e. wet phases between 8,000 and 4,300 years in the Ferris dunes (Stokes and Gaylord, 1993) in part supports a less xeric environment in this part of Wyoming during the mid-Holocene. The relatively continuous occupation of the Opal dunes from about 5,500 years to about 1,000 years B.P. would further support such an interpretation. Clearly, more information from other eolian studies in Wyoming will help to further refine the chronology of eolian events in Wyoming. The Opal dune chronology further show a very intense xeric period prior to 5,500 years B.P. not matched in stratigraphically younger sediments.

PALEOECOLOGIC IMPLICATIONS

At this point, paleo-Indian occupation of the Opal dunes is not documented, which is interesting in light of their known occupation of the Killpecker dunes which occur thirty miles east of the Opal dunes and east of the Green River drainage. There may be several explanations for this apparent absence of paleo-Indian sites: (1) the dunes are too young, i.e. they were not present in the Early Holocene; (2) the dunes migrated sufficiently in the Mid Holocene to remove Early Holocene artifacts from the interior of the dune leaving them upwind on the desert pavement; (3) Paleo-Indians did not choose to occupy Early Holocene dunes in this region, or (4) we have not excavated in areas likely to preserve Paleo-Indian artifacts.

Because the Opal Dunes have little interdune sediment, (.i.e. basically deflated interdunes with a resulting desert pavement occurring between interdunes) interdune areas are generally not favorable for in situ preservation of cultural material. Paleo-Indian archeologic sites would be more likely preserved in areas of more continuous deposition such as upwind sand sheets or areas where dune migration was minimized. Dune migration rates are reduced as dune size increases and/or where obstructed by topographic barriers (i.e. the lee of a cliff or in front of a hill assuming that the site was suitable for occupation and was not deflated) (Fryberger and Ahlbrandt, 1979). The small size of the Opal dunes would permit them to migrate rapidly during a very active dune phase, which would be detrimental to the preservation of early cultural material within such a dune. This assumes episodic reactivation since the Early Holocene which appears to be probable judging from multiple occupation levels.

Paleoclimatic conditions can be inferred from the time and mechanism of formation of the sand wedges and patterned ground observed in the trenches. The sand wedges and patterned ground could reflect either a periglacial climate (i.e. late Pleistocene) or intense desiccation (i.e. mid Holocene-Altithermal). As shown in figures 4, 6, 7, 7A, and 18, green clay nodules and blebs from the basal stratigraphic horizon are incorporated in higher stratigraphic horizons which are found several centimeters above the green clay layer. Frost heaving and frost churning are known to cause upturning of sediment adjacent to wedges forcing basal layers upward in the wedge due to periodic expansion of the ice within the wedge. A mechanism to permit forceful upward injection of material in a desiccation related wedge is not apparent to us. The wide spacing of the sand wedges and their dimensions (as previously discussed) resemble Late Pleistocene periglacial sand wedges described by Mears (1981) which are known to occur at many localities in Wyoming. We reviewed these sand wedges with Brainerd Mears. In Mear's (1987, p. 73-74) study, he refers to the Opal sand wedges and associated patterned ground, but concludes that they are of uncertain origin; i.e. having characteristics of both desiccation and periglacial wedges. Mears (1987) considered these wedges separately in his paper from those with more characteristic periglacial features including upturning of laminae adjacent to a wedge. In a subsequent paper, Nissan and Mears (1990), further refined criteria for periglacial sand wedge fills and noted that conchoidally fractured particles characterize periglacial wedge fills. They noted sand-wedges in a pipeline trench exposure along the southern margin of the Killpecker dune field. The wedge fill mantle and wedge fill show conchoidally fractured particles; this sequence is also overlain by eolian sand which does not show such conchoidal fracturing of grains. Nissan and Mears's (1990) observations supported the interpretation of Ahlbrandt and others (1983) that Wyoming wedge fills are derived from eolian sand sheets similar to those described in Pleistocene deposits of northern Europe by Ruegg (1983) wherein periglacial conditions restricted the migration of sand. Nissan and Mears (1990) conclude that "the interpretation of Ahlbrandt and others (1983) fits our concept that the conchoidally fractured quartz grains in Wyoming wedge-fills are products of in situ periglacial (i.e. cryogenic) weathering at the microscopic level." Applying this same criterion of conchoidal fracturing of periglacial affected sand, we conclude that the absence of such grain fractures on the sand grains in the Opal wedges implies that the Opal sands were not subjected to a periglacial climate. Also, the spacing and depth of the Opal sand wedges were somewhat smaller scale than the periglacial wedges that Mears (1987) describes elsewhere in Wyoming. Thus, the absence of early Holocene or Pleistocene C^{14} dated material, the dated Holocene charcoal above a wedge, the absence of Paleo-Indian artifacts and abundance of Middle Archaic (Mid-Holocene) artifacts and the associated caliche mounds argue for a desiccation origin for the Opal sand wedges. The origin may not be simply a desiccation mechanism, however, since a cold climate mechanism is also directly indicated for these wedges due to the reopening of the fractures within the wedges when the sediments within the trenches were exposed to subfreezing temperatures (figs. 23 and 24), and the dune field is in a region subjected to an extensive cold winter season. The presence of Pleistocene sand wedges in the Killpecker area, but separated from the dune sand, suggests a different depositional history there compared to that at the Opal dunes. Clearly, sediments affected by both cold climates and warm climates are represented in these two dune fields. The presence of Mid-Holocene sand wedges argue for an intense period of aridity and sand movement in the Mid-Holocene in the Opal dunes.

The archeologic data at the Opal dunes reflect a new and different view of Holocene environments relative to other dune fields in the region. We refer the reader to a much more comprehensive discussion contained in the WCRM (1984) report. Some preliminary archeologic observations are: (1) the Opal dunes address the two drought Altithermal hypothesis--the early Archaic transition usage of floral resources and small mammals which is the earliest Opal occupation may reflect a mesic interlude in the Altithermal; (2) The Middle Archaic occupation is substantial with artifact types transitioning from dart to arrow points; this transition is heralded by the Rose Springs arrow points in the Great Basin, but there is a much more homogeneous transition at Opal than elsewhere; (3) southwest Wyoming was a locus for indigenous development of the Dismal River Apache prior to 1400A.D. suggesting that the Fremont and Dismal River cultures are related based upon similar climatic and cultural adaptations; and (4) southwest Wyoming was occupied at a time when the Great Basin appears to have been abandoned by Fremont cultures. The cultural links to Plains cultures appear and suggest climatic continuity across more than a 1,000 mile area from eastern Nebraska to western Wyoming and into the Great Basin where eolian activity was prominent in the Late Holocene. New evidence by Forman and others (1992) and Madole (1992) demonstrate significant Late Holocene eolian activity on the eastern Plains of Colorado which is also coincident with Ahlbrandt's and others (1983) Phase III. Evidence from the Opal dunes and these recent studies suggests that the Late Holocene was a major, regional arid interval during which the extent of eolian sand movement may have at least been on a par with the Mid-Holocene, Phase III eolian activity.

CONCLUSIONS

The Opal Dune Field is unique in many ways. Some of the salient features of the Opal Dune Field are as follows: (1) dune forms are inactive but external morphology is well preserved and stabilized by both primary and secondary plant communities; (2) primary internal structures are obliterated even though the dunes are of Holocene age in a semi-arid to arid setting; (3) the eolian deposits are composed of texturally and mineralogically immature litharenitic (particularly volcanic rock fragments) sand; (4) a variety of eolian subenvironments are represented including dome, transverse, barchan, parabolic, shrub-coppice, and hanging dunes, dry and wet interdune deposits and abundant deflation lags; (5) sand-wedges commonly occur at the base of the eolian sand extending into substrate as evidenced in most dune trenches reflecting intense climatic changes; (6) there has been significant human occupation of the Opal Dunes since the Mid-Holocene reflecting a somewhat different climatic history for the Mid-Holocene than for other Rocky Mountain dune fields; (7) there are no Paleo-Indian artifacts, C^{14} or sedimentologic evidence of an early Holocene dune field which contrasts markedly with the nearby Killpecker Dune Field; and (8) there are important cultural linkages of the Opal Dune Field with Holocene Indian cultures in the Nebraska Sand Hills and the Great Basin.

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