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In 1991, the Soil Landscape Climate Program (SLCP) was organized as part of the Solid Earth Sciences Program at NASA. Part of the research to be conducted in the SLCP included studies of the systematics of carbon storage and flux in the terrestrial environment, specifically terrestrial soils. This report summarizes the results of the research funded through the SLCP that supported our efforts focussed on the nature of carbon behavior in arid environments, where the majority of the carbon is present as inorganic carbon stored as pedogenic carbonate in desert calcic soils. The funding was used to support studies of soils in two areas of western North America's major deserts: the Mojave Desert and the Chihuahuan Desert. Part 1 of this report summarizes the results of research conducted in the area of the Providence Mountains, California in the eastern Mojave Desert, part of which was also supported through a grant from the National Science Foundation. The bulk of this research effort forms the body of a doctoral study conducted under my advisement by Eric V. McDonald.
Part 2 of this report summarized the results of research in the Sevilleta Wildlife Refuge in central New Mexico, site of one of the UNM Biology Department's NSF-funded Long Term Ecological Research. The bulk this research forms the body of a doctoral study conducted under my advisement by Carol J. Treadwell. I believe that these research efforts have resulted in important new ideas regarding the factors influencing the rates, processes and magnitude of accumulation of carbon in desert soils, which occupy much of the area of arid regions of the world.

(NASA-CR-196820) [FACTORS INFLUENCING THE RATES, PROCESSES AND MAGNITUDE OF ACCUMULATION OF CARBON IN DESERT SOILS] (New Mexico Univ.) 30 p

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Part 1: Relationships Between Soil Hydrology/Soil-Geomorphic Processes and Environmental Changes and Soil Parent Materials in the Providence Mountains, Mojave Desert

TECHNICAL DESCRIPTION OF PROJECT AND RESULTS

Introduction

From 1 January, 1992 to 31 December, 1993 a project was conducted under the direction Of Dr. Leslie McFadden of the University of New Mexico to determine the relative influences of climatic change, desert dust, and lithology on soil hydrology and soil-geomorphic processes in the desert environment of the Eastern Mojave Desert, California. Eric McDonald served as principal assistant scientist and conducted research associated with this project for his Ph.D. dissertation.

Our purpose in this project has been to isolate and study some of the key variables controlling the formation of soils and the modification of geomorphic surfaces in arid and semi-arid environments. Soil-landscape relationships are widely used to provide fundamental stratigraphic and age information for Quaternary deposits in desert environments for studying neotectonics, surficial processes, paleoclimatology, archeology, stratigraphy, and environmental science. Many studies have shown, however, that processes controlling soil development and landscape modification in desert environments are extremely susceptible to the 1) effects of climate change, 2) the accumulation of fine-grained eolian sediment (dust), which in turn, is indirectly related to climate change, and 3) the influence of lithology on soil-geomorphic processes. The influence of these variables on soil-geomorphic processes have not been integrated into one comprehensive study that addresses both the individual affects, as well as the combined effects, on the origin and development of soils and desert landforms. Several key attributes of the study area that was the focus of this research project provided an unprecedented opportunity to evaluate and directly compare how climate change, the accumulation of desert dust, and lithology control processes of soil-development and landscape modification: 1) a well-defined record of Holocene and Late Pleistocene paleoclimatic and eolian activity in the Mojave Desert, 2) established Quaternary stratigraphy for alluvial fans along nearby mountain piedmonts, and 3) is the juxtaposition of four lithologically different sequences of Holocene and Pleistocene alluvial fan deposits along the same mountain piedmont.

Some of the key questions we have addresses in the conduct of this work are: 1) what are the ages of Quaternary deposits along the Providence Mountain piedmont and what are the local and regional stratigraphic relationships between these deposits and others within the region?, 2) how does soil formation and the development of desert pavements vary among different lithologies?, and 3) how do spatial and temporal changes in the accumulation of dust, climate, soil-water balance, and surface permeability influence soil-geomorphic processes on alluvial fans, especially the development of calcic soils?

PRELIMINARY DATA AND RESULTS

Quaternary Stratigraphy of Alluvial Fans in the Providence Mountains

An important first step in this project was the comprehensive and detailed mapping of Quaternary depositional units along the Providence Mountains. Seven major alluvial fan units and three eolian units were defined based on relative degrees of development of soils and desert pavements, stratigraphic relationships, and topographic position of depositional units (Table 1, Figure 1, 2). We defined four separate fan sequences based upon the dominant lithologies that make up the deposits in each sequence: 1) *PM*: leucocratic to mesocratic mixed-plutonic rocks (mostly syenite and quartz monzonite), 2) *QM*: quartz monzonite, 3) *VX*: volcanic-mixed (mostly rhyolitic tuff and rhyodacite with secondary amounts of mixed plutonic and carbonate lithologies), and 4) *LS*: limestone and marble (with small amounts of volcanics).

Preliminary age estimates and regional stratigraphic correlations of Quaternary alluvial deposits are based on 1) infra-red stimulated luminescence (IRSL) ages from the study area for dune sheets interstratified with distal fan units, 2) identification of the 0.74 Ma Bishop Tuff near the base of the oldest fan unit., 3) preliminary radiocarbon age estimates of pedogenic carbonate, and 4) soil-stratigraphic correlations to nearby, relatively well dated chronosequences in the Cima Volcanic Field and Soda Mountain areas (McDonald and McFadden, 1994).

IRSL: In March of 1992, Dr. Ann Wintle, Dr. Michelle Clarke, Dr. Nick Lancaster, and Eric McDonald collected 5 IRSL samples from eolian sand units that stratigraphically bracket four of the alluvial fan units. IRSL results provide that first age estimates for the Providence Mountain alluvial fans and were instrumental in determining the approximate ages of the latest Pleistocene and Late Holocene fan units and in confirming regional stratigraphic correlations to nearby areas of relatively well-dated alluvial fans (Clarke, 1994; McDonald and McFadden, 1994). Additional IRSL samples have since been collected in the Providence Mountains by Dr. Clarke and Dr. Wintle as part of their ongoing efforts to develop IRSL dating techniques of alluvial and eolian sediments in desert environments.

^{14}C dating of Pedogenic Carbonates: An important part of this study was collaboration with the ongoing work of Dr. Amundson to develop and test methods of radiocarbon dating of pedogenic carbonates. In June, 1992, Dr. Ron Amundson and Eric McDonald collected pedogenic carbonate samples from four soils developed on the PM fan sequence and four soils from the LS sequence. Dr. Wang has been working with Dr. Amundson in developing a diffusion/reaction model which takes into account various processes and factors controlling the ^{14}C content of soil carbonate (Amundson et al., 199_; Wang et al., 199_). Discrepencies between age estimates derived locally by IRSL and regionally based on soil-correlations with units dated with conventional ^{14}C techniques (Fig. 2) reflect the complicated systematics between the flux of soil CO_2 and organic matter in soil environments and the initial ^{14}C content in soil carbonates. Although the initial attempts to use ^{14}C were not entirely successful, the combination of 1) a geochronologic framework for the Providence Mountains alluvial fans and 2) the ongoing effort to understand the influence of environmental factors (i.e. climate, vegetation, soil-water balance) on the development of pedogenic carbonate will provide a solid scientific platform from which to continue evaluating the soil-carbonate-^{14}C system in calcic soils.

In summary, regional correlations among alluvial fan deposits in the eastern Mojave Desert strongly supports the concept that periods of fan aggradation primarily occur in response to time-transgressive changes in climate. The juxtaposition of four lithologically distinct chronosequences in the Providence Mountains provides an excellent opportunity to directly compare rates and processes of soil formation and modification of fan surfaces in different parent materials. A manuscript is in preparation that will set forth a Quaternary stratigraphic sequence of alluvial fan deposits based on comparisons among soils and desert pavements formed on alluvial fan derived from different lithologies (McDonald et al., 199_b). Such information will greatly facilitate local and regional correlations among fans derived from dissimilar lithologies and the development of a regional stratigraphic framework for further evaluation and testing of the regional impacts of climate change and the deposition of alluvial fans.

The Influence of Desert Dust and Lithology on the Origin and Evolution of Soils and Desert Pavements

Soil-Chronosequence Studies: Over 80 soil profiles were examined in the field of which 65 soils were described in detail and sampled for laboratory analysis. Soils were described for stratigraphic units Qf2 through Qf8 for each of the four fan-sequences. This large number of studied soil profiles provides one of the most comprehensive soil data sets for examining spatial, temporal, and lithologic variation among soils in one study area and provides a solid foundation for detailed evaluation of the physiochemical processes involved with soils and soil formation in desert environments. General attributes of each soil chronosequence are shown in Table 1.

Soil-Geochemical Characterization: Standard laboratory analyses of: particle-size distribution, calcium carbonate contents, pH, bulk density, and measurement of dithionite- and oxalate-extractable iron oxyhyroxides have been completed on many of the sampled soils. In addition, X-ray diffraction of soil clays and X-ray florescence has been completed on selected soils, totaling 47 soil horizons. We are currently in the processes of evaluating the tremendous volume of laboratory soil-characterization data. Data will be summarized and published a parts of several publications that are currently in preparation.

Modification of Alluvial fans and Formation of Desert Pavements: We examined the origin and development of desert pavements and associated changes in the surface morphology of alluvial fans using data from surface-transect measurements of features associated with desert pavements and development of underlying Av horizons (i.e. clasts size, clasts color, degree of development of rock varnish, packing and smoothing of pavement clasts, Av horizon thickness). Data was collected from over 100 25 meter transects across fan surfaces.

Results indicate that a strong correlation exists between pavement development and the accumulation of eolian fines below pavement stones and within soils developing on alluvial fan surfaces. Temporal relationships among the fan chronosequences show that there is a strong systematic trend between increases in the quality of the desert pavement and increases in the thickness of underlying Av horizons (Figs. 3, 4). These results prove the hypotheses regarding the accumulation of dust and development of desert pavements on basalt flows first proposed by Dr. McFadden and Dr. Wells (Geology, 15: 504-508). In addition, the results of this NSF funded study indicates that 1) formation of pavements and Av horizons begins soon after deposition of the alluvial deposits, 2) these two common desert features coevolve simultaneously, and 3) pavements on alluvial fans form the upward lifting of surface clasts from the accumulation of eolian fines below pavement clasts and not deflation or upward migration of clasts as had been generally hypothesized.

Our results also indicate that important differences also occur among pavements derived from different lithologies due to variations in dust trapping efficiency and bar-and-swale microtopography (Fig. 3, 5). Av horizons and desert pavements form fastest on Holocene fan-surfaces composed of resistant lithologies, such as limestone and fine-grained siliceous rocks, that produce coarse-grained fan deposits (cobble-gravel) that 1) have an initially open framework and 2) produce a strong bar-and-swale microtopography, features that increase dust trapping efficiency. In contrast, Av horizons and pavements form slowest on fan surfaces composed of poorly-resistant lithologies, such as quartz monzonite, that 1) produce finer-grained deposits (sandy-gravel) and 2) have a poor bar-and-swale microtopgraphy. Temporal relationships indicate that a pronounced degradation of bar-and-swale microtopography occurs with increased pavement development leading to the formation of broad, smooth pavement covered surfaces that are common sights across the Mojave and other desert regions (Fig. 5). Transect measurements indicate that progressive increases in the abundance of cracked, split, and spalled cobbles and boulders at the surface, especially in bars, provide a ready source of additional clasts for forming strong, interlocking pavements.

The results of our study of the origin and evolution of desert pavements on alluvial fans will be of benefit to many other scientist especially in the fields of remote sensing, Quaternary landscape evolution, and desert plant ecology. We have a manuscript in review that sets forth the results of our study of pavement development on alluvial fans (McDonald et al., 199_a). In addition, several sites in the Providence Mountains that have been mapped and analyzed in detail are currently the focus of an additional NSF funded project under the supervision of Dr. Steve Wells focused on the investigation the physical processes controlling pavement development.

Influence of the Accumulation of Desert Dust on Soil-Formation: Soil formation in all lithologies show an immediate and systematic increase in clay and silt in near-surface A and B horizons resulting form the accumulation of dust into developing soils (Fig. 6). In soils formed from granitic lithologies (PM and QM fan-sequences), dust provides the primary source of calcium carbonate. In soils formed in all lithologies the accumulation of dust provides essentially all temporal increases in clay- and silt-sized particles, with only small amounts of the secondary fine-grained material in these soils being derived from to the physiochemical alteration of primary soil minerals. An ongoing debate in the study of soil formation in desert environments is to what degree does the accumulation of eolian fines have on the chemical and physical changes that occur during soil formation. The results of this project will go a long way in addressing this issue.

Preliminary results also suggests that the rate of dust accumulation decreases over time with increased development of desert pavements. In addition, lithologies that have the fastest rates of pavement formation (VX and LS fan-sequences) also have slower rates of dust accumulation than soils developed in granitic fan deposits (QM and PM fan-sequences) where rates of pavement formation are relatively slower. For example, the accumulation of dust-derived silt and clay in LS and VX soils totals about 5 to 10 g/cm^2 in about 50,000 years (Qf4 fan surfaces), whereas 8 to 30 g/cm^2 of silt and clay have accumulated in soils QM and PM soils. These results indicate that the formation of smooth, flat-lying desert pavements probably exert a strong control on the accumulation of desert dust because of reductions in dust-trapping efficiency. Recognition of this type of intrinsic feedback between soil formation and the modification of alluvial fan surfaces is critical for interpreting the systematic changes in soil formation among soils formed in the different lithologies that make up the study area. Systematic trends in soil development among soils formed in the different lithologies will provide a powerful data base in which to directly quantify changes in developing soils that are due only to the accumulation of dust from those that are due only to in-situ alteration of the soils parent material. We are currently preparing a manuscript that will present our analysis of the influence of dust on soil formation in arid environments (McDonald and McFadden, 199_a). We are also currently developing a process-oriented model that uses soil particle-size distribution data and mineral composition (XRF) to describe the influx and mixing of desert dust within developing desert soils (McFadden et al., 199_a). This type of modelling approach is imperative for correctly interpreting physiochemical processes associated with soil development in arid and semi-arid environments.

Influence of the Accumulation of Desert Dust on Soil-Water Balance: Perhaps one of the most significant results of our study of dust accumulation in soils is the strong affect that temporal accumulations of dust have on soil-water balance. The development of Av horizons and desert pavements have a profound impact on infiltration rates (Fig. 7). Measured infiltration rates are reduced to about 35% to 1% of the infiltration rate for coarse-textured deposits that do not have Av horizons. Accumulation of desert dust into soil B horizons that underlie the Av horizon also have a strong effect on soil-water balance by decreasing infiltration rates and increasing the soil-water holding capacity. For example, significant differences in the annual flow of soil-water occur between weakly developed late Holocene soils and stronger developed Pleistocene soils that have silt- and clay-rich B horizons (Fig. 8). Recognition of the strong impact that temporal increases in texture have on soil-hydrology provide a very new direction in which to evaluate soil formation and landscape evolution. For example, increases in surface runoff that coincide with decreases in infiltration results in the degradation of soils and desert pavements eventually leading to the establishment of surface drainage and the eventual widespread dissection of alluvial fan surfaces. In other words, the systematic development of soils and desert pavements directly controls surface hydrology by causing temporal increases in surface runoff and promotes the eventual self-destruction of alluvial fan surfaces. Recognition of the strong impact that temporal increases in texture have on soil-water balance provides critical information for separating control of temporal changes in soil texture from climate change on the profile distribution of carbonate.

We believe that this method of integrating field studies of soil and geomorphic characteristics with quantification of soil-hydrologic characteristics and modeling of soil-water balance will provide a powerful new method of evaluating short- and long-term landscape evolution that will be of tremendous use to other geoscientists. We are currently preparing manuscripts that will set forth the results of study that integrate evaluation of soil-water balance modelling and soil formation (McDonald et al., 199_c; McDonald and McFadden, 199_a).

Influence of Lithology: The results of this study provide the first direct comparison of soils developed from different and contrasting lithologies (Table 1). Clay-rich argillic (Bt) horizons and strongly oxidized cambic (Bw) horizons have formed in soils developed from granitic materials (QM and PM) but these soil features are virtually absent in soils developed from calcareous materials (LS). By contrast, the accumulation of pedogenic carbonate is strongest in the LS soils and weakest in the PM and QM soils. Soils developed from mixed deposits (VX fan-sequence) represent a sort of half-way point between soil developed from granitic materials and soils from calcareous materials. Other influences of lithology on soils and desert pavements have been summarized above. The detailed quantitative analysis of the influence of lithology on the formation of calcic soils in desert environments will be the subject of a planned paper (McDonald and McFadden, 199_b).

In summary, the results of our examination of the origin and development of desert pavements and soils derived from different lithologies will provide critical information for 1) increasing the utility of desert pavements in establishing local and regional correlations among Quaternary stratigraphic units 2) in using the quality of desert pavements and soil formation to provide initial age information for Quaternary units, and 3) directly linking the influence of lithology and the accumulation of desert dust on soil formation.

The influence of Holocene Climate Change on the Formation of Calcic Soils

We have made important new advances regarding the influence of Holocene climate change on the profile distribution of pedogenic carbonates. Carbonate distribution in soils formed on Pleistocene surfaces is commonly bimodal, with carbonate accumulation occurring within the upper and lower parts of the soil profile (Fig. 9, 10). The bimodal distribution of carbonate is generally thought to correspond to a general shift to relatively drier climates in conjunction with the Pleistocene-Holocene climatic transition (line A, Fig 11). Paleoclimate records derived from nearby pluvial lakes, however, indicate that the Holocene has been punctuated by episodes of significantly wetter climate characterized by extreme increases in rainfall that resulted in the formation of short-lived (~50 to 200 years) pluvial lakes (line B, Fig. 11). Shallow flooding of desert playas in the Mojave Desert has occurred several times during the last 100 years during years with significant increases in winter and spring rainfall that are generally associated with El Nino/Southern Oscillation anomalies in the Pacific (line C, Fig. 11). An important part of this project has been to test our hypothesis that these episodic periods of extreme climatic during the Holocene have influenced the profile distribution of soil carbonate.

We have been collaborating with Dr. Gerald Flerchinger and Dr. Fred Pierson (Research Hydrologists: USDA-ARS) on adapting and applying a numerical soil-water/evapotranspiration model (SHAW) for studying soil-water movement under varied conditions of climate, soil-texture, and vegetation. Our strategy has been to use actual daily climate data from select years to examine how climate variables associated with relatively "wet" (playa-flooding years with extreme increases in rainfall) and "dry" climate (historical average annual rainfall) affect soil-water movement. Previous studies of soil-water movement in calcic soils have largely relied on monthly estimates of climate which provides only crude estimates of soil-water balance.

Preliminary results using SHAW indicate that carbonate within the upper and lower zones of modelled soils strongly corresponds with soil-water flow associated with dry and wet years (Fig. 9). The depth of soil-water flow can only reach the lower zone of carbonate accumulation during "wet" years when extreme increases in winter/spring storm activity resulted in the flooding of nearby desert playas. The depth of soil-water movement during "dry" years corresponds to the upper zone of carbonate accumulation in soils formed on pre-Holocene surfaces. Because of the linkage between extreme winter/spring storm activity and the flooding of desert playas, we believe that our current work strongly suggests that the carbonate distribution in calcic soils may largely be controlled by episodic and extreme climate events that have occurred throughout the Holocene (line B, Fig. 11) rather than climate change associated with the Pleistocene-Holocene transition (line A, Fig. 11). Empirical field relationships among carbonate distribution between Pleistocene and late Holocene soils also supports the conclusion that extreme climatic events during the Holocene have control the depths of accumulation of carbonate (Fig. 10). This conclusion is significant because 1) episodic changes in climate are likely to also have a strong influence of soil characteristics (in addition to carbonate) and surficial processes, and 2) calcic soils may provide a proxy record of Holocene climatic change. The latter point is significant because of the ubiquitous occurrence of calcic soils in desert environments. Two manuscripts are currently being prepared that will present the initial findings of our integration of numerical models of soil-water balance and models of climate change with the profile distribution of soil carbonate (McDonald et al., 199_c; McFadden et al., 199_b)

Our next step in this process will be to combine the SHAW model with the redevelopment of a geochemical model of the soil carbonate system (CALSOIL) to 1) study the physiochemical development of calcic soils, 2) to evaluate temporal changes in the profile distribution of pedogenic carbonate and 3) to use the vertical distribution of soil carbonate as a proxy indicator for evaluating the impact of climate change on soil-water movement in arid and semi-arid environments.

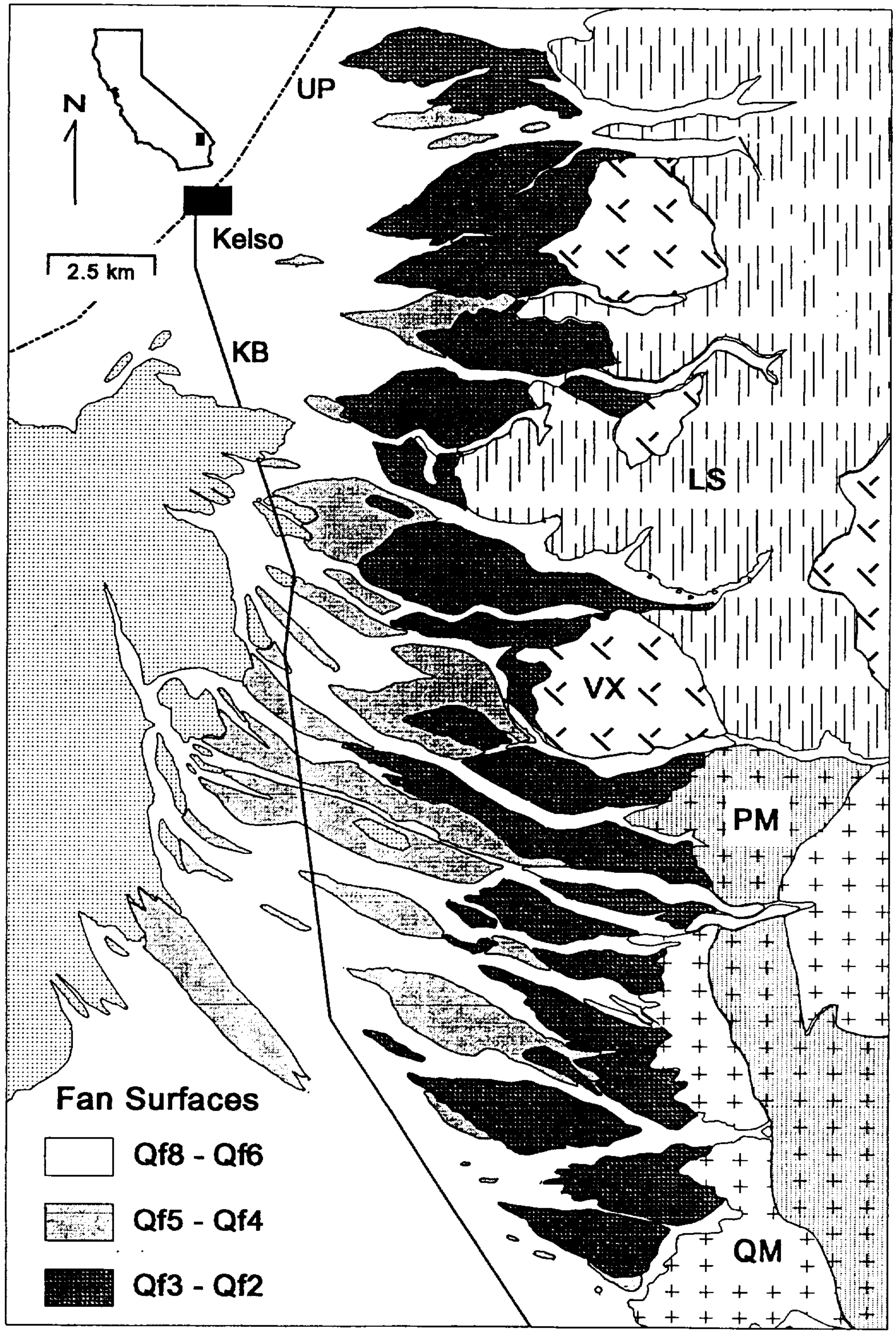

Figure 1. General distribution of Quaternary depositional units along the Providence Mountains piedmont. Four fan-sequences are defined based on lithologic composition: 1) PM: mixed-plutonic rocks, 2) QM: quartz monzonite, 3) VX: volcanic-mixed, and 4) LS: limestone and marble. KB: Kelbaker road, UP Union Pacific railroad tracks.

Study Area			Providence Mountains[a]									Soda Mountains / Silver Lake and Vicinity[b]					Cima Piedmont[c]		
Geologic Time			Fan Surface	Age Estimations (X1000 yr) Min	Max[d]		Best	Numerical Age Estimations IRSL[e]	14C[f]	Model[g]	SDI[h]	Fan Surface	SDI[i]	SDI[j]	SDI[k]	14C[l]	Fan Surface	SDI[k]	K-Ar (Ma)[l]
Quaternary	Holocene	Late	Qf8	0	2.8	(7)	0.1				0	Qf6	0	0	0		Qf9	0	
												Qe3							
			Qf7	0	4.2	(8)	1		3240 4410 ± 110 2770 ± 70	7.1k 7-8k 4-6k	2.1	Qf5	0.8	0.6	2.3		Qf8	3.6	
			Qe3	2.7	4.2	(8)	3.5	4250 ± 290											
		Middle	Qf6	2.8	8.4	(11)	4		4290 5380 ± 80 2770 ± 70	9.9k 8-11k 7-8k	4.2	Qf4	4.9	3.9	7.9	3400 ± 60	Qf7	6.5	
												"Ql5"[m]				3620 ± 70			
		Early	Qe2	2.8	10.4	(29)	8.5	3500 ± 220 3700 ± 425 4074 ± 334 8420 ± 795				Qe2							
												Qf3	7.5	5.3	6.6		Qf6	6.1	
	Pleistocene	Late	Qf5	8.4	18.1	(36)	10	10410 ± 890 12460 ± 1151 17300 ± 1935	18120 ± 150 16310 ± 100	29-36k 27-33k	12.1	Qf2/Ql2	14.3	12.2	19.7	8350 ± 300 9160 ± 400 10333 ± 120	Qf5	12.4	
			Qe1	10.4	28.7	(45)	15	16830 ± 1465				Qe1							
												Ql1				13670 ± 550 14660 ± 260 20320 ± 740			
			Qf4	16.8	75		50		28690 ± 440 26980 ± 290	48-57k 45-53k	25.9	Qf1	19.3	20.3	46.4		Qf4	19.2	
																	Qv5		0.06 ± 0.02 0.09 ± 0.04
			Qf3	>29	<730		150				47.0						Qf3	39	
		Middle															Qv4		0.13 ± 0.02
																	Qv3		0.15 ± 0.01 0.16 ± 0.02 0.17 ± 0.02
																	Qf2		
																	Qv2		0.24 ± 0.02 0.32 ± 0.05
			Qf2	>29	730		600	0.74 Ma Bishop Tuff									Qf1		
		Early															Qv1		0.46 ± 0.04 0.51 ± 0.02 0.58 ± 0.08
			Ql1	730	4000		1500										Qf1		3.88 ± 0.05
Tertiary	Neogene																		

a = This study.
b = Soda Mountains/Silver Lake stratigraphy from Wells et al., 1987; 1990.
c = Cima piedmont stratigraphy from Wells et al., 1990; correlations between Cima and Silver Lake stratigraphic sections by Wells et al., 1990; Qv = Quaternary volcanics
d = Maximum surface ages using modeled radiocarbon results from Wang et al., 1994.
e = IRSL dates from Clarke, 1994).
f = Radiocarbon age estimates from soil organic matter and soil carbonate reported in Wang et al., 1994.
g = Modeled radiocarbon age estimates from Wang et al., 1994.

h = Soil development index values calculated according to Harden, 1982; and Harden and Taylor, 1983.
i = Values for Soda Mountains piedmont, from McFadden et al., 1989.
j = Values for Salt Springs Hills area, from McFadden et al., 1989.
k = Values for Soda Mountains piedmont and Cima piedmont, from Harden et al., 1991.
l = Age estimations reported in Wells et al., 1990.
m = Unlabled late Holocene lake stand, Silver Lake playa, informally defined here for illustration.

Figure 2. Preliminary correlations among Quaternary stratigraphic units in the eastern Mojave Desert.

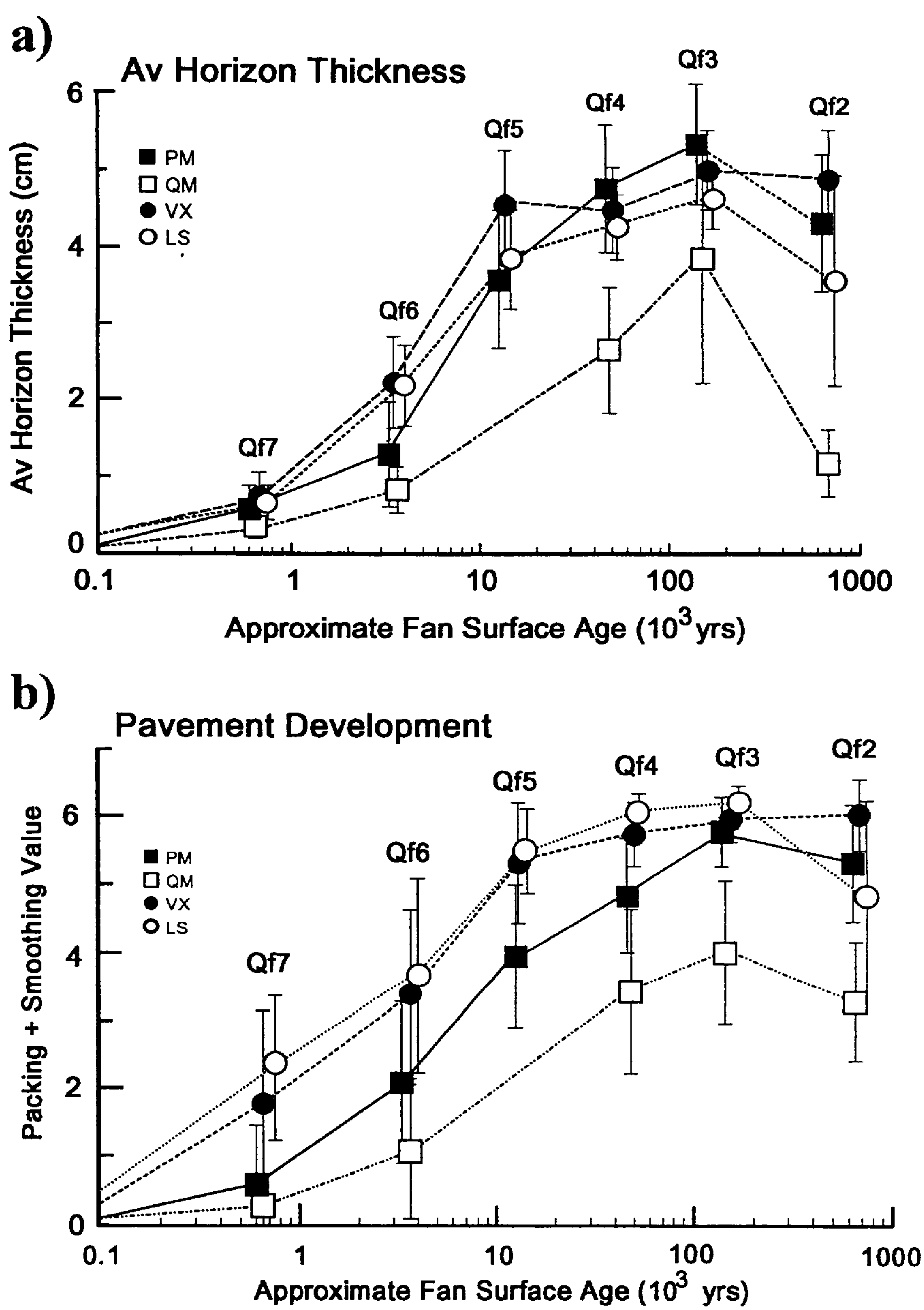

Figure 3. a) Temporal trends in mean Av horizon thickness in cm. Each point represents between 20 and 30 measurements for each particular fan sequence. Bars represent standard error. Displayed age for each set of fan units represents best age approximations. Ages of individual fan-units within each set of fan units are slightly offset to increase visibility of error bars. b) Temporal trends in pavement development based on mean alignment (packing) and smoothing (horizontal character) values. Each point represents between 20 and 30 measurements for each particular fan sequence.

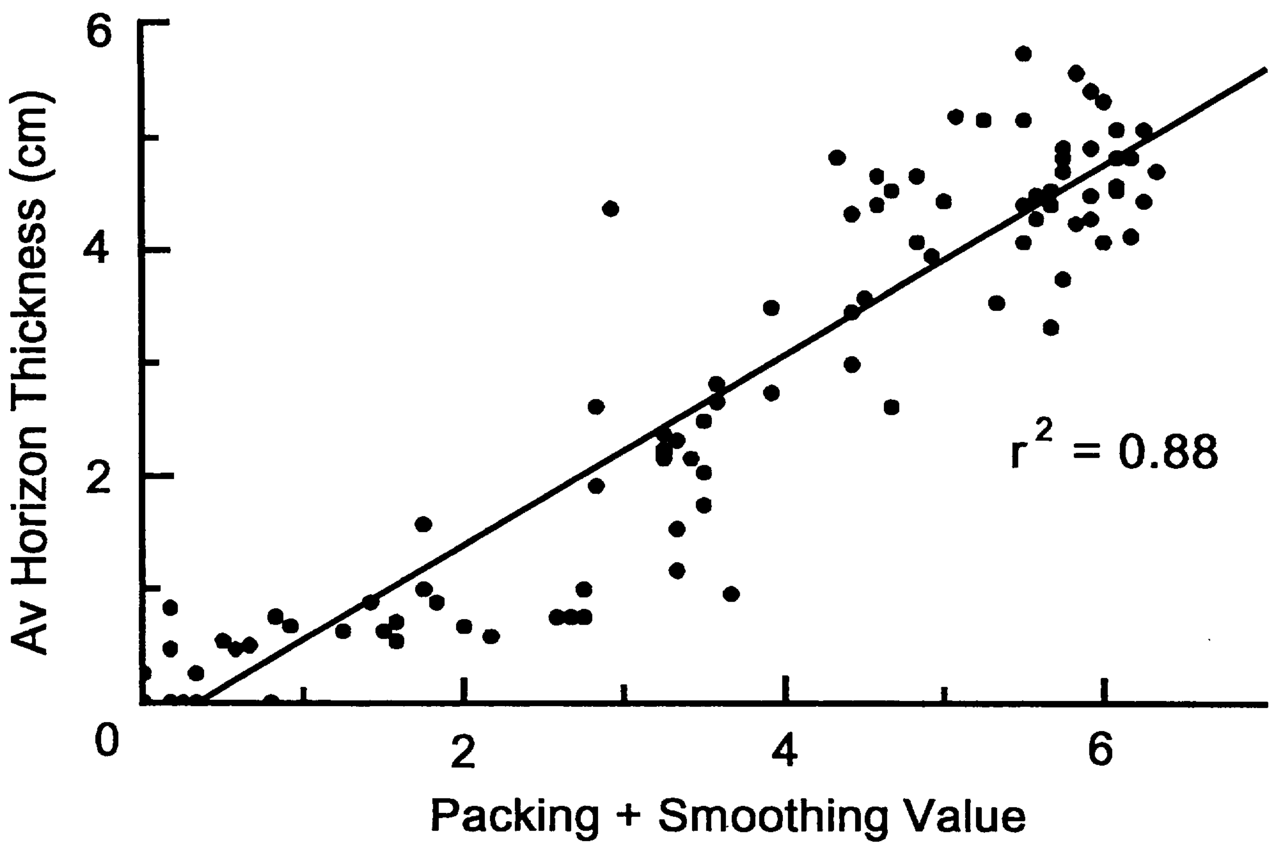

Figure 4. Linear regression analysis for Av thickness and pavement development (packing and smoothing (horizontal) values), based on mean values for each individual transect measurement. Number of points = 82.

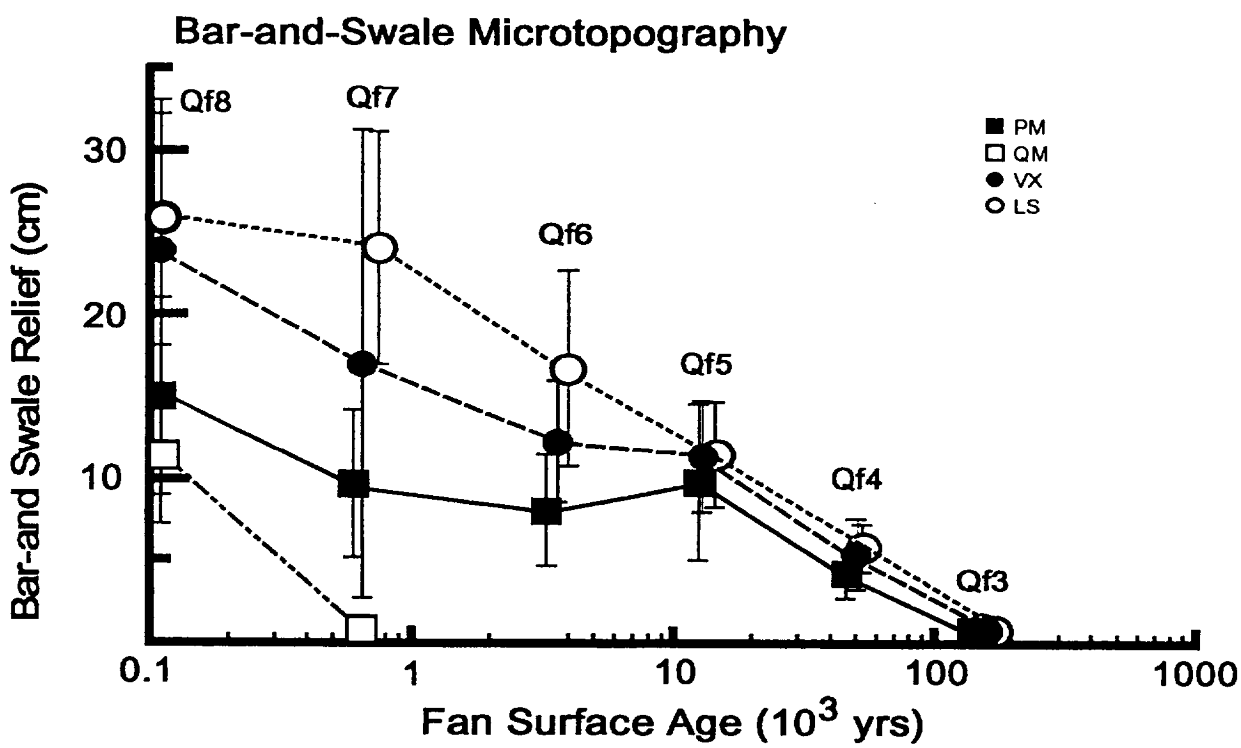

Figure 5. Temporal trends in degradation of mean bar-and-swale microtopgraphy. Each point represents between 20 and 50 measurements for each particular fan sequence.

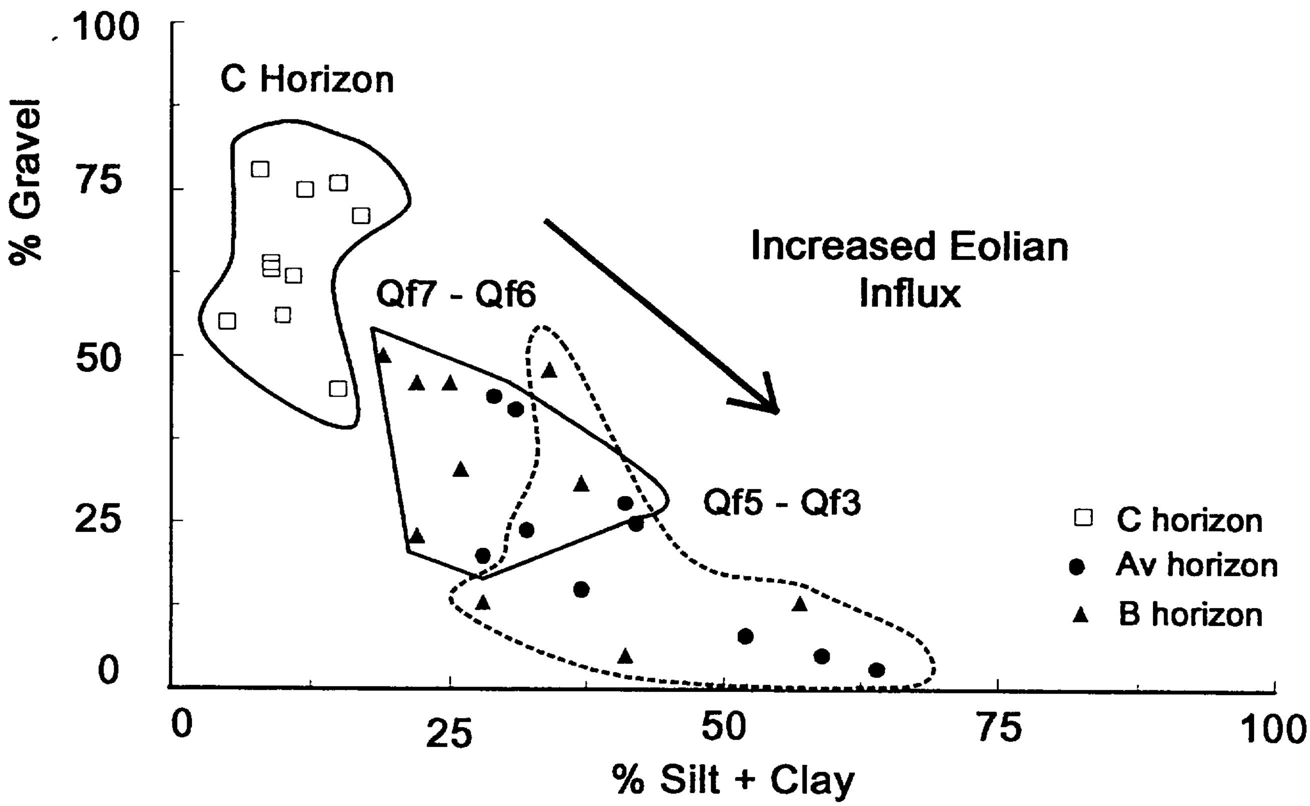

Figure 6. Changes in wt. % silt + clay and wt. % gravel due to accumulation of dust below pavement stones for 10 soils formed on Qf7 to Qf3 fan surfaces (selected from all four lithologic fan-sequences). Each soil has a plotted value for C horizon texture.

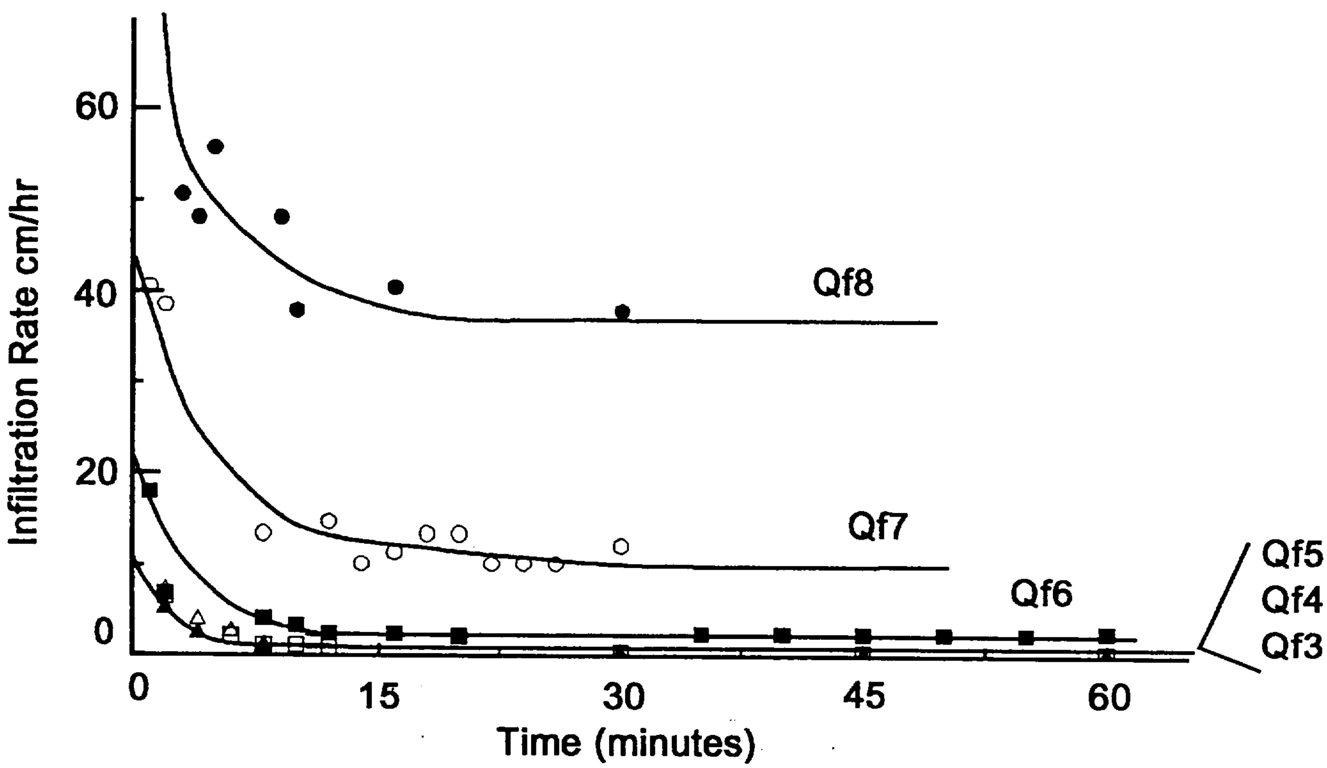

Figure 7. Infiltration rates for soils formed on the PM fans. Infiltration measured by double-ring infiltrometry with a diameter of 60 cm for the inner ring, a diameter of 100 cm for the outer ring, and 3 cm of hydraulic head.

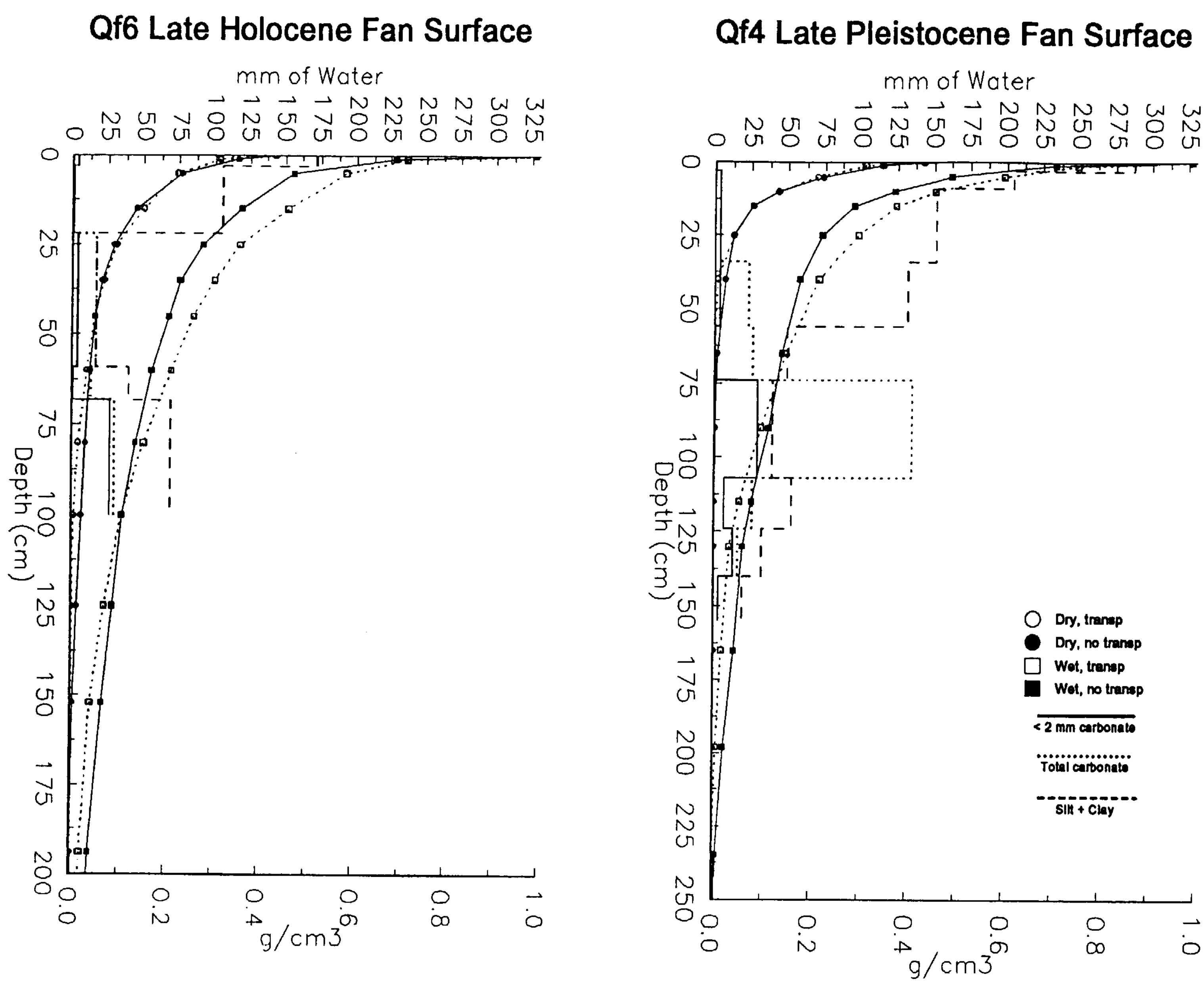

Figure 8. Results of SHAW modeling of annual soil-water movement through a weakly developed soil (Qf6 Late Holocene) and through a strongly developed soil (Qf4 Late Pleistocene). Climate data used for "dry" year typifies relatively dry climate that has existed throughout much of the Holocene; climate data for "wet" year typifies relatively wet climate that has existed throughout much of the Late Pleistocene and during extreme climatic events during the Holocene. Modeling of soil-water balance also included examination of relative affects of vegetation on soil water movement by conducting simulations with and without transporational-water loss.

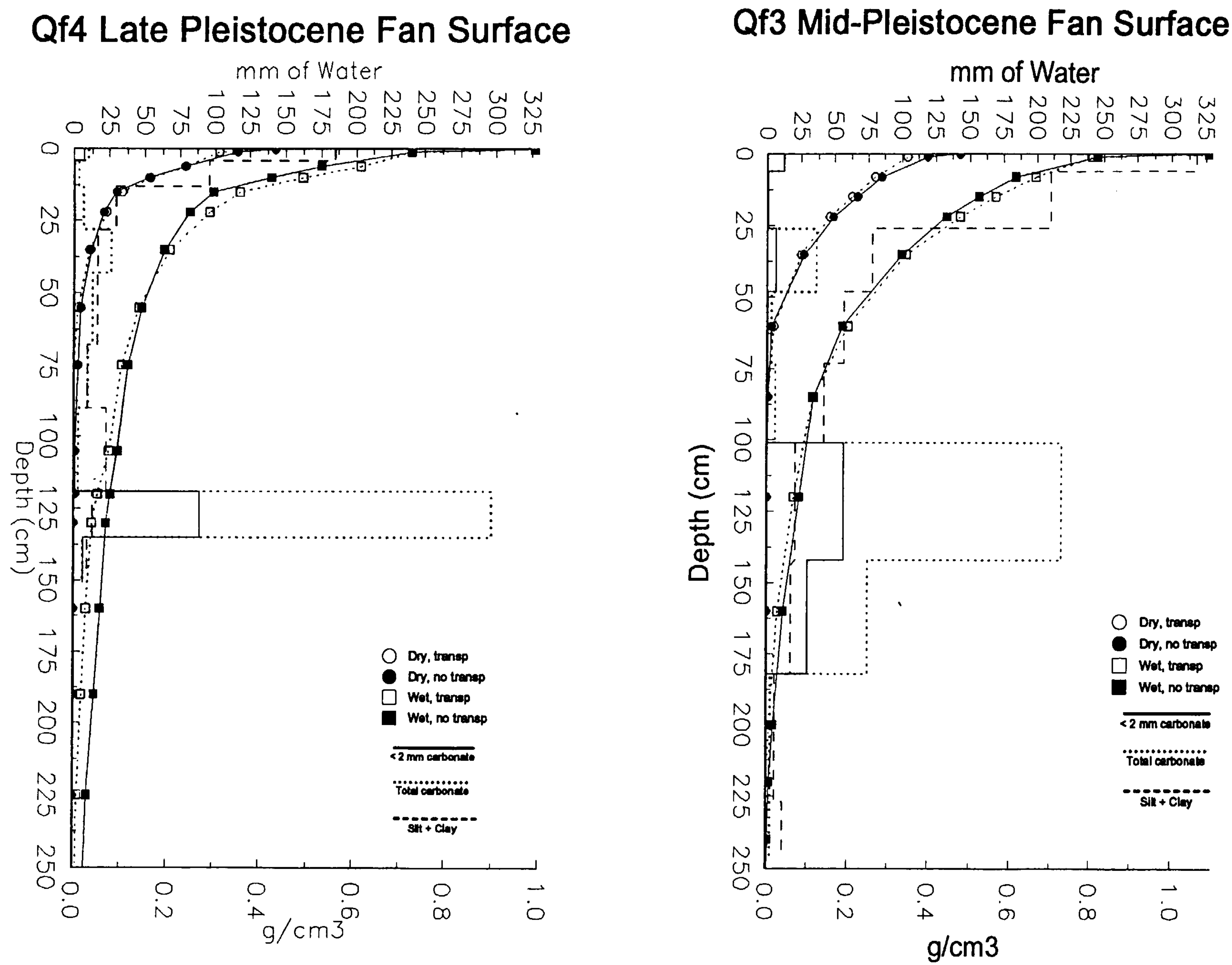

Figure 9. Results of SHAW simulations of annual soil-water movement and pedogenic carbonate distribution for soils formed on pre-Holocene fan surfaces. Depth of soil-water reaches lower zone of carbonate only during "wet" years when extreme storm events occur. Depth of soil-water movement during "dry" years only reaches upper zone of carbonate accumulation.

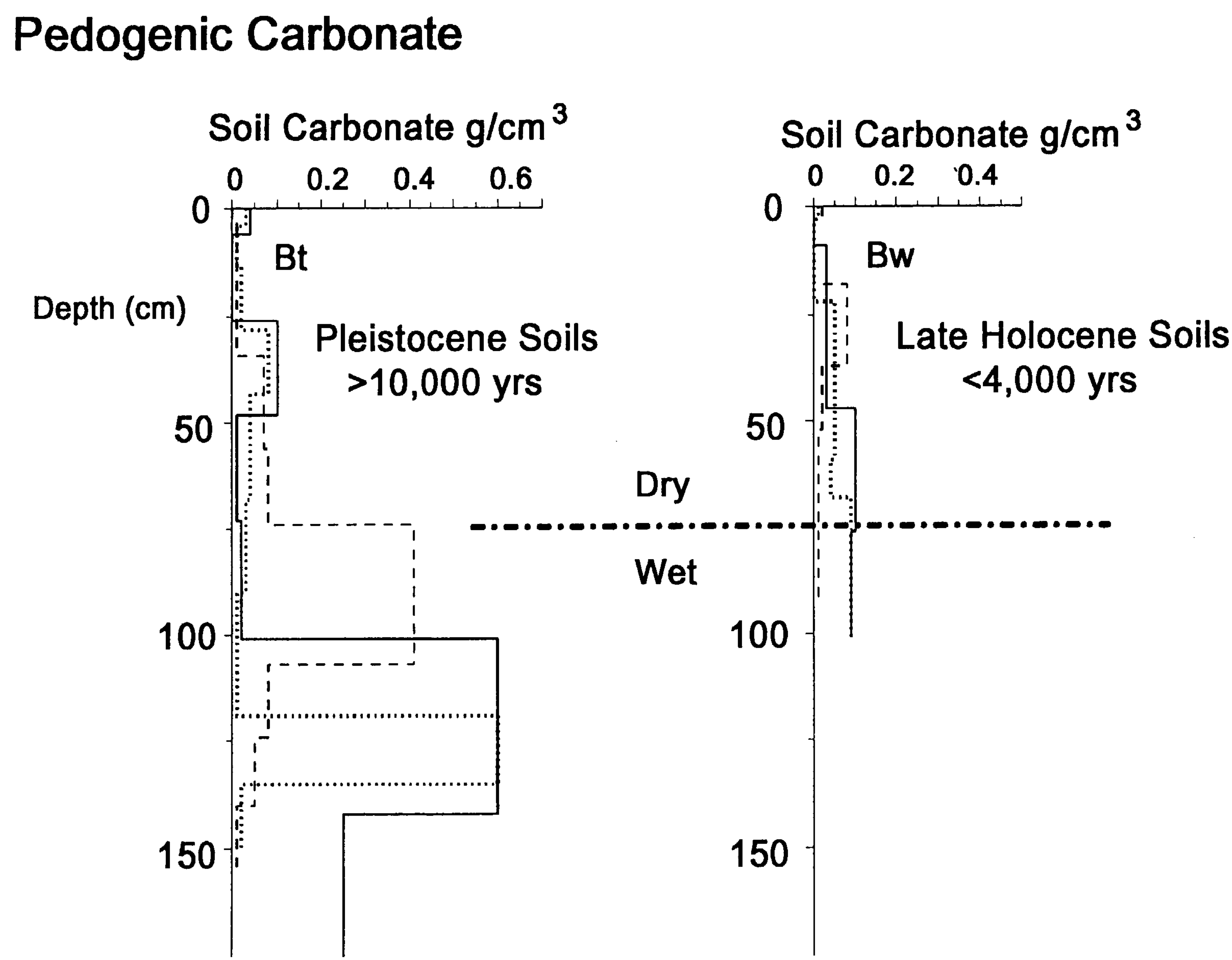

Figure 10. Profile distribution of soil carbonate for three soils formed on pre-Holocene fan surfaces and three soils formed on late Holocene fan surfaces. Carbonate contents within the upper 75 cm of the older soils is similar to carbonate contents in soils that have existed only during the late Holocene. This type of empirical relationship strongly suggests that carbonate contents within the upper parts of the older soils has largely accumulated since the last episode of extreme climate during the late Holocene and does not represent carbonate accumulation since the Holocene-Pleistocene transition. Dry-wet line represents approximate depth of boundary between the annual flow of soil-water that occurs during periods of wet and dry climate.

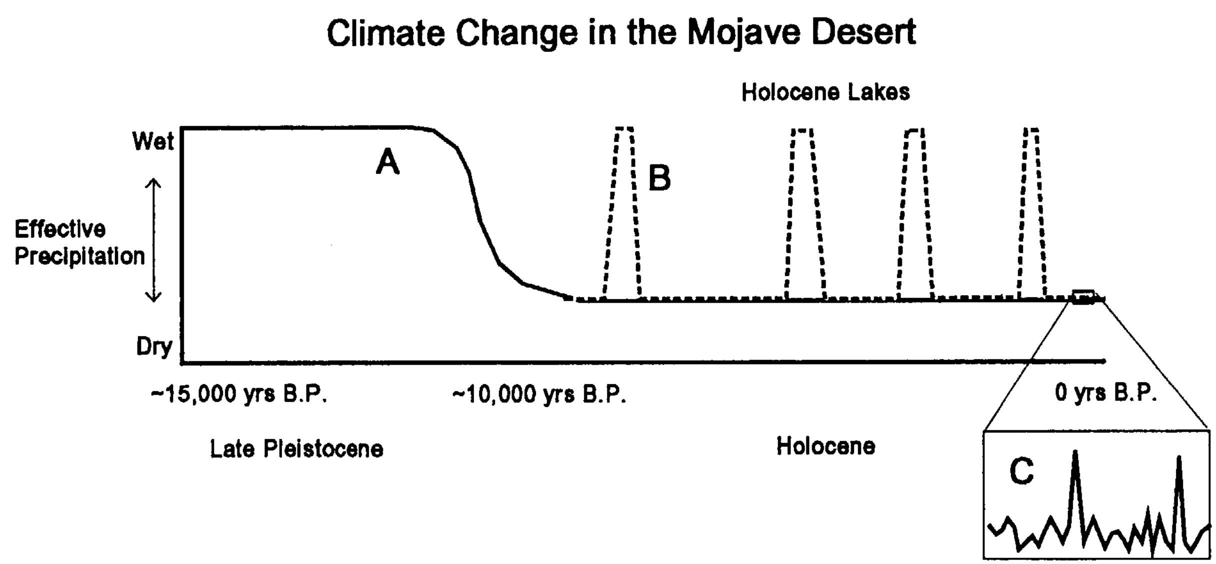

Figure 11. Schematic drawing of models of relative changes in effective precipitation during the late Pleistocene and Holocene.

Table 1. Typical soil charateritics of the four fan sequences.

Fan Unit[a]		Fan-Sequence PM	QM	VX	LS
Qf8 Late Holocene	Horizon:[b]	no soil	no soil	no soil	no soil
	Texture:[c]	sand	sand	sand to loamy sand	sand to loamy sand
	Stage:[d]	0	0	0	0
	Pavement:[e]	none	none	none	none
Qf7 Late Holocene	Horizon:	Avk-AC-Ck-C	Av-A-AC-Ck-C	Avk-ACk-Ck-C	Avk-ACk-Ck-C
	Texture:	loamy sand	loamy sand	loamy sand	sandy loam
	Stage:	I-	I-	I	I
	Pavement:	none	none	very weak to weak	very weak to weak
Qf6 Late Holocene	Horizon:	Avk-Bwk-Ck-C	Av-A-Bw-Ck-C	Avk-Bwk-Bk-Ck-C	Avk-Bwk-Bk-Ck-C
	Texture:	sandy loam	loamy sand	loamy sand	sandy loam
	Stage:	I	I	I	I-II
	SB:[f]	cambic	cambic	cambic	cambic
	Pavement:	weak	very weak to none	weak to moderate	weak to moderate
Qf5 Early Holocene to Latest Pleistocene	Horizon:	Avk-Bwk-Btk-Ck-C	fan unit not found	Avk-Bwk-Bk-Ck-C	Avk-Btvk-Bk-Ck-C
	Texture:	sandy loam		sandy loam	loam
	Stage:	I-II		I-II	II-III
	SB:	cambic or argillic		cambic/calcic	calcic
	Pavement:	moderate to weak		moderate to strong	moderate to strong
Qf4 Late Pleistocene	Horizon:	Avk-Btk-Bk-Ck-C	Av-ABv-Bt-Bk-Ck-C	Avk-BAv-Bwk-Bkm-Ck-C	Avk-Btvk-Bwk-Bkm-Bk-Ck-C
	Texture:	sandy clay loam	clay loam	sandy loam	loam
	Stage:	III	I-II	III-IV	III+
	SB:	argillic	argillic	petrocalcic	petrocalcic
	Pavement:	moderate to strong	weak to moderate	strong	strong
Qf3 Middle Pleistocene	Horizon:	Avk-BAvk-Bt-Bkm-Ck-C	Av-BAv-Bt-BCk-Ck-C	Avk-BAv-Btk-Bk-Bkm-Bk-Ck-C	Avk-Btvk-Bwk-Bkm-Bk-Ck-C
	Texture:	clay loam	loam	sandy clay loam	loam
	Stage:	III-IV	I-	IV	IV
	SB:	argillic/petrocalcic	argillic	argillic/petrocalcic	petrocalcic
	Pavement:	strong	moderate to weak	strong	strong to very strong
Qf2 Mid-Early Pleistocene	Horizon:	Avk-Btk/Bkm-Ck-C	Av-Bt-Btk-BCk-Ck-C	Avk-BAvk-Btk-Bk-Bkm-Ck-C	Avk-Bkm-Bk-Ck-C
	Texture:	sandy clay loam	sandy clay loam	sandy clay loam	sandy loam
	Stage:	IV	I-	IV	IV-V
	SB:	petrocalcic	argillic	argillic/petrocalcic	petrocalcic
	Pavement:	moderate to weak	weak to moderate	strong to moderate	moderate to strong

PM: mixed-plutonic, QM: quartz Monzonite, VX: mixed-volcanic, LS: limestone
a: Age estimations of fan units in Table 2. Unit Qf1 not shown because unit is highly eroded.
b: Typical soil horizon sequence.
c: Finest texture of any B or AC horizon.
d: Soil carbonate stage
e: General quality of desert pavement where either best developed or where best preserved.
f: Strongest diagnostic B horizon.

Part 2: Quaternary Carbon Storage and Cycling Times in a Semiarid Landscape, Sevilleta Long Term Ecological Research Site, New Mexico

Introduction

An increase in atmospheric PCO_2 since the start of the industrial revolution has created concerns about greenhouse warming of the Earth. Earth scientists have responded by searching for information about the causes for past and present atmospheric CO_2, fluctuations, but these remain poorly defined. For example, carbon budgets made for the most recent deglaciation seem to be missing a large carbon sink (Sundquist, 1993). Atmospheric CO_2 is very sensitive to changes in the larger pool of terrestrial carbon therefore, post-glacial uptake of carbon by vegetation and soil may account for the missing carbon (Adams, et al., 1990, Harden et al., 1993). Desert soils store copious amounts of carbon as calcium carbonate ($CaCO_3$) and have a carbon isotopic signature that indicates that it is a direct sink of atmospheric CO_2 (Cerling, 1984, Quade et al., 1989b). Furthermore, deserts cover one-third of the Earth's surface and therefore the soils in deserts may constitute a significant terrestrial carbon reservoir. A crude first estimate suggests that 35% of world soil carbon is stored as inorganic carbon in desert soils (Schlesinger, 1982). This has important implications for global climate because arid soils could act as a non-trivial sink or source for atmospheric carbon. It is the intent of this report to demonstrate the flux rates of carbon through and out a semi-arid landscape.

Method

Landscape dynamics are the key to long-term carbon fluxes in the terrestrial reservoir. By examining the processes which have shaped the landscape, temporal changes in carbon pools are estimated. Stable landforms promote carbon sequestration while degrading landscapes return carbon to atmospheric or oceanic pools (figure 1). This study measures the volume of carbon stored in pedogenic carbonate and assess its relative longevity in the landscape. Rates of carbon sequestration are estimated by from soils of different ages on landforms of different ages. Carbon efflux rates are measured by reconstructing erosional history and soil erosion rates in the landscape.

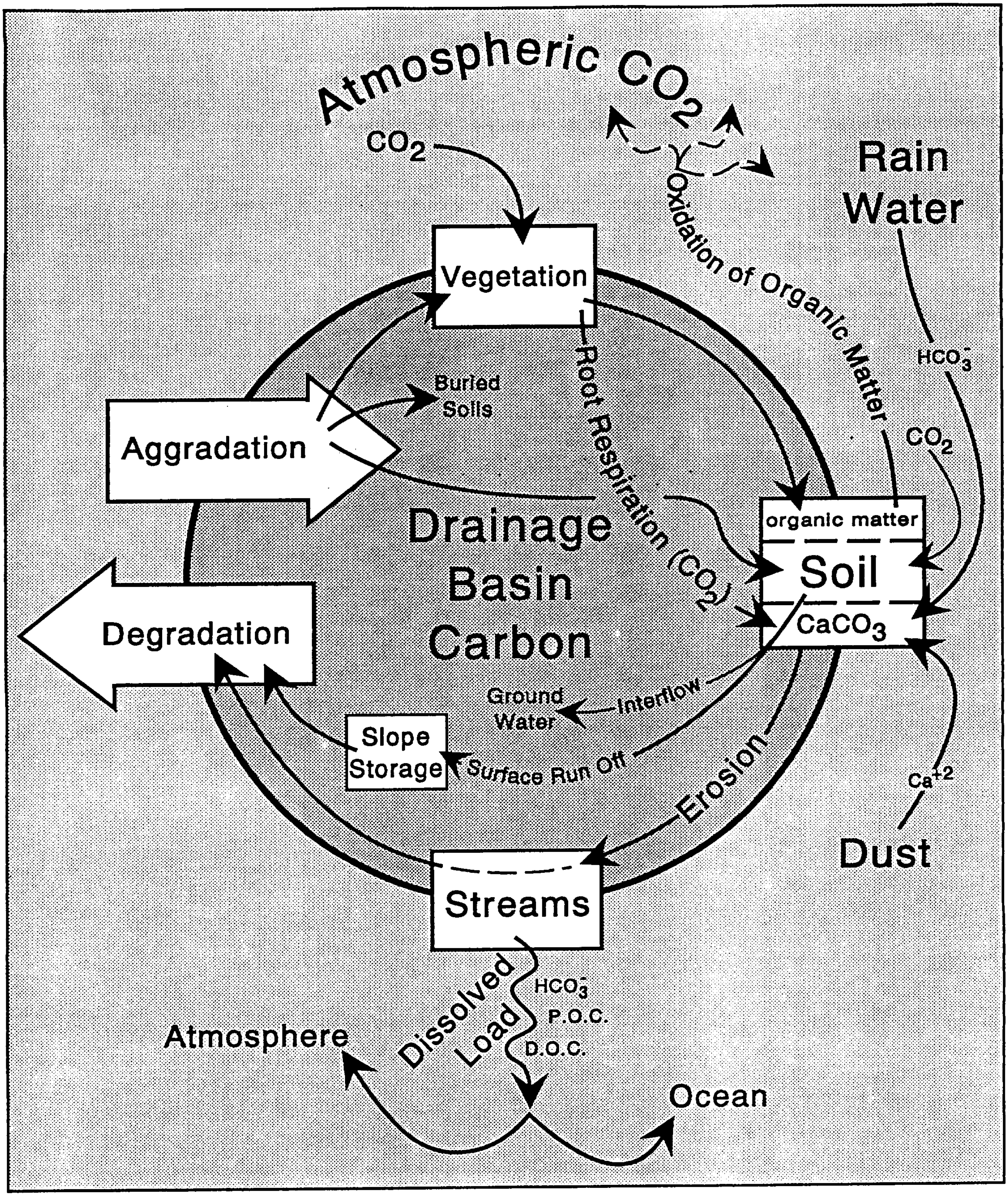

Figure 1. Flux of carbon into and out of a drainage basin.

A single drainage basin has been chosen to represent a unit of landscape. Defined this way, a drainage basin can be viewed as a closed system where inputs balanced against outputs define carbon storage. The drainage basin of Palo Duro Canyon is chosen for this study because it preserves a fill-cut terrace stratigraphy that resembles other Quaternary stratigraphies in New Mexico and the desert southwest (Hawley, 1976, Birkeland, 1971; figure 2). Central New Mexico is an ideal location for this study because the association of soil age to soil morphology and carbonate content is well established nearby in southern New Mexico (Gile et al., 1966). In addition, the study area is contained within the Sevilleta Long Term Ecological Research Site (LTER) which has been protected from grazing and other manmade landscape perturbations for the last 20 years.

The first step in field investigations was to map the distribution of geomorphic surfaces in the Palo Duro drainage basin. Next, a soil chronosequence were sampled in order to measure time dependent carbon sequestration. Soil toposequences were constructed to measure the spatial distribution of carbon in the landscape. The volume of stored soil carbon was calculated from mass of carbonate in each soil profile of different age and landscape position. Finally, the geomorphic processes that have shaped the landscape in Palo Duro Canyon have been reconstructed. These time dependent landscape changes are used to reconstruct changes in the volume of carbon stored in the landscape through time.

Results

Extensive geomorphic surfaces in the Rio Grande Rift represent 10^6 years of carbon storage. The carbon return time for these large reservoirs appears to be slow since the surface is relatively undisected. Trenches excavated on these surfaces, however, reveal channel forms truncating stage IV or stage V carbonate horizons that are overprinted by younger stage III carbonate accumulation (terminology of Gile et al., 1966). These channels represent smaller scale carbon fluctuations within a larger more stable reservoir.

A second time scale of carbon cycling is represented by the downcutting and aggradation cycles effecting Palo Duro. Aggradation adds surface area in the basin that begins to act as a carbon sink. Degradation removes surfaces that have accumulated significant amounts of carbon in the past. Estimated ages for inset fill terraces suggest that the changes in carbon storage driven by basin aggradation and degradation are on the same scale as Quaternary climate change (10^5 years).

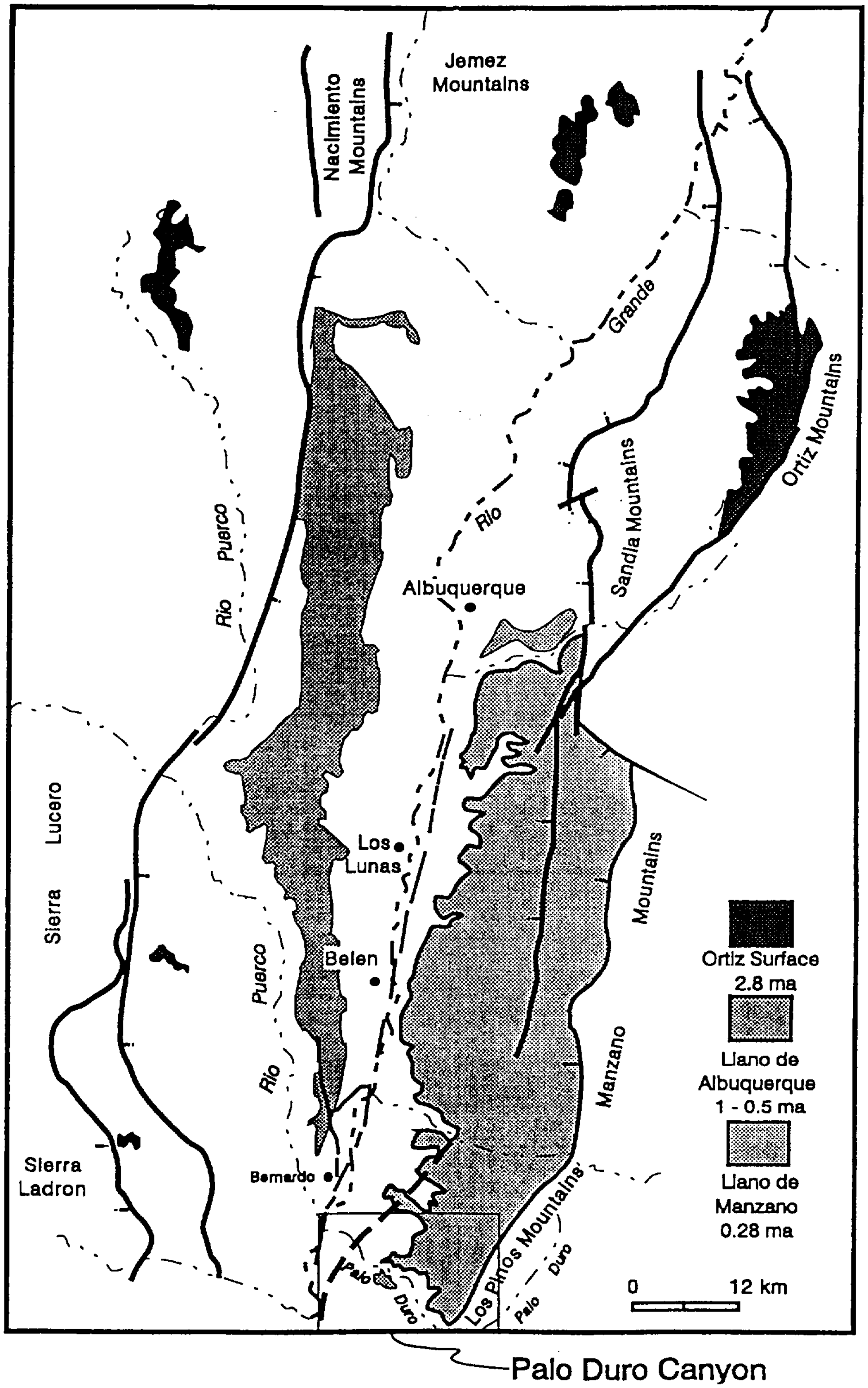

Figure 2. Location of the study area and major geomorphic surfaces in the Albuquerque-Belen Basin.

Superimposed on the cycle of basin degradation is the time it takes for eroded carbonate to be dissolved or removed on clasts from the drainage basin. Following terrace formation, the first stage of landscape development is manifested by truncation of soils at the front of terrace, while soils at the back and middle are buried by colluvium. Erosion of previously formed terraces contributes colluvial material to the younger terrace surface (figure 3a). The colluvial clasts have rinds of pedogenic carbonate which enhance carbonate accumulation in the younger terrace soils. This represents carbon "recycling" within the terrestrial reservoir.

As base level drops gullies incise the terrace (figure 3b). The gullies establish a dendritic drainage pattern that exploits the junction between the terrace and the adjoining scarp. At this second stage, the terrace is isolated from the scarp and no longer receives colluvium. The gullies intercept colluvium and divert it from the terrace surface into the main channel. This event is significant because accumulation of pedogenic carbonate in terrace soils is no longer augmented by colluvial contributions. In a third stage of landscape development, colluvium is stripped from the back of the terrace by the intercepting gully (figure 3b).

Timing of Carbon Loss

Early Holocene terrace treads are spatially isolated but the latest Holocene terrace is not; this indicates that 10^4 years are required for stage two to be completed. Late Pleistocene terrace treads are isolated and colluvium has been stripped from the terrace back so the third stage of development takes approximately 10^5 years to attain. These time scales of landscape development are critical because in stage one there is an overall carbon gains and carbon as pedogenic carbonate on colluvial pebbles is recycled back into the soils. At stage two, however, these clasts are diverted from the surface by the intercepting gullies. This process contributes to carbon loss from the landscape. In stage three of landscape development, the rate of carbon loss increases because colluvium containing carbonate is lost from the landscape. This sequence of landscape evolution represents initial gains of carbon followed by gradually accelerating losses of carbon from the drainage basin in the late Pleistocene and to present.

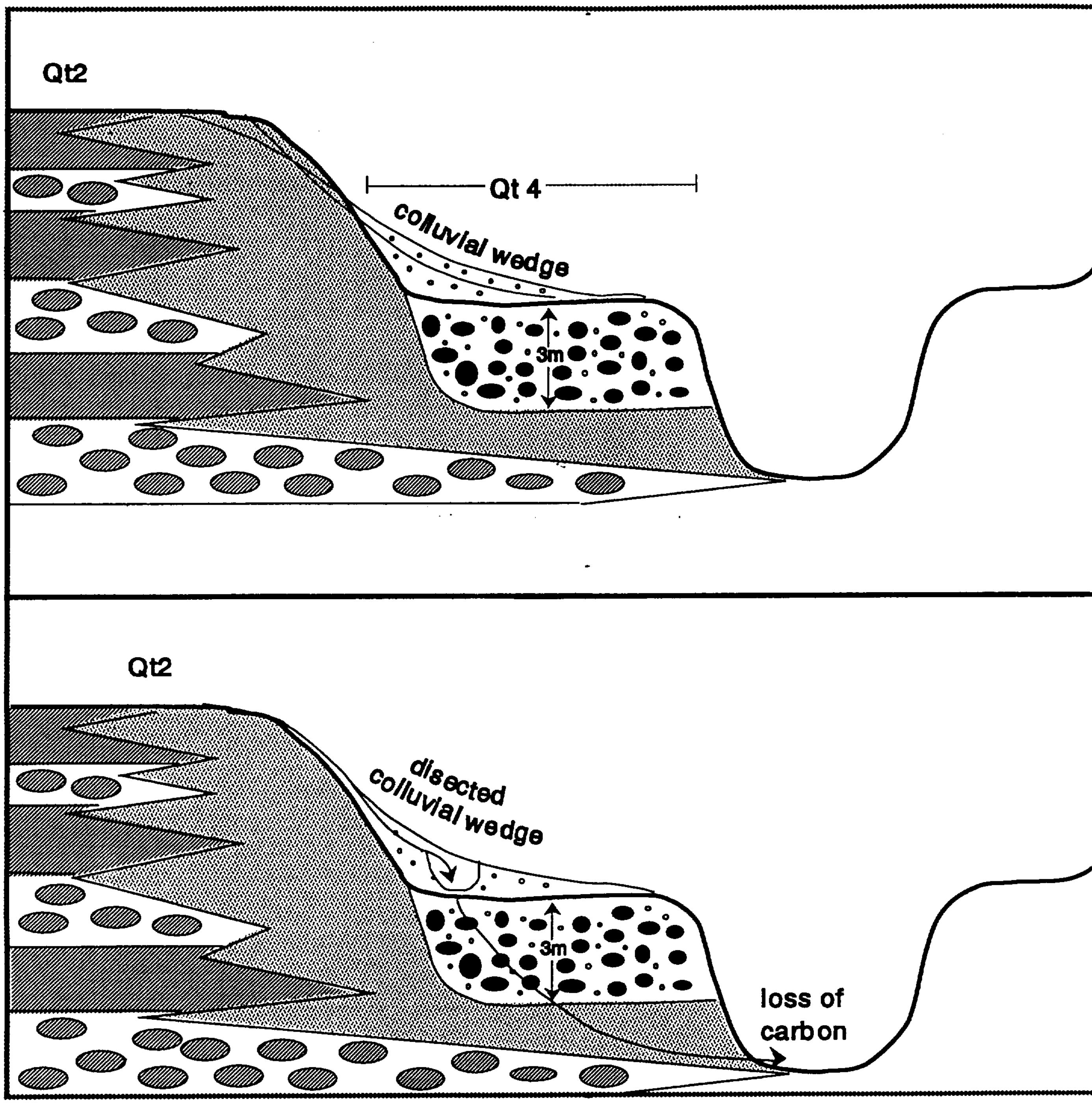

Figure 3. Stages of landscape development and carbon loss in the inner valley of Palo Duro Canyon. A) Stage 1: following terrace formation, the front of the terrace is truncated while the back of the terrace is covered with colluvium. Carbon is "recycled" during stage 1. B) Stage 2: Gullies cut headward into the back of the terrace and intercept colluvium containing secondary carbonate. Carbon loss begins to be lost from the landscape.

Volume Carbon Gain and Loss in the late Pleistocene and Holocene

Surface areas covered by a given terrace within a 1 km square area in the drainage basin are used to calculate carbon losses and gains over the time intervals that the terrace soils have been accumulating carbon. Present-day storage within the 1 km square block of landscape is 10,000 metric tons of carbon. The late Pleistocene terrace contains 8800 metric tons, early Holocene 1100 metric tons. The Recent terrace contains 77 metric tons of carbon in its soils. Yearly net losses for the late Pleistocene terrace, implied from area eroded from the terrace, are 26 kg/m/yr. The losses from the early Holocene terraces are 111 kg/m/yr. Yearly gains on the other hand suggest 87 kg/m/yr are sequestered by the late Pleistocene terrace while 133 Kg/m/yr are sequestered by the early Holocene terrace. This implies that gains are out-competing losses but carbon losses are catching up to carbon gains (figure 4).

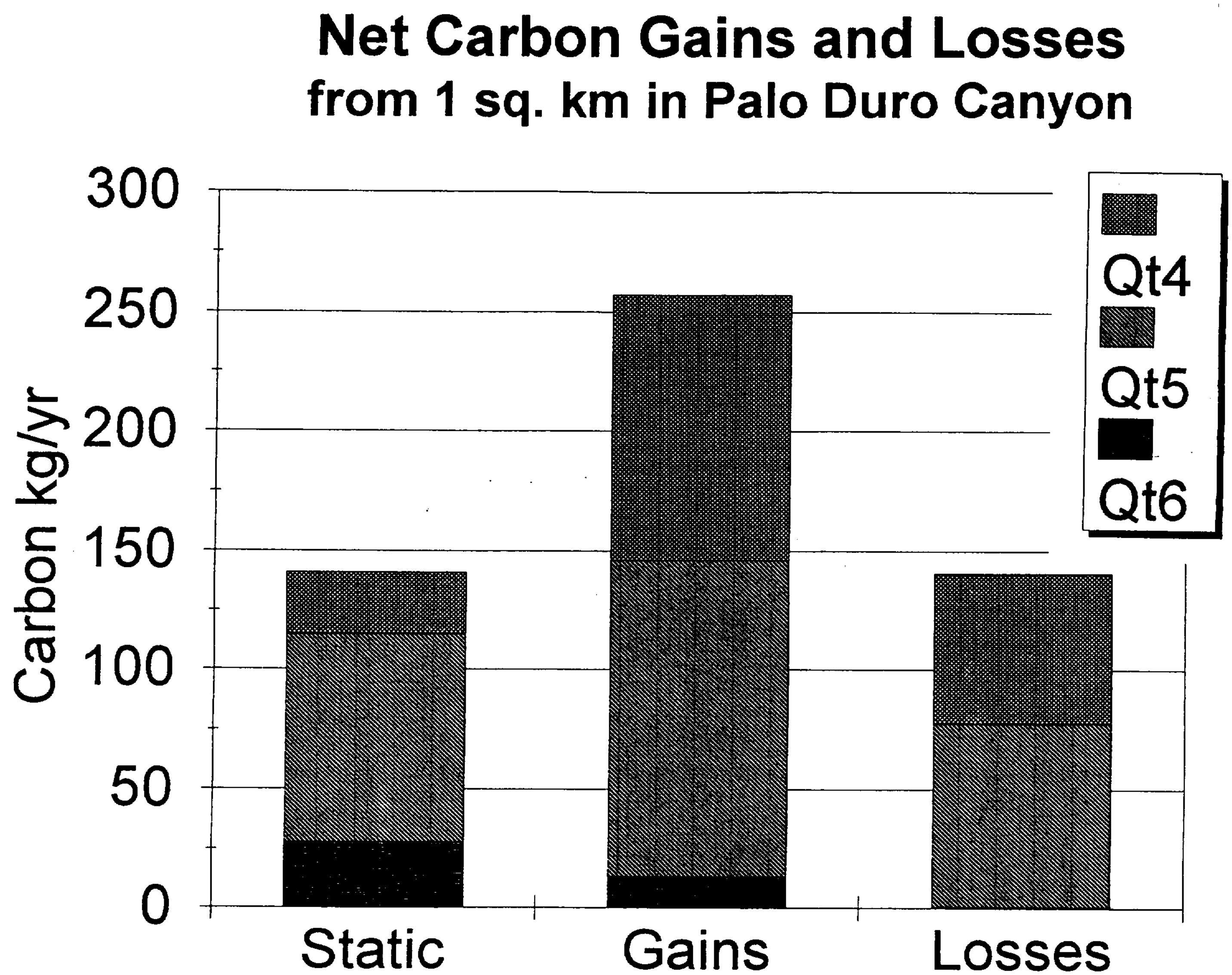

Figure 4. Net carbon gains and losses from 1 sq. km in Palo Duro Canyon.

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