Sediment and the Environment (Proceedings of the Baltimore Symposium, May 1989)
IAHS Publ. no. 184, 1989.

Sediment storage and movement on the Southern High Plains of Texas as indicated by beryllium-ten

W. R. Osterkamp
U. S. Geological Survey, Lakewood, Colorado 80225

ABSTRACT The Southern High Plains is an area in which most runoff and water-entrained sediment collects and is stored in ephemeral-lake basins, or playas. Ponded playa water recharges the High Plains aquifer. Measured thicknesses and carbon-isotope analyses of playa sediment lead to calculated rates of net playa deposition up to 0.48 meter per 1,000 years, of which 0.09 meter per 1000 years is estimated as the maximum possible contribution due to slope-wash processes. Most other sediment movement, including fluxes in and from playa bottoms, is inferred to occur by eolian processes.

Beryllium-ten (^{10}Be) is a naturally-occurring cosmogenic radioisotope (half-life 1.5 Ma) of known accumulation rate with precipitation. Because ^{10}Be becomes tightly bound and concentrated on soil sediment, its movement and storage are closely related to those of sediment. By measuring inventories, accountings of ^{10}Be per unit area, at playa and interplaya sites, comparisons are made with the known accumulation rate. The comparisons suggest that wind erosion removes an average depth of 0.1 mm of sediment annually, and that deflation accounts for roughly 35 times as much sediment transport as does flowing water.

Measured ^{10}Be concentrations with depth at playa and interplaya areas show significant transport of ^{10}Be into the unsaturated zone from playas; numerical modelling suggests that much of the ^{10}Be moves in solution, but movement on sediment through natural conduits may occur as well. The numerical model provides estimates of playa age, and suggests that those playas studied developed in late Pleistocene time.

INTRODUCTION

The Southern High Plains of Texas and New Mexico is dotted with roughly 30,000 ephemeral-lake basins. Until recently, these depressions, or playas, were considered deflation features from which wind-entrained sediment was either saltated and redeposited as lee-side dunes, or removed from the area in suspension (as examples, see Gilbert, 1895; Evans and Meade, 1945; Reeves, 1966; Holliday, 1988). While recognizing the influence of eolian processes, Osterkamp and Wood (1987) and Wood and Osterkamp (1987) suggested that playas develop largely by hydrologic processes. Among these processes are (1) ponding of runoff in depressions, leading to locally concentrated growth, death, and decay of biota, (2) infiltration and unsaturated-zone movement of playa water, with consequent transport of organic matter and possibly fine sediment, (3) dissolution of lithic carbonates and silicates by descending water, causing increased porosity and permeability in the unsaturated zone, and (4) oxidation at depth of organic matter, leading to formation of carbonic acid and continuing dissolution of carbonates.

Evidence for these processes has accumulated from many playa basins of the area (Osterkamp and Wood, 1987; Wood and Osterkamp, 1987). An expected effect of the hydrologic processes is development of natural piping, rapid downward movement of water and playa

sediment through the pipes, and **perhaps** gentle subsidence beneath **playa floors** as a consequence of increased porosity. Extensive **piping is** apparent around some playas, but significant movement of playa deposits into the subsurface has not been documented.

This study, using a radioisotope of beryllium as a natural tracer, was initiated to (1) determine whether playas are recharge sites from which water moves into the unsaturated zone of the Southern High Plains, (2) provide evidence for the possible movement of sediment from playas into the unsaturated zone, and (3) permit mass-balance estimates of sediment movement into and from playa bottoms. The mass-balance estimates consider sediment storage and depend partly on playa ages, which are indicated by inventories of beryllium-10 (^{10}Be) accumulations.

BACKGROUND

Beryllium-10

Beryllium binds tightly to soil compounds, particularly clay minerals, and exhibits a soil-water partition coefficient of about 1 x 10^5. Among the naturally-occurring isotopes of beryllium, ^{10}Be is heaviest and is formed in the atmosphere by cosmic-ray bombardment of nitrogen and oxygen. ^{10}Be is radioactive, having a half-life of approximately 1.5 Ma (million years). Upon deposition of ^{10}Be with precipitation at the land surface, the high affinity of soil for Be results in concentrations of ^{10}Be that change mainly by surficial erosion or deposition, radioactive decay, or transport in ground water. On stable landscapes, the world-wide deposition rate of 1.3 x 10^6 atoms per square centimeter per year (± 21 percent) (Monaghan and others, 1986), adjusted for variation in precipitation, permits calculated ^{10}Be inventories that are suggestive of soil age. Where subsurface concentrations of ^{10}Be are too high to be explained by solute transport in ground water, a likely explanation is the burial of ^{10}Be-rich deposits not yet depleted by radioactive decay. At playas, inventories of ^{10}Be -- that is, summations of ^{10}Be in a column beneath a unit surface area -- are easily interpreted. Lacustrine deposits of a playa represent an age of the depression, and therefore of relatively stable conditions of net deposition on the playa floor. Sediment removal by streamflow processes does not occur, indicating that all lacustrine deposition occurs by intrabasin slope-wash and eolian processes; long-term fluxes of eolian sediment and ^{10}Be into and from playa basins are presumed nearly equal.

Several studies have used ^{10}Be to interpret geomorphic surfaces or to trace the movement of sediment. From a ^{10}Be inventory, Pavich and others (1985) estimated weathering and erosion rates on the Virginia Piedmont, and Brown and others (1987) used ^{10}Be in fluvial sediment to estimate erosion in the eastern United States. A similar study of rapid erosion rates on Taiwan was conducted by You and others (1989). Relative ages of Merced River terraces in California were determined from ^{10}Be inventories by Pavich and others (1986).

Applications of ^{10}Be data to the earth sciences are summarized by Raisbeck and others (1981), Valette-Silver and others (1986), Brown (1987a and 1987b), and Pavich (1988). A brief description of this study is given by Osterkamp (1988).

Physical Setting

The Southern High Plains is a plateau about 80,000 km^2 in area. Almost all runoff of the area **collects** as playa lakes, where much of the water infiltrates to recharge the High Plains aquifer; the remainder is largely lost as evapotranspiration. In northern Texas the High Plains aquifer consists mostly of the Ogallala Formation (Gutentag and others, 1984), a thick series of eolian and fluvial silt, sand, and gravel beds locally containing pedogenic calcrete. The Ogallala Formation ranges in age from about 4.5 to 11 Ma (Gustavson, 1988), suggesting that in most places less than 10 percent of the original ^{10}Be inventories remain.

Overlying the Ogallala Formation in the eastern Southern High Plains is a widespread deposit of eolian sand, the Blackwater Draw Formation (Reeves, 1976). Based on several dating techniques, the Blackwater Draw Formation has accumulated through most or all of Quaternary time (Gustavson and Holliday, 1985).

MASS-BALANCE ESTIMATES

Rates of movement and storage of sediment on the Southern High Plains are not well known because (1) streamflow and fluvial-sediment discharge are meager and poorly measured, and (2) most sediment movement occurs by eolian processes, which are difficult to measure. Sparse sediment-yield and carbon-isotope data are used here to estimate rates of sediment storage in playas. Mass-balance estimates based on ^{10}Be inventories offer comparisons to the sediment-storage calculations, and provide support for interpretations of unsaturated-zone processes.

Playa Sedimentation

Volumes of organic lacustrine fill in three playa bottoms are listed in Table 1. The volumes were calculated from playa-floor areas and average thicknesses of playa deposition shown by drill-hole data and exposures at excavations. Minimum playa ages were determined by radiocarbon analysis of lowermost deposits of each depression. Thus, a rate of basin filling was determined for each playa (table 1).

Similar estimates of sediment deposited and the rate of filling by slope-wash processes were made for the three playas (table 1). These

Table 1 Sediment-accumulaton data in selected playa basins, Southern High Plains

Playa	Calculated volume of playa fill (m^3)	Estimated volume of slope wash[1] (m^3)	Radio-carbon age of playa (yrs)	Rate of filling (m/ 1000 yrs)	Rate of slope-wash (m/ 1000 yrs)
Gentry Pit (lat. 33° 42'N, long. 101° 50'W)	230,000	44,000	9,500 ± 700	0.48	0.09
Anton depression (lat. 33° 46'N, long. 102° 10'W)	2,200,000	400,000	24,830 ± 2,500[2]	.18	.03
Gore Avenue Amarillo, TX (lat. 35° 12'N, long. 101° 48'W)	2,500,000	960,000	18,050 ± 1,000[2]	.19	.07

[1] Based on calculated deposition rate of 4.0 m^3 km^{-2} yr^{-1}

[2] W.W. Wood, U.S. Geological Survey, written commun., 1988

estimates are based on 34 years of streamflow records from Running Water Draw at Plainview, Texas, and various sources of suspended-sediment data, including ranges of concentrations typical of ponded playa water. The streamflow data multiplied by an assumed suspended-sediment concentration yield a rate of sediment deposition by slope-wash processes of 4.0 m^3 km^{-2} yr^{-1}. This rate, multiplied by the radiocarbon age of a playa, indicates a sediment volume deposited during that period of time.

The estimated filling rates (table 1) suggest that less than half of most playa-bottom deposition occurs by slopewash. Thus, it follows that the majority of playa sediment is deposited by eolian transport of silt and fine sand. During ponding, water and lush vegetation trap sediment; following desiccation, surficial playa sediment is susceptible to renewed eolian movement, resulting in lee-side dunes adjacent to many playa bottoms.

Beryllium-10 Deposition and Inventories

By comparing measured ^{10}Be accumulations with those of a stable landscape, estimates are obtained for net erosion or deposition. A theoretical base inventory, N_b, for the eastern Southern High Plains is described by the decay function:

$$N_b = \frac{q\ (\ 1-e^{\lambda t})}{\lambda} \qquad (1)$$

where q, the world-wide deposition rate adjusted for mean annual precipitation, is 6.2 x 10^5 atoms cm^{-2} yr^{-1}, λ is the ^{10}Be decay constant of 4.63 x 10^{-7} yr^{-1}, and t (time) is assumed to be 4.5 Ma, the age of the uppermost Ogallala Formation. Evaluation of equation 1 yields a base inventory for ^{10}Be of 120 x 10^{10} atoms cm^{-2}, the amount of ^{10}Be that would be present in the study area if no losses (or gains) of the isotope occurred except by radioactive decay.

Inventories, calculated from ^{10}Be concentrations collected at various depths below the surface, are listed in Table 2 for playa sites in and southwest of Amarillo (A and B), and for a composite interplaya area near the eastern edge of the Southern High Plains (C). Table 2 shows that (1) ^{10}Be inventories at the playas exceed 200 x 10^{10} atoms cm^{-2}, whereas the interplaya inventory is about a fifth as great, (2) ^{10}Be concentrations decrease roughly exponentially with depth at the Amarillo playa site and the composite interplaya site, but decline erratically at the R.D. Hicks site, (3) relatively high ^{10}Be concentrations extend to much greater depths at the playa sites than in interplaya areas, and (4) most ^{10}Be at the Amarillo playa occurs within 30 m of the surface, but extends to about 70 m at the Hicks playa.

To assess ^{10}Be contributions to playa-basin inventories, the measured inventories (table 2) are applied to the floor and non-floor areas represented in Table 1. From these data, average basin inventories of ^{10}Be range from 50.8 x 10^{10} to 62.2 x 10^{10} atoms cm^{-2} (table 3). Relative to the base inventory for this area (120 x 10^{10} atoms cm^{-2}), these basin inventories range from 42 to 52 percent. Despite potential error, these estimates suggest that roughly half of the ^{10}Be deposited during the last 4.5 Ma, after accounting for radioactive decay, is absent. Thus, it is inferred that a similar amount of surficial sediment on which ^{10}Be was bound was deflated from the area.

Table 2 Beryllium-10 concentrations and inventories at selected sites, Southern High Plains

Depth of Sample (m)	Depth Interval (cm)	^{10}Be Concentration (atoms g^{-1} x 10^{6})	^{10}Be in Interval (atoms cm^{-2} x 10^{10})	Σ ^{10}Be (atoms cm^{-2} x 10^{10})
A. Well T-4, South Washington Street playa, Amarillo, Texas\1 (latitude 35° 9′ N, longitude 101° 51′ W)				
1.5	225	826	29.7	29.7
3.0	378	642	38.8	68.5
7.6	722	373	43.1	111.6
10.7	1105	200	35.4	147.0
15.2	1600	89	22.8	169.8
22.9	2288	50	18.3	188.1
30.5	3050	16	7.8	195.9
38.1	3810	25	15.0	210.9
45.7	760	3.5	.4	211.3
B. R.D. Hicks Well #1, Deaf Smith County, Texas\1 (latitude 35° 6′ N, longitude 102° 28′ W)				
1.5	460	1560	114.8	114.8
7.6	920	69	10.2	125.0
16.8	1520	20	4.9	129.9
32.0	2580	64	26.4	156.3
69.0	2330	85	31.7	188.0
78.0	750	75	9.0	197.0
84.0	900	24	3.5	200.5
C. Composite of samples collected from interplaya areas, Lubbock, Floyd, and Crosby Counties, Texas\2				
2.0	250	489	22.0	22.0
3.0	405	175	12.8	34.8
8.2	865	42	6.5	41.3
15.2	1400	8.7	2.2	43.5

\1 Dry bulk density of samples assumed to be 1.6 g cm^{-3}

\2 Dry bulk density of samples assumed to be 1.8 g cm^{-3}

DISCUSSION

Sparse hydrologic data and landscape stability requiring long time periods to recognize surficial change have prevented a full understanding of geomorphic processes on the Southern High Plains. The data summarized by Tables 1, 2, and 3, however, permit several interpretations regarding surface and near-surface processes.

Sediment Storage and Movement

Radiocarbon dates, paleontologic evidence, and enriched concentrations of ^{10}Be demonstrate net deposition of sediment during late Quaternary time in the several playa bottoms sampled; most of the sediment appears to be eolian. Runoff and sediment-concentration data, extrapolated from nearby areas, may provide reliable estimates of sediment movement by fluvial processes, but probably overestimate sediment infilling by slope wash. If none of the playa sediment deposited by slope wash was removed by deflation, the stored slope-wash sediment would account for a third or less of the total storage (table 1). Because the ^{10}Be data (tables 2 and 3) suggest that over

Table 3 Components of ^{10}Be inventories in selected playa basins, Southern High Plains.[1]

Playa basin[2]	Playa	Floor	Playa basin less floor	
	Percent of Basin Area	Component of Basin Inventory (x 10^{10} atoms cm^{-2})	Percent of Basin area	Component of Basin Inventory (x 10^{10} atoms cm^{-2})
Gentry Pit	4.2	8.6	95.8	42.2
Anton	11.3	23.2	88.7	39.0
Gore Avenue	4.7	9.6	95.3	41.9

	Average Basin Inventory (x 10^{10} atoms cm^{-2})	Percent of Base Inventory N_b[3]
Gentry Pit	50.8	42
Anton	62.2	52
Gore Avenue	51.5	43

[1] Based on measured ^{10}Be inventories, Table 2.

[2] Locations given in Table 1.

[3] Based on assumed base inventory, N_b, of 120 x 10^{10} atoms cm^{-2}.

half of the sediment deposited is later removed, reducing the average ^{10}Be inventories, it follows that no more than 15 percent of playa sediment is of a water-entrained origin. Instead, the data suggest that a large majority of the sediment stored is from eolian deposition, and that net deposition is a small, unmeasured percentage of the sediment flux through playa basins.

The Blackwater Draw Formation is absent in parts of the western Southern High Plains, but eastward it thickens to nearly 30 m (Reeves, 1976). As it thickens downwind, surficial-sediment sizes tend to decrease (Seitheko, 1975), indicating that the primary source of eolian sediment in the Blackwater Draw Formation was the Pecos River valley. The combined results of the sediment and ^{10}Be-budget studies suggest that these patterns may be results of late Quaternary deflation. Gustavson and Holliday (1985) noted that significant deposition of the Blackwater Draw Formation ended at least 40,000 years ago; the lack of Quaternary-age sediment in the western part of the Southern High Plains is probably due to deflation in late-Pleistocene and Holocene time (Reeves, 1983; McCauley and others, 1981).

Recent studies (see Osterkamp and others, 1987) show that dust storms deflate and transport sediment from the Southern High Plains thousands of kilometers downwind. Sorting and estimated quantities of airborn sediment are compatible with the conclusion that most of the Southern High Plains is presently a net source of eolian sediment, playa floors being exceptions of net deposition. It is inferred, therefore, that atmospherically deposited ^{10}Be of the last 40,000 years largely has been removed with sediment from the Southern High Plains by deflation. Although little glacial outwash presently moves through the Pecos River valley, a small but unmeasured inflow of eolian sediment and ^{10}Be is added from the west.

Assuming that the influx of eolian sediment with adsorbed ^{10}Be to the area is small compared to that leaving, differences between the base inventory and the measured average basin ^{10}Be inventories provide a means of estimating losses by deflation. From Table 3, up to 50 percent of the ^{10}Be base inventory, or 60 x 10^{10}atoms cm^{-2}, is missing and presumed transported eastward. If during the last 40,000 years (after cessation of Blackwater Draw Formation deposition), surficial sediment had a mean ^{10}Be concentration of 1,000 x 10^6 atoms g^{-1} and a bulk density of 1.8, it is easily calculated that an average of 4,000 mm, or 0.1 mm yr^{-1}, of eolian erosion ocurred. This estimate converts to a yield of 140 m^3 km^{-2} yr^{-1}, or 35 times the estimated sediment eroded by water (table 1). The calculated denudation rate of 100 mm per 1,000 years is consistent with rates measured in numerous other settings (Saunders and Young, 1983). Although error in these estimates may be substantial, the calculations demonstrate that much of the Southern High Plains is generally degradational, and that most sediment deposited on playa floors is stored temporarily and then remobilized.

Playa Processes

Table 2 shows that ^{10}Be is highly enriched by playa processes. Because most playa sediment is not stored permanently and because about half of the playa ^{10}Be occurs in Ogallala Formation beds too old to retain the observed concentrations, it appears that enrichment is caused by emplacement of ^{10}Be during residence in playa bottoms. Comparing concentrations listed in parts A and C of Table 2, for playa and interplaya environments, it is evident that at depths below 5 m, in the Ogallala Formation, as much as a 10-fold enrichment occurs in a playa setting. Explanations for the ^{10}Be enrichment include (1) transport by water descending from playas through the unsaturated zone, (2) transport on particulates descending with water through the unsaturated zone, and (3) local emplacement by regional ground-water flow during periods of high water levels. The third explanation is untenable because ^{10}Be concentrations decrease with depth, and post-Miocene hydrologic isolation of the Southern High Plains largely precludes significant ^{10}Be influx by ground water.

The remaining possibilities suggest that playa lakes provide ground-water recharge because only they appear to account satisfactorily for observed ^{10}Be concentrations. If particulate transport occurs through pipes or other natural conduits beneath playa floors, an erratic profile of ^{10}Be concentrations seems likely. Samples from the Hicks Well (table 2, B) were selected for ^{10}Be analysis because the well is beside a playa with extensive piping. The non-linear erratic ^{10}Be profile from the well is not evidence for particulate transport in the unsaturated zone, but the data are consistent with that possibility. Also consistent with the possibility of downward movement of sediment and ^{10}Be with water is the depth, at least 84 m, to which emplacement has occurred; calculations using accepted aquifer constants and the ^{10}Be partition coefficient suggest an improbability of ^{10}Be migration to that depth solely by solute transport.

In contrast, Well T-4 (table 2, A) exhibits an exponential decrease in ^{10}Be concentrations with depth; no evidence of pipes or similar conduits was apparent. From these observations, it appears unlikely that significant ^{10}Be is transported on sediment into the unsaturated zone. Based on the assumption that ^{10}Be at Well T-4 moves solely by solute transport and that only transport by solution adequately explains the exponential decrease of ^{10}Be with depth, a one-dimensional nonequilibrium solute-transport model was developed to describe the movement.

The model is based on an equation for reactive-solutes movement through soils (Selim and Mansell, 1976):

$$K \frac{\partial C}{\partial t} + \theta \frac{\partial C}{\partial t} = - v \frac{\partial C}{\partial z} - \lambda C (K + 1) \qquad (2)$$

in which K is the soil/water partition coefficient for ^{10}Be, C is the ^{10}Be concentration in the soil solution, θ is the soil-water content, v is the Darcy water velocity, and z is depth of the ^{10}Be profile. Simplification and combining with an expanded form of equation 1 leads to an expression for the effective deposition rate of ^{10}Be in playas, q_p:

$$q_p = \lambda \frac{(N_p - N_i e^{-\lambda t})}{1 - e^{-\lambda t}} \qquad (3)$$

in which N_p is the playa ^{10}Be inventory and N_i is the interplaya inventory. Following evaluation of equation 3 and a solution to equation 2 for concentration, an estimate for time, or playa age, is developed in terms of playa ^{10}Be deposition rate, Darcy water velocity, and the ^{10}Be partition coefficient. For the South Washington Street playa, with a surface ^{10}Be concentration of 826 x 10^6 atoms g^{-1} (table 2), age, t, is evaluated as:

$$t = \frac{4.1 \times 10^6 \text{ cm}}{(v - 3.58 \times 10^4 K) \text{ cm yr}^{-1}} \qquad (4)$$

Assuming a Darcy water velocity of 3.0 x 10^4 cm yr^{-1} (Klemt, 1981; W.W. Wood, U.S. Geological Survey, personal commun., 1987), equation 4 suggests that playa initiation occurred about 50,000 years ago. Because the Hicks Well #1 does not exhibit an exponential decline of ^{10}Be concentrations with depth, a similar calculation is not feasible. An inventory for Gentry Pit playa is not available, but near-surface measurements of ^{10}Be suggest a playa age two or three times greater than the 9,500-year age indicated by carbon-isotope analysis (table 1). Regardless of the accuracy that equation 4 provides, the indicated ages are in general support of other dating techniques and suggest that many or most playas are of pre-Holocene age.

ACKNOWLEDGEMENTS Among colleagues who provided invaluable assistance in this study are Milan Pavich, U.S. Geological Survey, Reston, Virginia, who offered suggestions on experimental design as well as sample preparation, and Louis Brown, Department of Terrestrial Magnetism, Carnegie Institution, Washington, D.C., who contributed much of the numerical-modelling effort to yield estimates of playa age. A group of very talented researchers at the Tandem Accelator Laboratory, University of Pennsylvania, did the ^{10}Be analyses; their help, essential to this study, is deeply appreciated.

REFERENCES

Brown, Louis (1987a) ^{10}Be: recent applications in Earth sciences. Philosophical Transactions of the Royal Society, London, A. **323**, 75-86.

______(1987b) ^{10}Be as a tracer of erosion and sediment transport. Chemical Geology (Isotope Geoscience Section), **65**, 189-196.

Brown, Louis, Pavich, M. J., Hickman, R. E., Klein, Jeffrey, & Middleton, Roy (1988) Erosion of the eastern United States observed with ^{10}Be. Earth Surface Processes and Landforms, **13**, 441-457.

Evans, G. L. & Meade, G. E. (1945) Quaternary of the Texas High Plains. Texas Univ. Publ. 4401, 485-507.

Gilbert, G. K. (1895) Lake basins created by wind erosion. Jour. Geol. **3**, 47-49.

Gustavson, T. C., ed. (1988) Guidebook, Tertiary and Quaternary stratigraphy of parts of eastern New Mexico and northwestern Texas. Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas, USA (in press).

Gustavson, T. C. & Holliday, V. T. (1985) Depositional architecture of the Quaternary Blackwater Draw and Tertiary Ogallala Formations, Texas Panhandle and eastern New Mexico. Bureau of Economic Geology Open-file Report OF-WTW1-1985-23, The University of Texas at Austin, Austin, Texas, USA.

Gutentag, E. D., Heimes, F. J., Krothe, N. C., Luckey, R. R., & Weeks, J. B. (1984) Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. U.S. Geological Survey Professional Paper 1400-B.

Holliday, V. T. (1988) Gentry Playa. Origin by geomorphic processes. In: Guidebook, Tertiary and Quaternary stratigraphy of parts of eastern New Mexico and northwestern Texas (ed. T. C. Gustavson), 57-59. Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas, USA (in press).

Klemt, W. B. (1981) Neutron-probe measurements of deep soil moisture as an indication of aquifer recharge rates. Texas Department of Water Resources Report LP-142.

McCauley, J. F., Breed, C. S., Grolier, M. J., & Mackinnon, D. J. (1981) The U.S. dust storm of February, 1977. In: Desert dust; Origin, characteristics and effect on man. (ed. T. L. Pewe), 123-147. Geological Society of America Special Paper 186.

Monaghan, M. C., Krishnaswami, S., & Turekian, K. K. (1986) The global-average production rate of ^{10}Be. Earth and Planetary Science Letters, **76**, 279-287.

Osterkamp, W. R. (1988) Beryllium-10 as a natural tracer of water movement in the unsaturated zone, Southern High Plains of Texas. In: V. M. Goldschmidt Conference, Program and Abstracts. The Geochemical Society, Baltimore, Maryland, USA.

Osterkamp, W. R., Fenton, M. M., Gustavson, T. C., Hadley, R. F., Holliday, V. T., Morrison, R. B., & Toy, T. J. (1987) Great Plains. In: Geomorphic systems of North America. Centennial Special Volume 2 (ed. W. L. Graf), 163-210. Geological Society of America, Boulder, Colorado, USA.

Osterkamp, W. R. & Wood, W. W. (1987) Playa-lake basins on the Southern High Plains of Texas and New Mexico, Part I. Hydrologic, geomorphic, and geologic evidence for their development. Geol. Soc. Amer. Bull. **99**, 215-223.

Pavich, M. J. (1988) ^{10}Be in saprolite and soil. In: V. M. Goldschmidt Conference, Program and Abstracts. The Geochemical Society, Baltimore, Maryland, USA.

Pavich, M. J., Brown, Louis, Harden, Jennifer, Klein, Jeffrey, & Middleton, Roy (1986) ^{10}Be distribution in soils from Merced River terraces, California. Geochim. et Cosmochim. Acta **50**, 1727-1735.

Pavich, M. J., Brown, Louis, Valette-Silver, J. N., Klein, Jeffrey, & Middleton, Roy (1985) ^{10}Be analysis of a Quaternary weathering profile in the Virginia Piedmont. Geology **13**, 39-41.

Raisbeck, G. M., Yiou, F., Lieuvin, M., Ravel, J. C., Fruneau, M., & Loiseaux, J. M. (1981) ^{10}Be in the environment: some recent results and their application. Proc. Symp. on Acceleration Mass

Spectrometry. Argonne National Laboratory, Argonne, Illinois, USA.

Reeves, C. C., Jr. (1966) Pluvial lake basins of west Texas. Jour. Geol. **74**(3), 269-291.

_______ (1976) Quaternary stratigraphy and geologic history of Southern High Plains, Texas and New Mexico. In: Quaternary stratigraphy of North America (ed. W. C. Mahaney), 213-234. Dowden, Hutchison, & Ross, Stroudsburg, Pennsylvania, USA.

_______ (1983) Pliocene channel calcrete and suspenparallel drainagein west Texas and New Mexico. In: Residual deposits: Surface related weathering processes and materials (ed. R. C. L. Wilson), 179-183. Geol. Soc. London.

Saunders, Ian & Young, Anthony (1983) Rates of surface processes on slopes, slope retreat and denudation. Earth Surface Processes and Landforms **8**, 473-501.

Seitlheko, E. M. (1975) Studies of mean particle size and mineralogy of sands along selected transects on the Liano Estacado. MS Thesis, Texas Tech Univ., Lubbock, Texas, USA.

Selim, H. M. & Mansell, R. S. (1976) Analytical solution of the equation for transport of reactive solutes through soils. Wat. Resour. Res. **12**(3), 528-532.

Valette-Silver, J. N., Brown, Louis, Klein, Jeffrey, & Middleton, Roy (1986) Detection of erosion events using ^{10}Be profiles. Examples of the impact of agriculture on soil erosion. Earth and Planetary Sci. Letters **80**, 82-90.

Wood, W. W. & Osterkamp, W. R. (1987) Playa-lake basins on the Southern High Plains of Texas and New Mexico, Part II. A hydrologic model and mass-balance arguments for their development. Geol. Soc. Amer. Bull. **99**, 224-230.

You, C. F., Lee, Typhoon, Brown, Louis, Shen, J. J., & Chen, J. C. (1989) Beryllium-10 study of Taiwan's rapid erosion. Geochim. et Cosmochim. Acta, (in press).