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Investigation of the Meers Fault, Southwestern Oklahoma

Kenneth V. Luza, Richard F. Madole, Anthony J. Crone

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INVESTIGATION OF THE MEERS FAULT, SOUTHWESTERN OKLAHOMA

Kenneth V. Luza
Oklahoma Geological Survey
Norman, Oklahoma

Richard F. Madole
Anthony J. Crone
U.S. Geological Survey
Denver, Colorado

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ABSTRACT

The Meers fault is part of a major system of NW-trending faults that form the boundary between the Wichita Mountains and the Anadarko basin in southwestern Oklahoma. A portion of the Meers fault is exposed at the surface in northern Comanche County and strikes approximately N. 60° W. where it offsets Permian conglomerate and shale for at least 26 km. The scarp on the fault is consistently down to the south, with a maximum relief of 5 m near the center of the fault trace.

Quaternary stratigraphic relationships and 10 ^{14}C age dates constrain the age of the last movement of the Meers fault. The last movement postdates the Browns Creek Alluvium, late Pleistocene to early Holocene, and predates the East Cache Alluvium, 100-800 yr B.P. Fan alluvium, produced by the last fault movement, buried a soil that dates between 1,400 and 1,100 yr B.P.

Two trenches excavated across the scarp near Canyon Creek document the near-surface deformation and provide some general information on recurrence. Trench 1 was excavated in the lower Holocene part of the Browns Creek Alluvium, and trench 2 was excavated in unnamed gravels thought to be upper Pleistocene. Flexing and warping was the dominant mode of deformation that produced the scarp. The stratigraphy in both trenches indicates one surface-faulting event, which implies a lengthy recurrence interval for surface faulting on this part of the fault. Organic-rich material from two samples that postdate the last fault movement yielded ^{14}C ages between 1,600 and 1,300 yr B.P. These dates are in excellent agreement with the dates obtained from soils buried by the fault-related fan alluvium.

ACKNOWLEDGMENTS

We thank David Kimbell and Charlie Bob Oliver for their cooperation and permission to excavate the trenches on the Kimbell Ranch. Mrs. Dixie Oliver, Kimbell Ranch, and Chris and Joe Maranto, Meers General Store, contributed greatly to the operation of the seismograph station. We appreciate the cooperation the landowners have given for this project. We thank Lester Brown for graciously permitting access to the stream-cut exposures on his property. We appreciate Irene Stehli's (Dicarb Radioisotope Co.) diligent work on the samples submitted for age-date determinations. Stephen F. Obermeier and Kenneth S. Johnson reviewed this manuscript and provided several thoughtful suggestions. Kathy Haller prepared many of the samples for ^{14}C age-date determinations.

INTRODUCTION

The southern Midcontinent has been widely regarded as part of the tectonically stable central interior of the United States, with no well-documented cases of Quaternary faulting in the region (Howard and others, 1978). The dispersed seismicity can be spatially related to specific geologic structures only in a general way (Algermissen and others, 1982; Nuttli, 1979; D. W. Gordon, 1985, written commun.). As a result, seismic source zones in the Midcontinent have been defined primarily on the basis of the location of historic earthquake epicenters (P. C. Thenhaus, 1985, written commun.), with a limited contribution from geologic and geophysical data.

Recent mapping in southwestern Oklahoma has identified a prominent scarp in Quaternary alluvium along part of the Meers fault (Fig. 1). The scarp in youthful deposits indicates that movement on the fault may have produced large earthquakes in the geologically recent past (Donovan and others, 1983; Slemmons and others, 1985), and thus the fault may be capable of producing earthquakes in the future. The presence of a possible major seismogenic fault in southwestern Oklahoma raises serious questions about the presumed tectonic stability and the potential for damaging earthquakes in the entire southern Midcontinent. Assessing the earthquake threat posed by the Meers fault requires understanding the characteristics and history of the recent displacements that have created the scarp.

In connection with activities performed under contract NRC 04-82-006-01 to study the seismicity in the vicinity of the Nemaha ridge in Oklahoma, a project was initiated in March 1984 to evaluate recent movement of the Meers fault. An important part of this study included the excavation of two trenches across the Meers fault scarp.

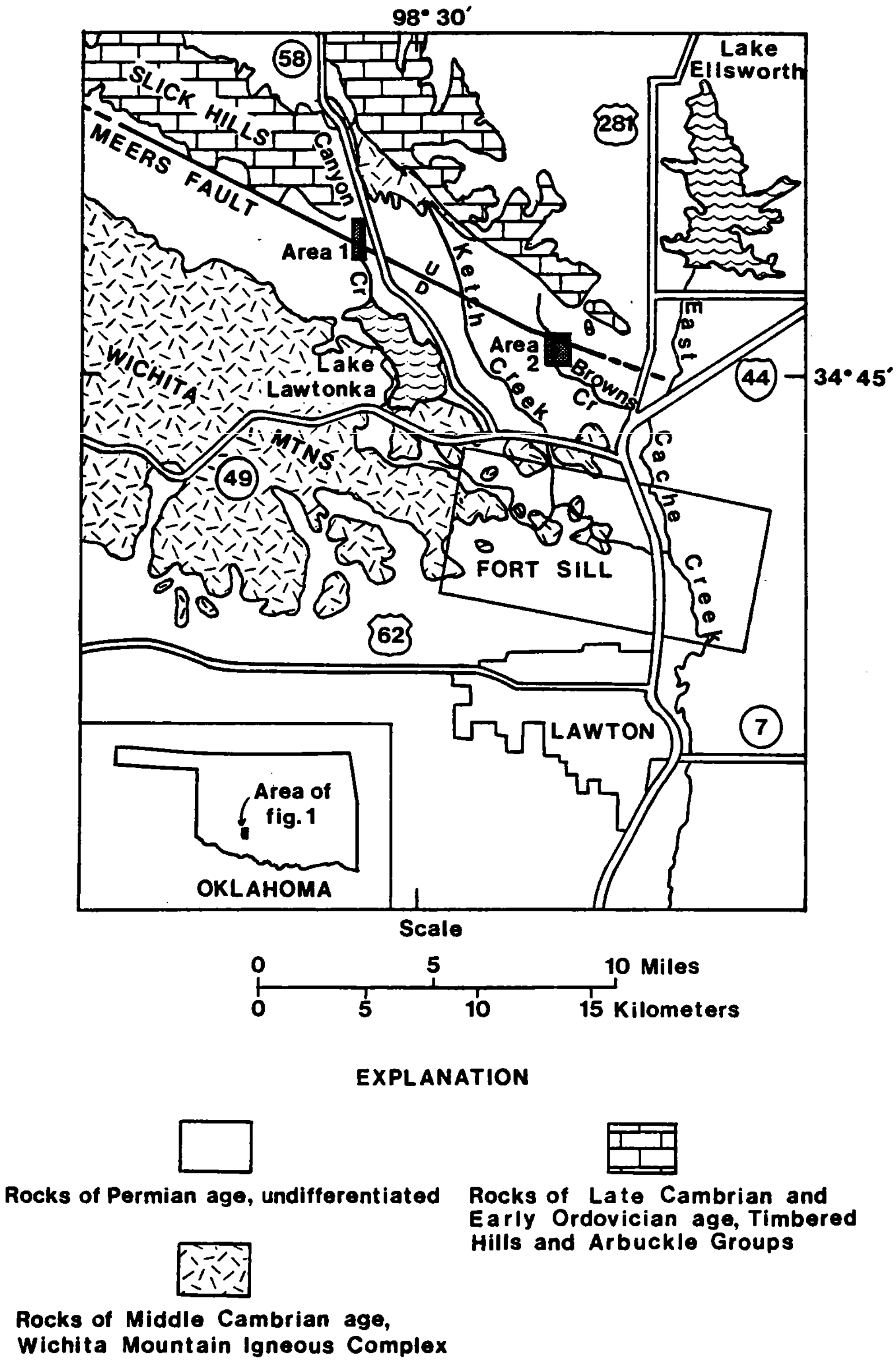

Figure 1. Generalized bedrock geologic map of the region, showing the location of the Meers fault and the two study areas. The trench sites are located in area 1.

The fault scarp is on private land, and, because ranching and farming are the principal land uses in this region, the landowners were concerned with possible long-term erosion problems created by removal of pasture grasses in the vicinity of the trenches. Therefore, the landowner who consented to permit excavation of the trenches on his property requested that the trenches be backfilled and the surface reseeded before April 1, 1984. Unfortunately, the supplemental contract to the Nemaha study was not approved until March. Two weeks of rain in middle to late March limited access to the trench sites and delayed the trenching program until March 1985.

In the interim, Richard F. Madole, U.S. Geological Survey, began a reconnaissance study of the Quaternary stratigraphy in the vicinity of the Meers fault (Madole and Rubin, 1985). Regional and the local Quaternary stratigraphic relationships determined from this study were useful in interpreting the history of recent movement of the Meers fault. Furthermore, the study served as a guide for locating trench sites that would yield pertinent information about the fault's recent history.

A microearthquake study was initiated in April 1984. A volunteer-operated seismograph station, which consisted of a Geotech S-13 short-period vertical seismometer and a Sprengnether MEQ 800-B recording unit, was installed 2 km north of the fault trace. In May 1985, Meers fault station MFO was closed, and a new station, MEO, was opened on June 11, 1985. This station is located at the store in Meers, 3.9 km southwest of the Meers fault. A 24-month period of monitoring has revealed only two probable earthquakes; however, these two events may only be quarry blasts.

There is a high liklihood that no earthquakes exceeding magnitude 4 have occurred along the Meers fault since Fort Sill was established 116 years ago. No earthquake exceeding magnitude 3 has occurred in this area since station TUL (near Tulsa, Oklahoma) was established in December 1961 (station WMO, west of Meers, Oklahoma, was in operation from December 1961 to June 1971). Only one earthquake exceeding magnitude 1.6 has occurred in the vicinity of the Meers fault since the Oklahoma seismic network was established in 1977. Therefore, the Meers fault has been essentially aseismic for the last 25 years or longer (Lawson, 1985).

This report is divided into three parts. A description of the geologic setting is followed by a discussion of the Quaternary stratigraphy in the vicinity of the Meers fault (by Madole). Two areas, where the fault intersects the valley of Canyon Creek, and an unnamed stream (here referred to as Browns Creek), have the best potential for dating recent movement of the Meers fault (Fig. 1). The only natural cross-sectional exposure of the Meers fault that shows displacement of Quaternary deposits is in the valley of Browns Creek. The Browns Creek area was studied in detail in April and May 1984, and the Canyon Creek area was studied in March 1985.

The third part is the history of faulting interpreted from the trenching studies (by Crone; area 1, Fig. 1). Trench 1, located about 150 m east of Canyon Creek, was excavated in young alluvial deposits thought to be late Pleistocene to early Holocene in age. About 200 m further east, trench 2 was excavated in older deposits thought to be Pleistocene in age. By determining the amount of slip in deposits of different ages, we can identify recurrent movement and, with appropriate age information on the deposits, estimate recurrence intervals and long-term slip rates.

GEOLOGIC SETTING

Southern Oklahoma contains a series of uplifts (Amarillo, Wichita, and Arbuckle) that trend N. 60-70° W. across the southern Midcontinent (Fig. 2). The southeastern end of the trend is terminated by the Ouachita Mountains overthrust belt. The central part of the uplift trend, near Lawton, Oklahoma, contains the Wichita Mountains uplift. The Wichita uplift is a large fault-bounded block, and the magnitude of deformation associated with the uplift gradually diminishes westward toward Amarillo, Texas (Gilbert, 1983a).

The Anadarko, Ardmore, and Marietta basins are north of the Wichita uplift and Waurika-Muenster uplift, and southwest of the Arbuckle uplift (Fig. 3). These basins have a combined width of 60 to 80 km, a length across Oklahoma of 320 km, and contain Paleozoic sedimentary rocks that in places are extensively folded. In the deep parts of these basins, the depth to the top of the basement is estimated to be 9-11 km. The Anadarko basin is the deepest sedimentary basin in the North American craton, having more than 11 km of sedimentary rocks in the deepest part (Rowland, 1974a,b).

The Wichita uplift is bounded on the north and south by major subsurface fault zones. On the north, the Wichita frontal fault system separates the uplift from the Anadarko-Ardmore basins (Harlton, 1963). Most of the movement on this fault system was during the Pennsylvanian. The Meers fault is part of the Wichita Frontal Fault system. To the south, the Burch-Altus-North Fork faults separate the uplift from the Hollis-Hardeman basin (Fig. 3).

General Geologic History and Regional Stratigraphy

Ham and others (1964) recognized three stages in the geologic history of southern Oklahoma. The earliest stage was rifting, dominated by intrusive and

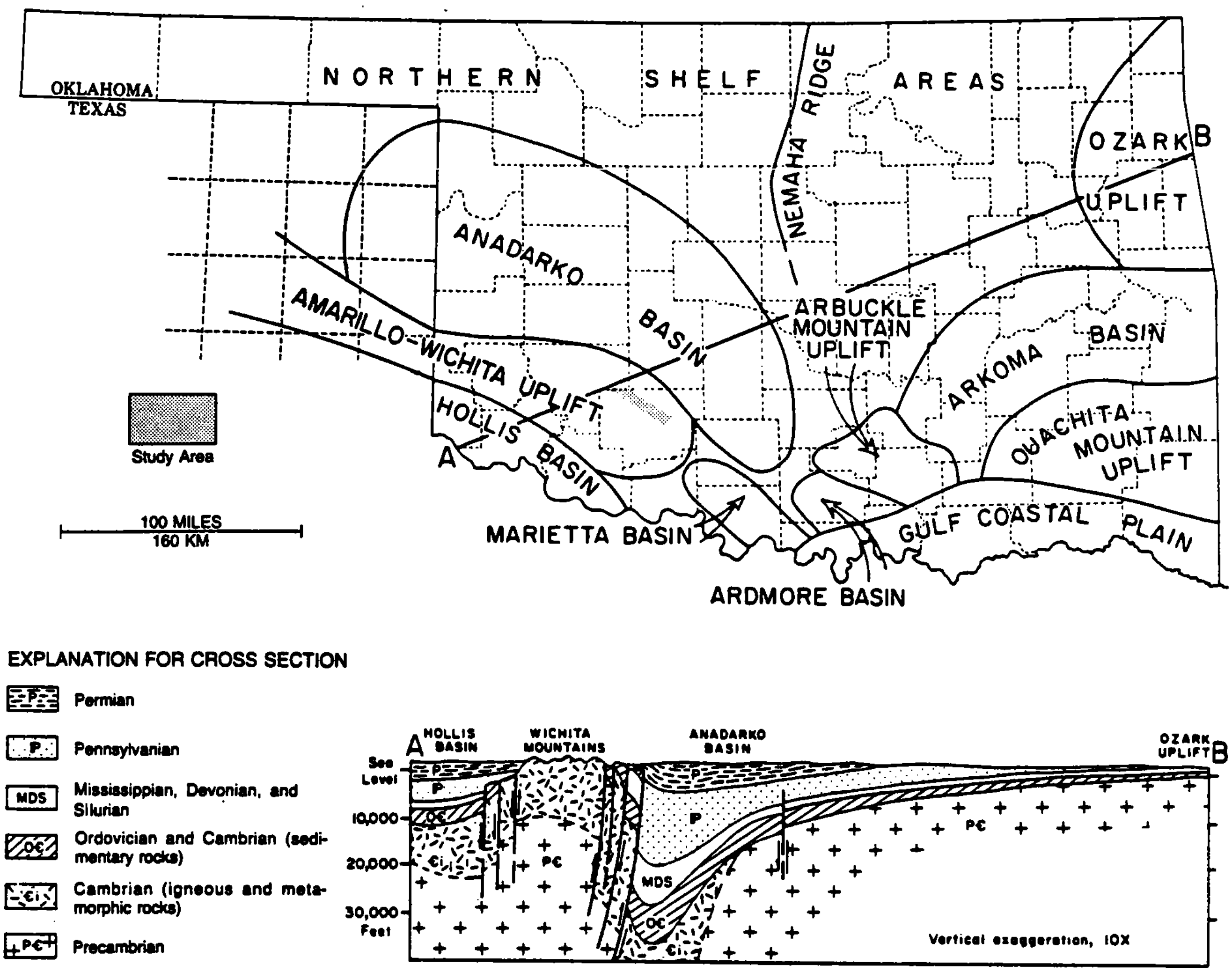

Figure 2. Major geologic and tectonic provinces of Oklahoma (after Johnson and others, 1972). Cross section shows thick Paleozoic sedimentary rocks in Anadarko basin, and the Wichita frontal fault system, which separates the Wichita Mountains and the Anadarko basin.

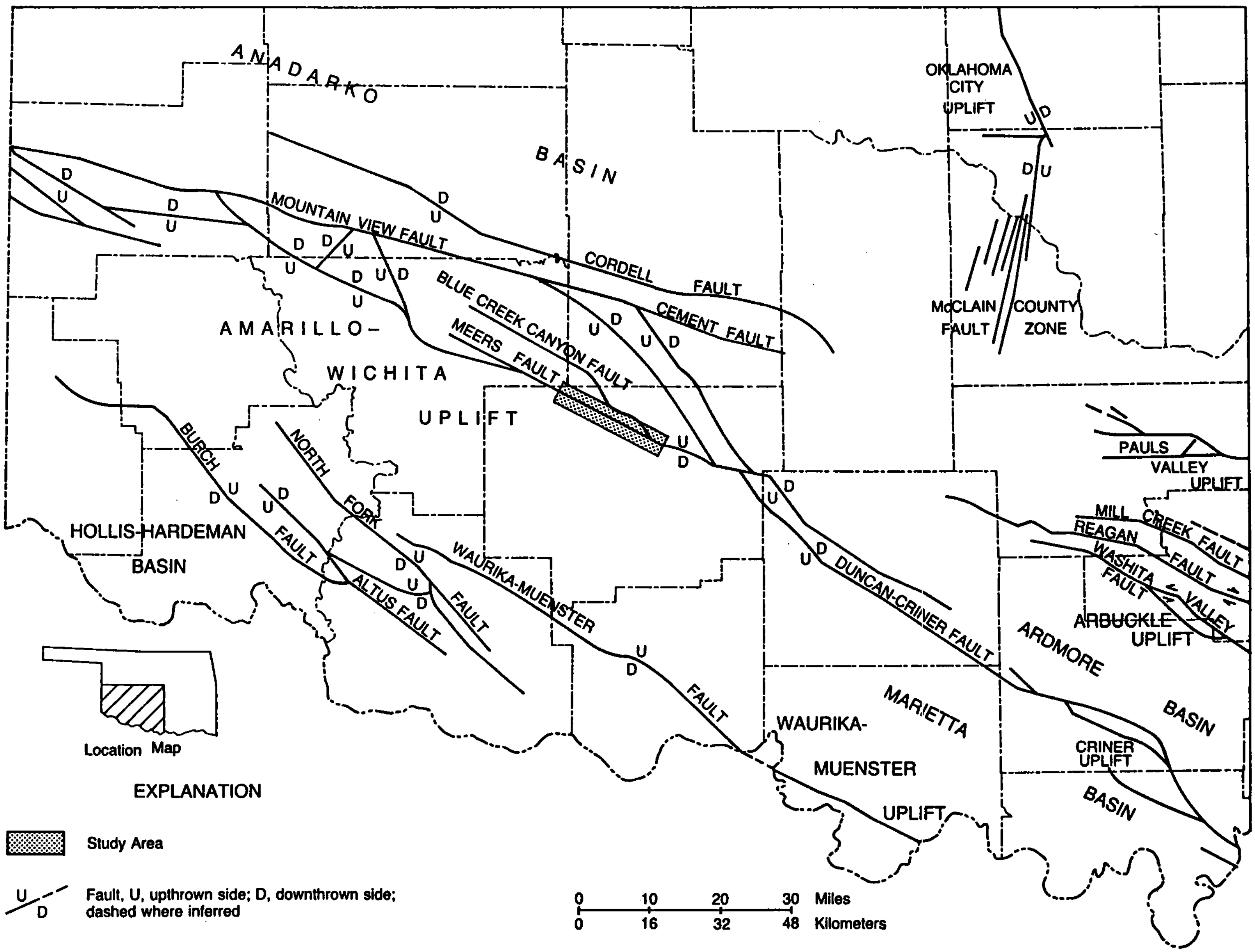

Figure 3. Major structural features in southwestern Oklahoma. Compiled from Ham and others (1964) and Harlton (1951, 1963, and 1972).

extrusive rocks of Eary and Middle Cambrian age (Fig. 4). The igneous rocks consist of an early sequence of gabbro, anorthosite, and troctolite, and a later sequence of hypabyssal granite and rhyolite. Normal faulting associated with crustal extension accompanied the igneous activity (Hoffman and others, 1974; Wickham, 1978). This stage ended with the outpouring of thick rhyolite units.

The second stage of Ham and others (1964), or the subsidence stage of Hoffman and others (1974), is represented mostly by Upper Cambrian through Lower Mississippian carbonates and clean, well-sorted quartz sandstones. In ascending order, the principal stratigraphic units include the Timbered Hills Group, Arbuckle Group, Simpson Group, Viola Group, Sylvan Shale, Hunton Group, and Woodford Shale (Fig. 4). In the deepest part of the basin, the Cambrian to Lower Mississippian sediments have a total thickness of over 3 km (Ham and others, 1964).

During last stage, mostly clastic sediments were deposited from the Late Mississippian through the Permian were deposited. In the deep part of the Anadarko basin, these sediments attained a thickness of more than 7.5 km (Ham and others, 1964). In part, the sedimentation patterns were controlled by the uplift of the Wichita-Amarillo Mountains. Uplift began in the Late Mississippian or Early Pennsylvanian and lasted through the Pennsylvanian (possibly into the Early Permian). Uplift along the Wichita-Amarillo trend probably occurred along preexisting zones of weakness created during the initial Cambrian rifting (Ham and others, 1964).

In the vicinity of the Meers fault, Cambrian-Ordovician rocks are exposed in the Slick Hills (Limestone Hills) along the northeast flank of the Wichita Mountains. These outcrops were exhumed because of erosion of the overlying Permian sedimentary rocks.

SYSTEM	SERIES	GROUP	FORMATION
Quaternary	Holocene		Alluvium, colluvium, dune sand
	Pleistocene		Terrace deposits
Tertiary	Pliocene		Ogallala
	Miocene		
Cretaceous	Upper		
		Dakota	
	Lower		Kiowa
Jurassic			
Triassic			
Permian	Ochoan		Elk City Ss
		Foss	Doxey Sh
			Cloud Chief
	Guadalupian	Whitehorse	Rush Springs Ss
			Marlow
		El Reno	Dog Creek Sh
			Blaine
			Flowerpot Sh
			Duncan Ss
	Leonardian		Hennessey Sh / Post Oak Congl
		Sumner	Garber Ss
			Wellington
	Wolfcampian	Pontotoc	Numerous interbedded sandstone and shale units; some limestone units / Granite Wash - Post Oak
Pennsylvanian	Virgilian	Cisco	
	Missourian	Hoxbar	
	Desmoinesian	Deese	
	Atokan	Dornick Hills	
	Morrowan		
Mississippian	Chesterian	? (Springer) ?	Goddard
			Delaware Creek Sh (Caney Sh)
	Meramecian		Sycamore Ls
	Osagean		
	Kinderhookian		Woodford Sh
Devonian	Upper		
	Middle		
	Lower	Hunton	
Silurian	Upper		
	Lower		
Ordovician	Upper		Sylvan Sh
		Viola	
	Middle	Simpson	Bromide
			Tulip Creek
			McLish
			Oil Creek
			Joins
	Lower	Arbuckle	West Spring Creek
			Kindblade
			Cool Creek
			McKenzie Hill
Cambrian	Upper		Butterly Dol
			Signal Mountain Ls
			Royer Dol
			Fort Sill Ls
		Timbered Hills	Honey Creek Ls
			Reagan Ss
	Middle	Wichita Granite; Carlton Rhyolite	
	Lower	Navajoe Mtn Basalt	
		Raggedy Mtn Gabbro	
Precambrian		Tillman Meta-sedimentary	

Figure 4. Generalized stratigraphic column for west-central portion of the Anadarko basin (modified from Moore, 1983; R. O. Fay personal communication, 1986).

Decker (1939a,b) Chase and others (1956), and Donovan (1982, 1986) have provided excellent discussions of the sedimentary rock units in the Slick Hills. The Carlton Ryolite Group is the oldest rock unit exposed in the vicinity of the Meers fault (Fig. 5). The best exposures are a few kilometers north of the fault, on the east side of Canyon Creek. The Timbered Hills Group, which comprises the basal Reagan Sandstone and overlying Honey Creek Limestone, unconformably rest on the Carlton Rhyolite Group. The Arbuckle Group, which overlies the Timbered Hills Group, comprises over 1,200 m of sedimentary rocks, mainly thin- to thick-bedded limestones with numerous intraformational flat-pebble conglomerates. The Cambrian portion of the Arbuckle Group present near the fault comprises the Fort Sill and Signal Mountain Formations. The Ordovician portion of the Arbuckle Group consists, in ascending order, of the McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek Formations.

Approximately 2000 m of Middle Ordovician through Early Mississippian rocks were deposited in this area, but these units were eroded as a result of the uplift of the Wichita Mountains in Pennsylvanian time. With continued erosion, the mountains were lowered, and many Upper Pennsylvanian and Permian formations contain limestone, rhyolite, and granite conglomerates derived from older Paleozoic rocks exposed in the nearby high-relief areas.

The Permian sedimentary rocks that surround the eastern two-thirds of the Wichita Mountains were designated the Wichita Formation by Miser (1954). The Post Oak Conglomerate Member of the Wichita Formation was thought to be equivalent in age to the Wellington Formation in south-central Oklahoma (Chase, 1954). However, the term Wichita Formation was dropped when subsequent geologic mapping determined that this unit contained several formations younger

SYSTEM	SERIES	GROUP	FORMATION	
Quaternary	Holocene		Alluvium; colluvium	
	Pleistocene		Terrace deposits	
Permian			Hennessey Sh	Post Oak Congl
Ordovician	Lower	Arbuckle	West Spring Ck	Post Oak Conglomerate (Permian sediments truncate these rock units)
			Kindblade	
			Cool Creek	
			McKenzie Hill	
Cambrian	Upper		Signal Mtn Ls	
			Fort Sill Ls	
		Timbered Hills	Honey Creek Ls	
			Reagan Ss	
	Middle	Carlton Rhyolite		

Figure 5. Generalized stratigraphic column for the rocks exposed in the vicinity of the Meers fault (modified from Donovan, 1982).

than the Wellington; subsequently, the Post Oak Conglomerate was given formation status (Fay, 1968).

The Post Oak Conglomerate, which is exposed in the eastern half of the Wichita Mountains, surrounds exposures of the igneous and lower Paleozoic sedimentary rocks. The conglomerate ranges from a 120-m-thick series of interstratified arkose and shale beds to 180 m of boulder conglomerate in and near the mountains (Chase and others, 1956). On the north side of the Wichita Mountains, the conglomerate is composed mostly of limestone boulders and pebbles derived from the Slick Hills. The limestone conglomerate grades southward to a granite-boulder conglomerate near the igneous-rock outcrops, and it interfingers with marine red shale and fine-grained, calcareous sandstone away from the outcrop areas (Chase and others, 1956). In T4N, R13-14W, the limestone-conglomerate facies of the Post Oak is offset by the Meers fault.

Structural Setting of the Meers Fault

The Meers fault is part of a complex system of NW-trending faults forming the boundary between the Wichita Mountains and the Anadarko basin. This fault system, generally referred to as the Wichita frontal fault system, extends for approximately 475 km across southern Oklahoma and part of the Texas Panhandle (Harlton, 1963; Ham and others, 1964). The Mountain View fault, Duncan-Criner fault, Cordell fault, and the Meers fault are the major fault segments that comprise the Wichita frontal fault system (Fig. 3). The frontal fault system is dominated by moderately dipping to steeply dipping reverse faults which have a combined net vertical displacement of over 9 km (Ham and others, 1964). Of these faults, the Meers fault has the greatest net throw, about 6.4 km.

Harlton (1951), who did field work in the late 1930s, originally named the Meers fault the Thomas fault, for exposures in T4N, R13-14W, on the George Thomas Ranch. Harlton described the fault trace as a continuous, straight line that offsets Permian sediments (Fig. 6). Harlton reasoned that this fault is, in part, responsible for the large structural offset between the Wichita Mountains to the south and the Cambrian-Ordovician rock exposures on the north. The fault was originally described as down to the south (Harlton, 1951). However, regional and subsurface data indicated that a major fault in the vicinity of the surface Meers fault was part of the frontal fault zone, which has an overall down-to-the-north displacement (Harlton, 1963). Important data of Ham and others (1964) on the basement rocks and structural evolution of southern Oklahoma support this view.

On the Geologic Map of Oklahoma, Miser (1954) renamed the Thomas fault the Meers Valley Fault. Ham and others (1964) and Havens (1977) dropped the word "Valley" from the fault name. Today, the commonly accepted name for Harlton's Thomas fault is the Meers fault.

The Meers fault trends N. 60° W. and displaces Permian conglomerate and shale for a distance of at least 26 km, from near the Comanche-Kiowa County boundary to East Cache Creek. At the northwest end of the fault trace, the fault displaces limestone-pebble conglomerates (Post Oak), whereas at the southeast end sandstones and calcrete-bearing shales of the Hennessey are displaced. The topographic expression of the fault is consistently down-to-the-south; the highest scarps are 3-5 m high along the central part, about 5 km southeast of State Highway 58 in sec. 33, T4N, R12W. Harlton (1963) extended the fault from the outcrop northwestward into the subsurface to the Texas-Oklahoma state line and southeastward to the intersection with the Criner uplift.

Figure 6. Aerial view (looking north) of the Meers fault displacing Post Oak Conglomerate on the Kimbell Ranch (secs. 15, 16, T4N, R13W). Photograph by D. B. Slemmons, 1983.

The topographic scarp was initially interpreted as a fault-line scarp. The date of the last movement was thought to be Permian and related to the last adjustment between the Anadarko basin on the north and the Wichita uplift on the south.

Moody and Hill (1956) briefly noted that the Meers fault (Thomas fault) offsets Quaternary alluvium, and that the fault scarp is recent. This observation was generally overlooked until Gilbert (1983b,c) presented convincing evidence to support Quaternary movement on the Meers fault. Gilbert (1983b,c), Donovan and others (1983), and Tilford and Westen (1984,1985) presented geomorphic evidence for recent movement. Their arguments are strongly supported by the continuity of the fault trace across Paleozoic rocks and Quaternary alluvium. Other evidence supports recent movement. For example, streams flowing normal to the fault scarp have incised channels into bedrock on the upthrown side of the fault and deposited recent alluvial fans on the downthrown side. In addition, Quaternary deposits exposed in a stream cut in sec. 2, T3N, R12W (Browns Creek exposure) are clearly offset by the fault.

QUATERNARY STRATIGRAPHY

Attention was focused on the southeast half of the area where a prominent scarp is associated with the Meers fault, because the valleys there have an alluvial stratigraphy that can be used to date movement on the fault. The scarp is more impressive in the northwest half of the area, where the Meers fault offsets the resistant Post Oak Conglomerate, but the potential for dating fault movement is poor in that area because Quaternary alluvial deposits are sparse. Because of the high relief in the Post Oak Conglomerate, the streams flow in relatively steep, narrow valleys. On the upthrown (northeast) side of the fault, the streams have removed most of what little alluvium might have floored the valleys and have incised channels into bedrock. Downstream (southwest) from the fault, aggradation has dominated, cutbank exposures are small and shallow, and recent flood deposits conceal older alluvium over much of the area.

Two valleys that cross the southeast half of the Meers fault were identified as offering the best potential for study. These localities are where the fault intersects the valleys of Canyon Creek and informally named Browns Creek (areas 1 and 2, Fig. 1). The valley of Canyon Creek is the largest intersected by the fault and has the greatest volume of alluvium and the most extensive Quaternary stratigraphy. The valley of Browns Creek is the second largest intersected by the fault and has the only exposure of the Meers fault displacing Quaternary deposits.

Alluvial Stratigraphy

Six fluvial allostratigraphic units were identified in the study areas (Figs. 7,8). The units range in age from late Holocene to middle Pleistocene,

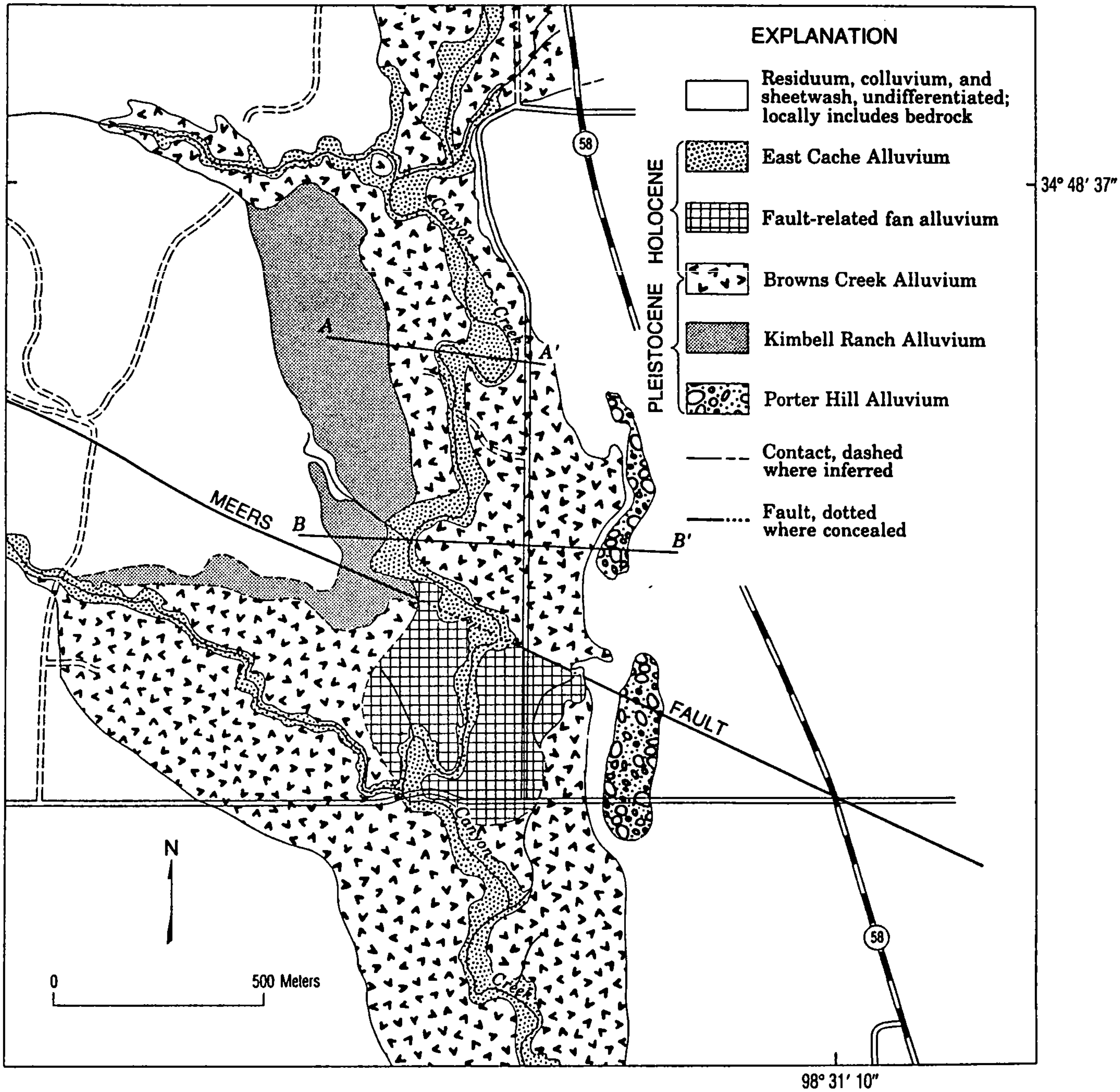

Figure 7. Map of surficial deposits along Canyon Creek (area 1, Fig. 1). Lines A-A' and B-B' are locations of cross sections shown in Figure 10.

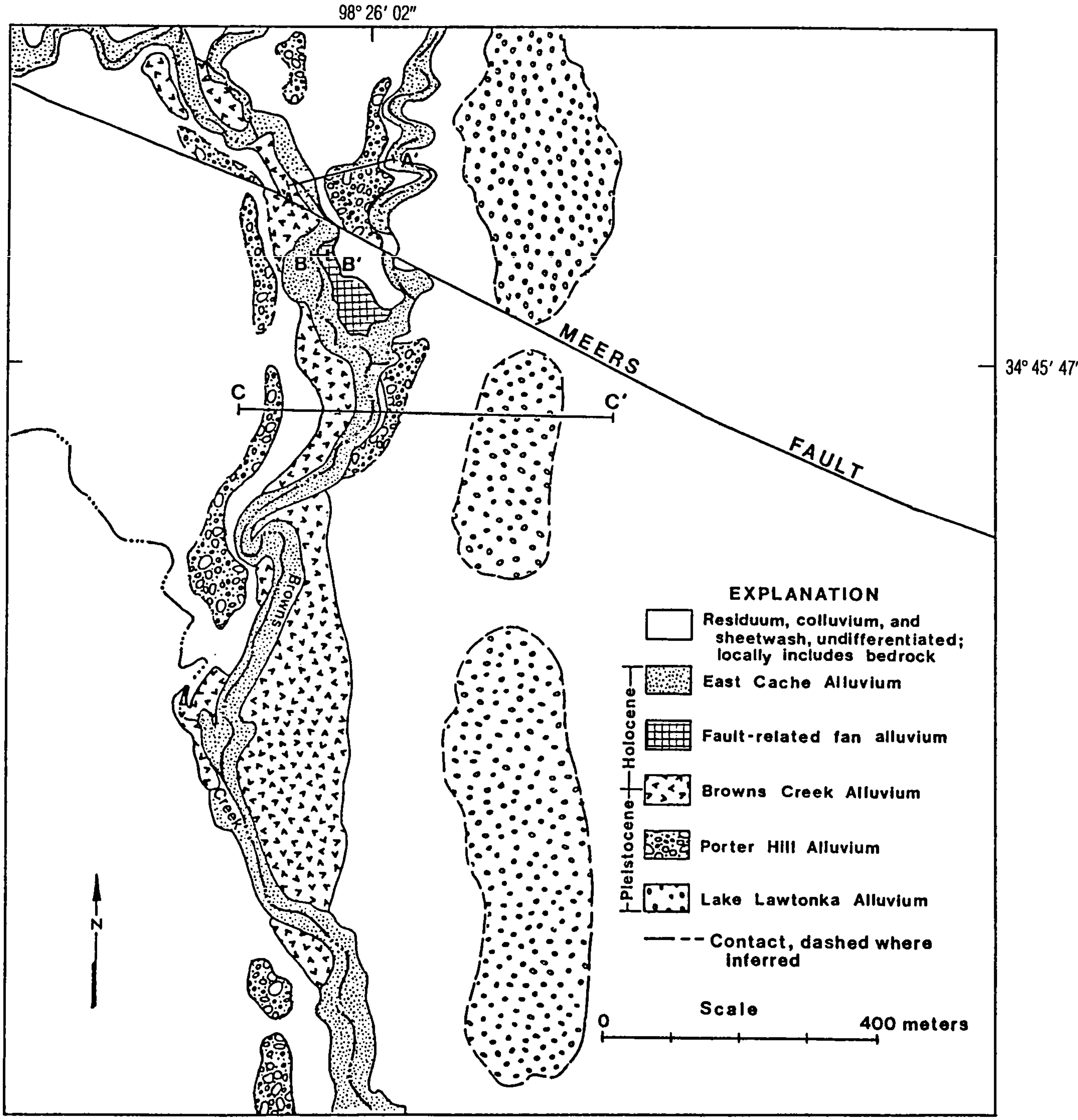

Figure 8. Map of surficial deposits along Browns Creek (area 2, Fig. 1). Lines A-A', B-B', and C-C' are locations of cross sections shown in Figure 11.

and possibly even to early Pleistocene. Five units are believed to have regional distribution, but the sixth unit exists only in close proximity to the fault, to which it is genetically related. Because of the special nature of the fault-related deposits, they are discussed separately. The alluvial units are identified and correlated by (1) their position in the landscape, (2) superposition and crosscutting relations, and (3) differences in the soils formed in them (Fig. 9).

Allostratigraphic units (North America Commission on Stratigraphic Nomenclature, 1983) are defined by the discontinuities that bound them, rather than by differences in lithology. Lithologic characteristics may be useful for identifying units within a given drainage basin, but not between drainage basins, unless the basins are underlain by similar rock types and the streams are of similar size. A given unit differs lithologically from one drainage basin to another in much the same way as do present-day stream deposits. Consequently, detailed descriptions of lithology are not given for each unit in this report.

Differences in soil development, particularly depth of leaching and carbonate morphology (Gile and others, 1966), are useful for identifying and correlating units. The degree of soil development is also used to estimate the ages of the deposits and to check the reasonableness of ^{14}C ages. Soil data must be interpreted carefully, however, because erosion has removed the upper part of the soil profile in many places, especially on the older Pleistocene deposits.

Lake Lawtonka Alluvium

The oldest recognized unit in the area, the Lake Lawtonka Alluvium, is here named for exposures in the vicinity of Lake Lawtonka, in north-central

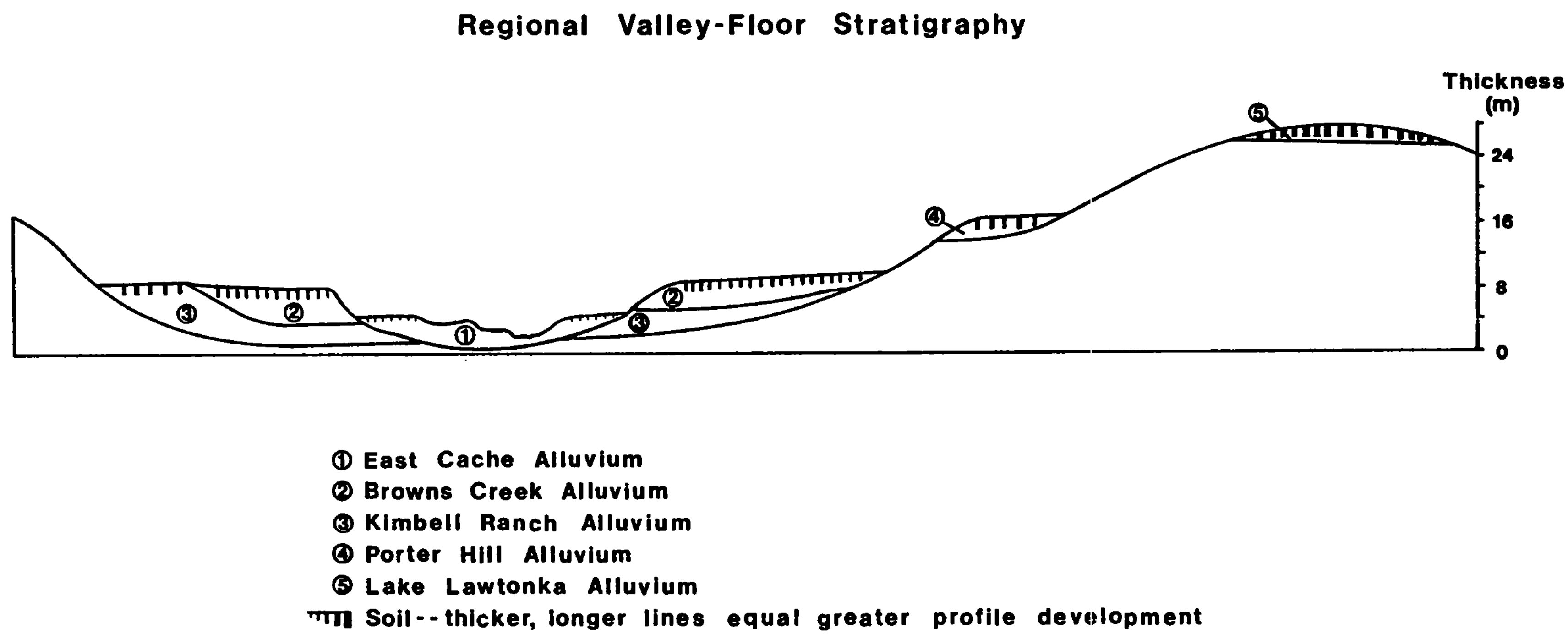

Figure 9. Schematic diagram showing stratigraphic relations of five allostratigraphic units present along the larger streams of the area.

Comanche County, southwestern Oklahoma. Individual deposits of alluvium are difficult to relate to each other or to paleovalley systems because they are poorly exposed and widely separated in small remnants on interfluves. One such gravel remnant serves as a type locality and can be found in roadcuts along both sides of Oklahoma Highway 58 in the SE 1/4 of sec. 31, T4N, R12W, in Comanche County. This deposit is largely composed of rhyolite clasts. Another deposit on a ridge about 5 km to the east that trends north-south through the center of sec. 2, T3N, R12W, just east of Browns Creek, is composed mostly of clasts of limestone and granite.

The Lake Lawtonka Alluvium may include deposits of more than one age. The deposits are on the higher parts of interstream areas (Fig. 9) and clearly predate formation of the present-day valley system. Some deposits are near and approximately parallel to present-day streams, and others are remote from them. The topography has inverted since the Lake Lawtonka Alluvium was deposited.

Stratigraphic information about the Lake Lawtonka Alluvium is limited to observations in a few shallow roadcuts. The distribution of the Lake Lawtonka Alluvium is inferred partly from the distribution of the Lawton soil series (Mobley and Brinlee, 1967), the principal soil developed in this alluvium. Most deposits of Lake Lawtonka Alluvium are estimated to be 2-5 m thick and composed mainly of reddish-brown gravel overlain by thinly bedded fine sand, silt, and clay. Estimates of thickness and lithology are based in part on a presumed similarity to Porter Hill Alluvium, which is better exposed.

The Lake Lawtonka Alluvium is at least as old as middle Pleistocene (defined here as 790,000-130,000 yr B.P.) and is possibly as old as early Pleistocene (1,700,000-790,000 yr B.P.). The age of the unit is estimated on the basis of its position in the landscape and the strongly developed soil formed in it. The soil is thicker, redder, and more clayey than soils developed in the other units and appears, at least locally in two road cuts, to have a K horizon with stage III carbonate morphology (Gile and others, 1966).

Stage III carbonate morphology is characterized by essentially continuous coatings of carbonate that impart a white color to the soil. Stage II carbonate morphology also is present in some soils in this area. Stage II differs from Stage III in that carbonate coatings are not continuous. Stage II in nongravelly parent materials is characterized by the development of nodules, and, in gravelly materials, it is characterized by carbonate coatings that are generally continuous on clasts but discontinuous in the matrix.

Depth of leaching in the Lake Lawtonka Alluvium is as much as 1.9 m. The Lawton soil series is defined as having developed in noncalcareous alluvium. However, judging from the younger alluvial deposits, most alluvium in this area was initially calcareous. Therefore, the noncalcareous character of the Lawton soil in this area is attributed to leaching over a long time, rather than to derivation from noncalcareous sources.

Porter Hill Alluvium

The Porter Hill Alluvium is here named for Porter Hill, located at the intersection of U.S. Highways 277 and 281/62 in north-central Comanche County, southwestern Oklahoma. A type locality is designated in a cutbank exposure on the west side of Browns Creek in the SE1/4 SW1/4 NW1/4 sec. 2, T3N, R12W, Comanche County. Another representative exposure is present about 180 m northeast of where the Meers fault crosses Browns Creek along the west bank of a stream tributary to Browns Creek. This locality is in the NW1/4 NE1/4 NW1/4 sec. 2, T3N, R12W. The Porter Hill Alluvium also is poorly exposed near Canyon Creek in a roadcut in the SE1/4 SW1/4 SW1/4 sec. 24, T4N, R13W.

The Porter Hill Alluvium is a stream-terrace deposit that, unlike the Lake Lawtonka Alluvium, is related to present-day valleys (Figs. 9-11). Only one terrace was found in the study areas. Along Browns Creek, the upper surface of the terrace is about 9-14 m above stream level, and along Canyon Creek it is about 16 m above stream level.

The Porter Hill Alluvium ranges in thickness from 2.3 m to 3.9 m at five localities. Gravel is a major component of the alluvium, and the deposits are oxidized throughout; red hues (5YR and 7.5YR)[1] dominate. Along Browns Creek, the lower one-third (1.3-1.6 m) is pebble gravel, whereas the upper two-thirds (2.1-2.5 m) is mud (chiefly clay and silt) and sand. Almost all of the upper part has 5YR hues, and the clayey strata are heavily mottled with iron oxide and contain mottles and 1-mm specks of manganese oxide. Along Canyon Creek, Porter Hill Alluvium was studied in only two exposures, a trench excavated across the Meers fault and a roadcut just south of the trench. At these two sites, the alluvium is mostly gravel, 2.5 m thick and 2.3 m thick, respectively, capped by about 0.5 m of finer sediment. The gravel unit consists of 25-40% clasts, predominantly pebbles, but includes abundant small and large cobbles and a few small boulders. The matrix is sticky, mostly noncalcareous, red, clayey sand.

The age of the Porter Hill Alluvium is not known; however, its position in the landscape and the soil developed in it suggest that it is significantly older than 30,000 yr B.P. It probably was deposited during middle Pleistocene time (790,000-130,000 yr B.P.). A detailed study was not made of the soil developed in this unit, because it is difficult to find natural exposures where

[1]Color descriptions are based on the Munsell Soil Color Chart (Munsell Color Co., Inc., Baltimore, Md.)

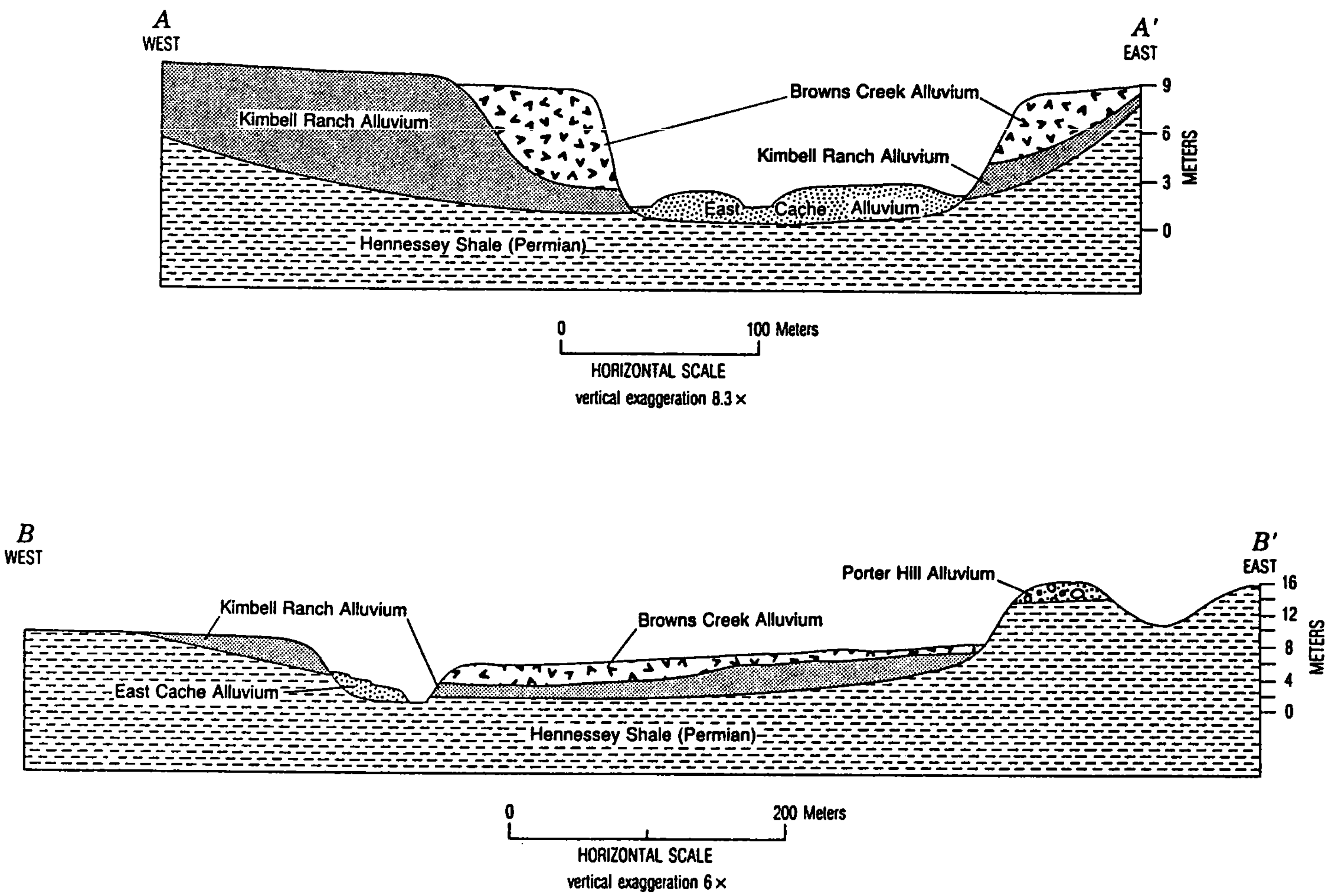

Figure 10. Cross-sections showing stratigraphic relations of alluvial units along Canyon Creek. Section locations are shown in Figure 7.

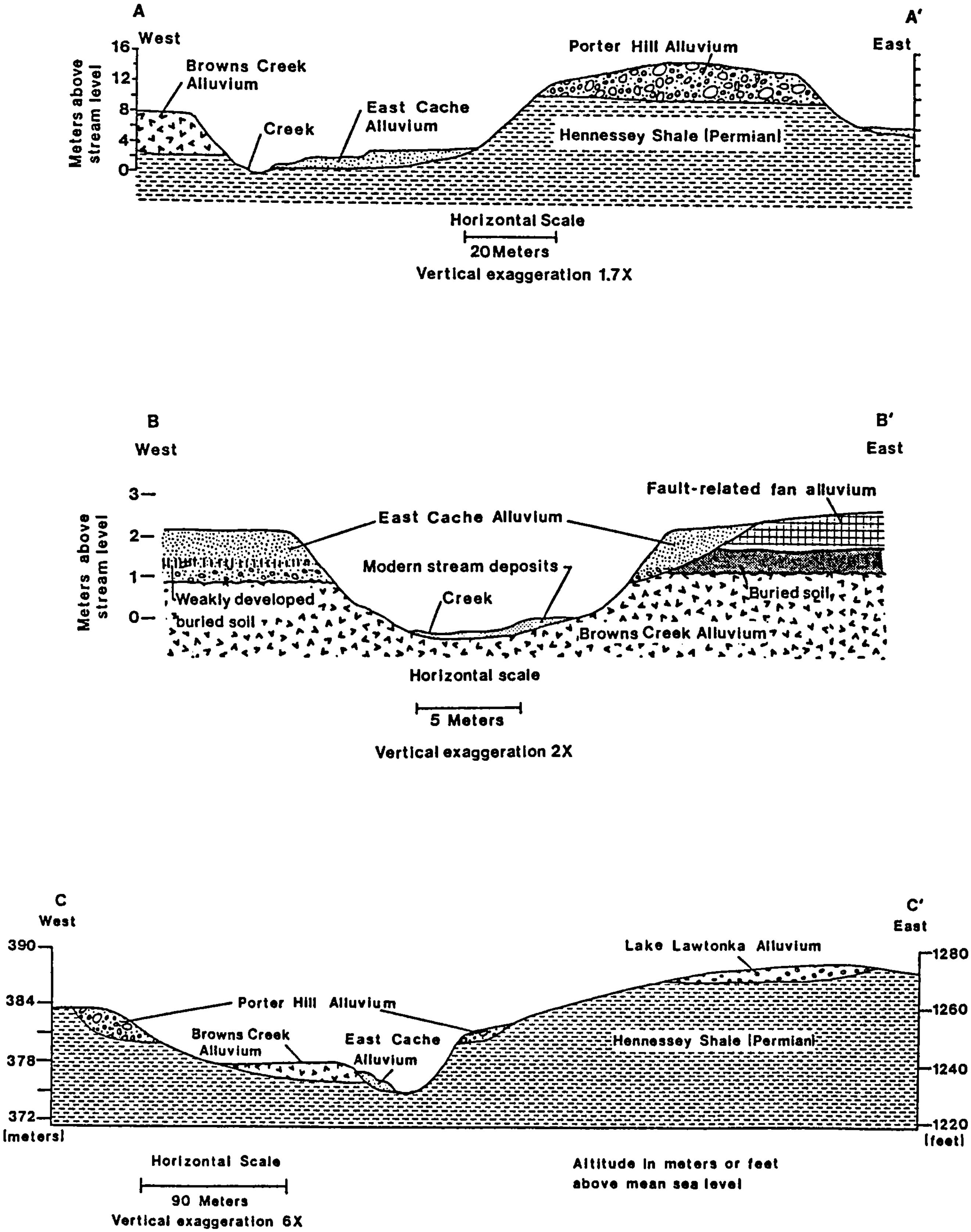

Figure 11. Cross-sections showing stratigraphic relations of alluvial units along Browns Creek. Section locations are shown in Figure 8.

a complete soil profile is present. In most places, erosion has stripped part or all of the relict soil. A weak stage-III carbonate morphology is developed locally in gravelly parent material.

Kimbell Ranch Alluvium

The Kimbell Ranch Alluvium is here named for the Kimbell Ranch, which is located on Canyon Creek in the NE corner sec. 14, T4N, R13W, in north-central Comanche County, Oklahoma. A type area is designated along the valley of Canyon Creek for about 0.8 km upstream from the point where the Meers fault crosses the valley floor. The most complete section is exposed in gully banks on the west side of the valley near the fault in the NW1/4 NE1/4 SE1/4 sec. 23, T4N, R13W. The alluvium is also exposed at all localities along Canyon Creek where reference sections are identified for the overlying Browns Creek Alluvium.

The Kimbell Ranch Alluvium was observed only in the Canyon Creek area. It has a similar appearance (in color and texture) to the Porter Hill Alluvium in this valley, but occupies the valley floor, rather than a terrace. The Kimbell Ranch Alluvium is exposed in numerous stream cuts and gully banks along the valley axis, but is overlain by Browns Creek Alluvium over much of the valley floor (Figs. 9,10). The Kimbell Ranch Alluvium is easy to distinguish from the younger valley-floor alluvial deposits because it is red and contains gravel, whereas the younger deposits are brown and predominantly silt and clay.

The Kimbell Ranch Alluvium is clast-supported pebble and cobble gravel interbedded with lesser amounts of red, muddy sand. The coarser gravel is mostly in discontinuous beds 20-30 cm thick. Much of the Kimbell Ranch Alluvium was eroded prior to deposition of the Browns Creek Alluvium. The axis of the valley cut into Kimbell Ranch Alluvium is now filled with the thickest sections of Browns Creek Alluvium. Along this axis, only 1.4-1.5 m of Kimbell Ranch alluvium remains. The maximum thickness of Kimbell Ranch Alluvium is unknown because of poor exposure, but it is estimated to be 7-9 m.

The age of the Kimbell Ranch Alluvium is not known precisely. It is older than 14,000 yr B.P., the age of the basal part of the Browns Creek Alluvium, and is judged to be significantly younger than the Porter Hill Alluvium on the basis of the amount of valley deepening that occurred between deposition of these two units. Conceivably, the Kimbell Ranch Alluvium could be as old as 150,000-130,000 yr B.P.

Browns Creek Alluvium

Browns Creek Alluvium is here named for Browns Creek, an informally designated tributary to East Cache Creek. A type locality is designated for cutbank exposures on the west side of Browns Creek about 80 m upstream from where the Meers fault crosses the creek. The exposures are in the NE1/4 NW1/4 NW1/4 sec. 2, T3N, R12W. A reference section for the Browns Creek Alluvium in the valley of Canyon Creek is located in a cutbank about 0.7 km upstream from the point where the Meers fault crosses Canyon Creek. The section is on the west side of Canyon Creek in the NW1/4 SE1/4 NE1/4 sec. 23, T4N, R13W. Two additional reference sections are found in cutbank exposures in this valley, one located 200 m upstream to the east, and another located 475 m to the north of the reference section identified above.

Browns Creek Alluvium underlies the modern valley floors of the area and locally forms a terrace on the upthrown side of the Meers fault because of post-faulting stream incision (Figs. 9-11). The alluvium is composed mainly of mud and sand and is generally more drab in color than the older alluvial deposits. In the valley of Browns Creek, the Browns Creek Alluvium is predominantly browns of 10YR hue, whereas the older alluvial deposits are redder, mostly 7.5YR and 5YR hues. In the valley of Canyon Creek, Browns Creek Alluvium is predominantly of 5YR hue, whereas the older alluvial deposits are even redder (2.5YR).

Browns Creek Alluvium is 5-6 m thick in the Browns Creek area and 6-7 m thick in the Canyon Creek area. Along Browns Creek, it is mostly thinly bedded and clayey. Stratification is weakly expressed, and most strata, except a few sandy beds, are mottled with iron oxide and minor manganese oxide. Along Canyon Creek, the contact between Browns Creek Alluvium and Kimbell Ranch Alluvium rises toward the valley sides, and in places the two units are side by side at the surface (Figs. 9,10). Where they are side by side, their upper surfaces may or may not be separated by slight topographic breaks; thus, the contact between them is not easily located. The two units can be differentiated, however, on the basis of the soils developed in them.

Three ^{14}C ages of samples from the Browns Creek Alluvium indicate that it began to be deposited about 14,000 yr B.P. (Table 1). Snails from the base of the Browns Creek Alluvium along Browns Creek, about 80 m upstream from the fault, yielded a ^{14}C age of 13,670 ± 120 yr B.P. (Sample DIC-3166[2]). At two localities along Canyon Creek, lenses of clayey sediment contained enough colloidal-sized organic matter for radiocarbon dating. At one locality about 1 km downstream from the fault, an organic-rich lens of clayey sediment at the

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[2]Samples for ^{14}C dating were pretreated with alkaline solutions to remove soluble organic contaminants, and with acidic solutions to remove inorganic carbonates. Both of these components may contribute to inaccurate dates.

TABLE 1.--RADIOCARBON AGES OF ALLUVIAL DEPOSITS USED TO DATE MOVEMENT ON THE MEERS FAULT

Stratigraphic Unit	^{14}C Age	Laboratory No.	Stratigraphic Position	Material
East Cache Alluvium	70 ± 150	DIC-3165	near the floor of present stream channel	charcoal and carbonized wood
	310 ± 150	W-5533	same interval as above	clay-humus
	470 ± 150	W-5540	35-55 cm above bottom contact	soil-humus
	600 ± 50	DIC-3161	1.6 m above bottom contact	charcoal
Fault-related alluvium	1,280 ± 140	DIC-3167	beneath bottom contact	charcoal
	1,360 ± 100	DIC-3169	beneath bottom contact	soil humus
	1,740 ± 200	W-5543	beneath bottom contact	soil humus
Browns Creek Alluvium	9,880 ± 160	DIC-3179	70-90 cm above bottom contact[1]	clay-humus
	12,240 ± 240	DIC-3170	25-30 cm above bottom contact	clay-humus
	13,670 ± 120	DIC-3166	5-30 cm above bottom contact	snails

[1]This sample is at least 1-1.5 m higher stratigraphically than the other two samples from this unit.

base of the Browns Creek Alluvium, where it unconformably overlies red gravel of the Kimbell Ranch Alluvium, had an age of 12,240 ± 240 yr B.P. (Sample DIC-3170). At a locality about 50 m upstream from the fault, a less clayey and less organic-rich lens of sediment, 70-90 cm above the contact with the Kimbell Ranch Alluvium, provided a ^{14}C age of 9,880 ± 160 yr B.P. (Sample DIC-3179).

Differences in the soils formed in Browns Creek Alluvium suggest that it probably includes deposits of two ages. Most of the unit is of late Pleistocene age, but over large areas the uppermost 1.0-1.5 m may be Holocene. The soil profile in Browns Creek Alluvium upstream from the fault on Browns Creek consists of A/Bt/Bk/C horizons. Collectively, the A and Bt horizons are about 75 cm thick. Soil structure is strongly developed, and clay films are present in the Bt horizon, largely because of the high percentage of clay in the strata in which the soil formed. Clay content is 28% in the A horizon, 31% in the Bt horizon, and 40% in the Bk horizon. Carbonate has been leached to a depth of 75 cm, but below this depth secondary carbonate is prominent over a zone a little more than 1 m thick (Bk horizon). The upper 35 cm of this zone contains abundant carbonate nodules (Stage II morphology 5-10 mm long.

The other soil series widely associated with the valley floors at the area, the Port series (Mobley and Brinley, 1967), contrasts with the soil described above. Soils of the Port series are weakly developed, as are most soils developed in deposits of Holocene age. Characteristically, the Port soil is thick and dark-colored. The profile of the Port loam examined in cutbanks along Canyon Creek consists of A/AC/Ck/C horizons and typically is leached to depths of 35-45 cm. The Port loam lacks a B horizon, but exhibits stag II carbonate morphology in the form of abundant small nodules (5-12 mm long, 2-5 mm wide) and a percepitble whitening of the Ck horizon. The accumulation of this much secondary carbonate generally requires thousands of years. The Port soil is estimated to be at least several thousand years old, but substantially less than 10,000 yr. The soil is much better developed than the soil in fan alluvium (discussed later) that represents about 1,000 yr of pedogenesis, but it is younger than the sediment from the lower part of the Browns Creek Alluvium that provided the 9,880 ± 160 yr B.P. age (Sample DIC-3179).

According to Mobley and Brinlee (1967, p. 53), buried soils are commonly found at depths of 75-150 cm in areas where the Port soils are developed. Unequivocal evidence of an unconformity in the upper part of the Browns Creek Alluvium was not found, but a stratigraphic break exists that is nearly coincident with the bottom of the Port soil. This break was initially attributed to bioturbation, but it may be an unconformity. However, until better physical evidence of an unconformity is found or until ^{14}C ages demonstrate its existence, this valley-floor alluvium will be treated as a single unit.

East Cache Alluvium

The youngest unit in the area, the East Cache Alluvium, is named for exposures in the valley of East Cache Creek, the largest stream in Comanche County, Oklahoma. A type area is designated along Browns Creek, which is the principal north-south drainage in sec. 2, T3N, R12W, in north-central Comanche County. Limited exposures are present 80 m upstream and downstream from the point where the Meers fault crosses Browns Creek in the NW 1/4 of sec. 2. A good exposure is also present where the stream crosses the southern section boundary.

East Cache Alluvium is the youngest unit and is present in relatively narrow bands along present-day streams (Figs. 7-9). It fills channels cut into the older valley-floor alluvial units or through these units into bedrock

(Figs. 10,11). The East Cache Alluvium has a stepped appearance in most places because two terraces, not including an incipient surface near present stream level, are cut into this fill (Fig. 11). Along Browns Creek, the upper surface of the unit is about 3 m above stream level, and the two terraces are 2 m and 1 m above stream level. The terraces along Canyon Creek are only a little higher (2.0-2.2 m and about 1.5 m), but are more uneven because of a greater amount of flood erosion and deposition on them. These terraces appear to be mainly cut surfaces, rather than separate alluvial fills. Even so, they mark times of stability between episodes of channel incision.

The East Cache Alluvium is 1.2-3.5 m thick; it is calcareous and ranges from clayey sand to mud composed of nearly equal amounts of sand, silt, and clay. Because of its high silt and clay content, the unit commonly maintains steep stream banks and is hard when dry. Stratification is generally absent to weak. Although the alluvium is calcareous, it does not contain accumulations of secondary $CaCO_3$.

Four ^{14}C ages indicate that the East Cache Alluvium is latest Holocene in age (Table 1). Although the upper and lower age limits of this alluvium are not known precisely, we believe it was deposited between 800 and 100 yr B.P. A large fragment of clean charcoal from near the middle of a 3-m-thick section along Canyon Creek had an age of 600 ± 50 yr B.P. (Sample DIC-3161). Humus from a thin buried A horizon within this alluvium on the west side of Browns Creek about 40 m downstream from the Meers fault provided an age of 470 ± 150 yr B.P. (Sample W-5540). Charcoal and carbonized plant fragments in a cut-and-fill deposit along the present channel of Browns Creek had an age of 70 ± 150 yr B.P. (Sample DIC-3165), and colloidal-size organic matter from this deposit had a ^{14}C age of 310 ± 150 yr B.P. (Sample W-5533).

The East Cache Alluvium has been incised to depths of about 3 m, and two terraces have been cut in it, one at 2.0-2.2 m above stream level and the other 1.0-1.5 m above stream level. The incision of valley floors and the formation of the relatively narrow stream channels of today had occurred prior to 100 yr B.P. The 70 ± 150 yr B.P. (Sample DIC-3165) ^{14}C age cited above provides an imprecise minimum age for the time of incision. Also, East Cache Creek, the principal stream of the area, had incised its channel to depths of as much as 8 m prior to 1884, the date on the stone foundation of an abandoned bridge built across the channel at Fort Sill (Hall, 1978). Although dendrochronologic data were not collected, many large trees rooted in the bottoms and sides of channels cut in the East Cache Alluvium appear to be 100 yr or more old.

The soil formed in the East Cache Alluvium consists of a weakly developed A/C profile. The A horizon is very dark gray (10YR 3/1, moist) to very dark grayish brown (10YR 3/2, dry) and is typically about 16-18 cm thick. The C horizon is dark brown (7.5YR 4/4, moist) to brown (7.5YR 5/4, dry). This alluvium is essentially unleached, or at most is leached only in the upper 1-2 cm, and it does not contain accumulations of secondary carbonate. Little or no A horizon has formed on the terraces, suggesting that they were cut well after the main body of alluvium was deposited. The weakly developed soil indicates an age for this unit consistent with that determined by radiocarbon dating.

Fault-Scarp Alluvial Deposits

Deposits of sheetwash and fan alluvium are found locally on the downthrown side of the Meers fault (Figs. 7,8). The fan alluvium was deposited where the fault displaced streams, and the sheetwash accumulated along the foot of the fault scarp in interstream areas. These deposits are of such limited extent and so widely scattered that it is difficult to characterize them as a unit.

Nevertheless, they are important deposits for dating recent movement on the fault. Much of this alluvium is coeval with faulting, or closely postdates faulting. Where exposed, as along the larger streams of the area, the fault-scarp alluvial deposits can be related to other stratigraphic units that both predate and postdate faulting.

Sheetwash

Sheetwash, being the product of unconfined runoff, is generally not dissected by streams and therefore is not generally well exposed. It is, however, well exposed in a cutbank where Browns Creek crosses the fault (Fig. 12). The sheetwash is dark-colored and resembles a soil having an over-thickened A horizon, but the dark color was inherited largely from soil eroded from the fault scarp, rather than from pedogenesis in place. Because the vertical component of displacement that formed the scarp was high-angle reverse movement and most of the topographic offset was produced by warping, soil would have remained on most of the scarp initially. This soil was subsequently stripped as erosion beveled the warp, and eventually a weakly developed A/C soil profile formed on the beveled surface.

The soil on the fault scarp in the cutbank along Browns Creek consists of an 18-cm-thick, unleached, calcareous A horizon over parent material (C horizon). A similar soil is formed in Browns Creek Alluvium on the fault scarp in a trench excavated near Canyon Creek (trench 1). At this locality, the thick, dark-colored Port loam has been stripped from the fault scarp and redeposited at the foot of the scarp. This sheetwash, like that along the Browns Creek (Fig. 12), is dark colored and as much as 1 m thick.

Figure 12. Sheetwash resembling an overthickened A horizon overlying Porter Hill Alluvium (light colored sediment) on the downthrown side of the Meers fault along Browns Creek.

Fault-Related Fan Alluvium

Small but morphologically distinct alluvial fans formed where the fault displaced small emphemeral streams and gullies; the best examples are in the Slick Hills (Fig. 13). Larger, but less distinct fans formed where the fault displaced perennial streams; the best examples are on Canyon Creek and Browns Creek. The small fans remain essentially undissected because the drainage areas are small and runoff is seasonal. The fans along the larger streams, however, were incised in late Holocene time, and younger alluvium was deposited in channels in the fans (Figs. 7;8;11, B-B'). The stratigraphic relations in exposures along the larger streams show that the fan alluvium was deposited in response to movement on the Meers fault.

The principal evidence linking the deposition of the fan alluvium to faulting includes (1) the location and shape of the deposits of fan alluvium and (2) the presence of large, angular clasts of bedrock in the fan alluvium along Browns Creek. Fan alluvium is present only on the downthrown side of the fault, and is thickest and has the widest lateral extent at the fault. It is at least 1.4 m thick near the fault along both Canyon Creek and Browns Creek and was presumably as wide as the pre-fault valley floor at each of these localities. The limits of fan alluvium are difficult to distinguish, except in stream cuts, because the fans grade gradually into the surrounding landscape. Along Browns Creek, the fan alluvium extended at least 180 m down valley from the fault, and along Canyon Creek it extended at least 500-600 m down valley.

Deposits like the fan alluvium were not observed anywhere else in either of the drainage basins studied. If deposits like the fan alluvium were present elsewhere, it is unlikely that they would go unnoticed, because the fan alluvium is conspicuous. It differs sharply in texture from the underlying pre-fault valley fill, and the pale brown to brown color of the fan alluvium

Figure 13. View (north at the top) of the Meers fault displacing Post Oak Conglomerate. Ephemeral streams are incised on the upthrown side of the fault and terminate in small, undissected alluvial fans deposited on the downthrown side of the fault. Photograph by D. B. Slemmons, 1983.

contrasts with the nearly black color of the buried soil in the underlying alluvium. The buried soils are commonly about 75 cm thick and difficult to overlook. The fan alluvium is mostly sand and gravel that includes large cobbles and, in places, boulders. In contrast, the underlying valley fill, in both study areas, is chiefy silty clay and clayey silt.

Large, angular clasts of gray sandstone in the fan alluvium along Browns Creek are as anomalous as the buried soil underlying the fan alluvium. Most of the fan alluvium is pebbly sand derived from incision of alluvium on the upthrown side of the fault. The sandstone clasts compose less than 5% of the deposit, but are conspicuous because of their size and angularity. Most of the sandstone clasts are 15-25 cm across, but one is a boulder measuring 85 x 33 x 25 cm (Fig. 14). This boulder is particularly anomalous in a small, low-relief drainage basin where the bedrock is chiefly shale.

The sandstone boulder links the fan alluvium to movement on the Meers fault. Similar gray sandstone fragments were not observed in the older alluvial units along Browns Creek, and this rock type does not crop out on the valley sides. However, gray sandstone is exposed on the upthrown side of the fault zone and in places along the present stream channel for about 200 m upstream from the fault. This is the obvious source for the sandstone clasts, but it would not have been available as a sediment source until movement on the Meers fault caused Browns Creek to incise its channel on the upthrown side of the fault. Hence, the fan alluvium on Browns Creek clearly postdates faulting. The sandstone boulder suggests that deposition of the fan alluvium closely postdates faulting. Incision of the valley-fill alluvium on the upthrown side of the fault probably occurred soon after faulting, because the unconsolidated alluvium would have eroded easily. The only time that stream gradient and discharge were probably sufficient to transport a nearly 1-m-long boulder a

Figure 14. Angular, nearly 1-m-long boulder of Permian sandstone, locally derived from bedrock on the upthrown side of the fault (left of photograph), embedded in the upper part of a 1.4-m-thick section of fault-related fan alluvium along Browns Creek.

distance of 30 m was shortly after faulting had produced the 5-m-high warp in the landscape.

Newly uplifted landscapes tend to be modified quickly. Morisawa (1975) described several examples of the immediacy of modification, including the adjustment of streams to fault-induced knickpoints. Knickpoints on perennial streams in northwestern Wyoming formed by faulting in the 1959 Hebgen Lake earthquake were eliminated in a period of less than a year to a few years. The drainage basins of the Wyoming streams are comparable in size to those of Canyon Creek and Browns Creek, although the relief within the Wyoming basins is somewhat greater. Also, the heights of the Wyoming fault scarps, about 3-6 m, were similar to the Meers fault scarp. The scarps across the Wyoming streams, however, were formed in much coarser material than the scarps across Canyon Creek and Browns Creek. The former were in boulder gravels that contained many 1-m-long boulders.

It is unlikely that the rate of fault-scarp modification along Canyon Creek and Browns Creek differed much from that along the Wyoming streams. If anything, modification in the Meers area was probably faster because the finer-grained alluvial fills would have been less resistant to erosion. Hence, regrading of stream channels across the Meers fault and deposition of the fan alluvium on the downthrown side of the fault was probably completed in less than a decade. Consequently, the ^{14}C ages of materials collected from the surface buried by the fan alluvium are believed to closely date the time of faulting.

Movement of the Meers fault produced a sharp knickpoint in stream channels that crossed the fault. Streams responded to the disruption by regrading their channels across the knickpoint. Upstream from the fault, the adjustment was by degradation; stream incision is pronounced on the edge of the upthrown block all along the surface trace of the fault. Downstream from the fault, adjustment was by aggradation, and the fan alluvium is the product of this adjustment. Along the larger streams, Canyon Creek and Browns Creek, channel incision upstream from the fault penetrated the pre-fault valley fill and exposed bedrock beneath (Figs. 10, B-B'; 11, A-A'). Downstream from the fault, fan alluvium buried the surface of the pre-fault valley fill (Fig. 11, B-B').

Late Holocene Movement on the Meers Fault

The Meers fault has crosscutting relations with valley-fill alluvium and terrace deposits of at least five ages, ranging from early or middle Pleistocene to late Holocene (Fig. 15). It displaces all but the East Cache Alluvium, the youngest alluvial unit, which was deposited between 800 and 100 yr B.P. Soil humus, charcoal, and carbonized wood from surfaces buried by fault-related alluvium provide maximum ^{14}C ages for the fan alluvium and closely date the time of faulting (Fig. 16). Similar materials from the East Cache Alluvium, which is unfaulted and truncates the fault-related fan alluvium, provide a minimum age for the fan alluvium and a minimum date for faulting.

Two ^{14}C ages of charcoal from the Canyon Creek area indicate that movement on the Meers fault occurred after 1,280 ± 140 yr B.P. (Sample DIC-3167) but before 600 ± 50 yr B.P. (Sample DIC-3161). Faulting is thought to have occurred nearer the older limit than the younger limit, because deposition of fan alluvium probably began soon after the streams were displaced by faulting, and it was probably complete within a matter of years. Two ^{14}C ages of soil buried by fault-related fan alluvium on Browns Creek provided similar limiting dates. Soil humus concentrated from the uppermost part of the burried soil provided ^{14}C ages of 1,740 ± 200 yr B.P. (Sample W-5543) and 1,360 ± 100 yr

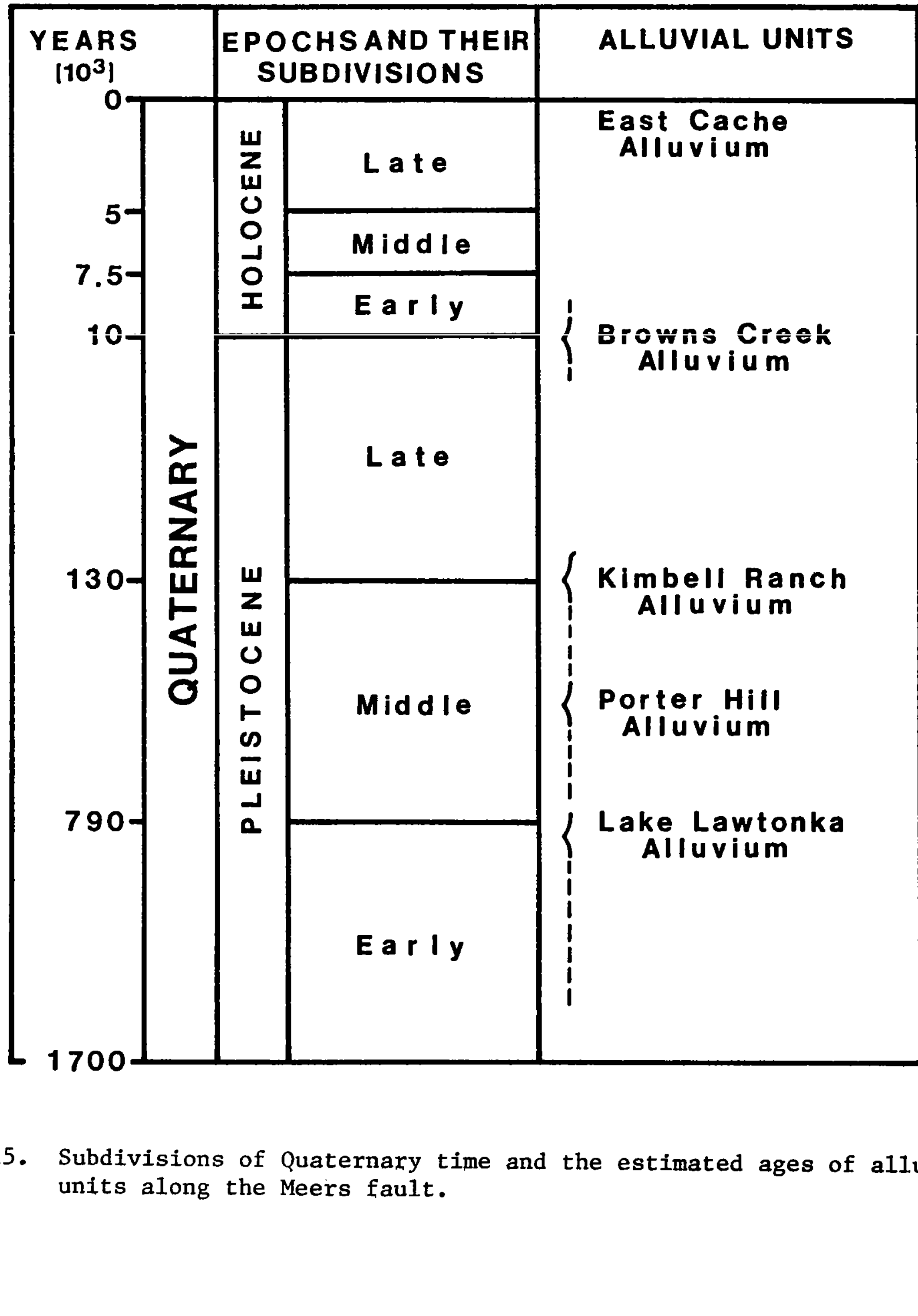

Figure 15. Subdivisions of Quaternary time and the estimated ages of alluvial units along the Meers fault.

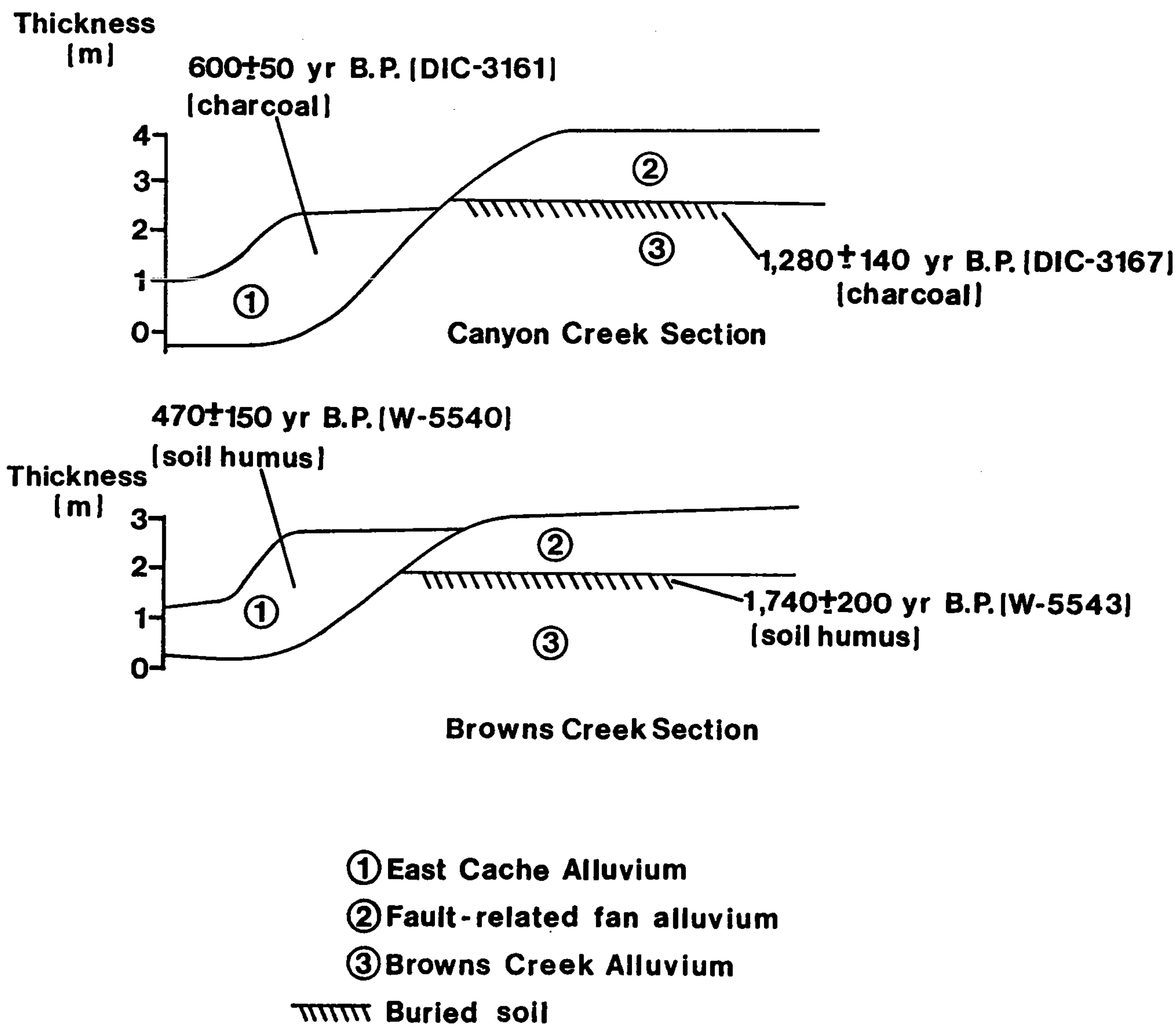

Figure 16. Schematic sections showing the stratigraphic relations and ^{14}C ages that provide limiting dates for the time of recent movement on the Meers fault.

B.P. (Sample DIC-3169). The older age is from a site on the east side of Browns Creek about 25 m downstream from the fault, and the younger age is from a site on the west side of Browns Creek about 120 m southwest of the fault.

The agreement between the charcoal ages and the soil-humus ages is particularly good, considering that the latter represent averages (mean residence times) for humus formed over the range of time that the soil was at the surface. Soil-humus ages are minimum ages for the beginning of soil formation and maximum ages for the time of burial. Generally, the longer the soil was at the surface, the more imprecise the soil-humus ages. Humus is stable with respect to biological and chemical attack and tends to survive for hundreds to thousands of years, depending on the environment (Paul and others, 1964; Campbell and others, 1967; Sharpenseel and others, 1968; Gerasimov, 1971). The turnover time of humus (the time between formation and disappearance) tends to be hundreds of years in forest soils and thousands of years in grassland soils. The mean residence time of the organic matter in the thin A horizon buried in East Cache Alluvium (470 ± 150 yr B.P., Sample W-5540) is probably not much different than the date of burial, because the soil was at the surface for a short time. On the other hand, the soil buried by fault-related fan alluvium contained humus that probably had an average age of at least a few centuries at the time of burial.

Although charcoal is capable of providing more-precise ^{14}C ages than soil humus, charcoal in fluvial deposits is also capable of being recycled from older to younger deposits, thus providing erroneous ages for the younger deposits (Blong and Gillespie, 1978). It is desirable, therefore, to have cross-checks on ^{14}C ages for fluvial deposits--either more than one charcoal age per alluvial unit, or age determinations for more than one kind of sample.

In this study, the reasonably close agreement between the ^{14}C ages of charcoal and those of soil humus provides the desired cross-check.

The differing degrees of soil development in the various alluvial deposits provide an additional check on the reliability of the ^{14}C dating. The ages of the alluvial deposits estimated on the basis of relative soil development are consistent with the ^{14}C ages. The soil in the East Cache Alluvium is weakly developed. It consists of a simple A/C profile: a 16- to 18-cm-thick A horizon overlying a C horizon of essentially unaltered calcareous alluvium. Only the upper 1-2 cm of the calcareous A horizon is leached, and the profile does not contain any accumulations of secondary carbonate. This minor soil development is consistent with ^{14}C ages that place deposition of the East Cache Alluvium between 800 and 100 yr B.P. Little or no soil is present on the terraces cut in the East Cache Alluvium.

The soil formed on the slope of the fault scarp is similar to that in the East Cache Alluvium, and the soil formed in the fault-related fan alluvium is only slightly more developed. The soil in the fault-related fan alluvium has a slightly better-developed A horizon than that in the East Cache Alluvium, and in addition, it has an A/C horizon. Also, the soil in the fault-related fan alluvium is leached to depths of 8 cm, as opposed to the 0-2 cm of leaching found in the soil in East Cache Alluvium. The soil in sheetwash at the foot of the fault scarp has an exceptionally thick A horizon, but otherwise is weakly developed. Depth of leaching in all of these soils is minimal, secondary carbonate has not accumulated in any of them, and none have a B horizon. This indicates that the deposits and landforms with which they are associated are all geologically young and of similar age, which supports the conclusion that faulting closely preceded deposition of the East Cache Alluvium. In contrast, the soils formed in Browns Creek Alluvium, described earlier, are much more developed, suggesting that faulting occurred long after deposition of this alluvium.

TRENCH SURVEYS

In March 1985, two trenches were excavated across the scarp near Canyon Creek to document the near-surface deformation associated with the scarp and to provide some basic information about the recency and recurrence of large earthquakes associated with the fault. The stratigraphy in the trenches and the history of faulting recorded by the stratigraphy were described. Radiocarbon ages of selected samples from the trenches constrain the age of the last surface-faulting event to the late Holocene.

The trenches are located in the SW1/4 SW1/4, sec. 24, T4N, R13W, Comanche County, Oklahoma (Figs. 17,18). The Meers fault near the trench sites is marked by a prominent, linear, down-to-the-south scarp that strikes N. 64° W. in this area. The trenches were oriented perpendicular to the strike of the fault scarp and were located so they could be excavated in Quaternary deposits of two different ages. Trench 1 was excavated in Holocene deposits, the youngest alluvial deposits known to be displaced by the fault, whereas trench 2 was excavated in deposits of Pleistocene age. By determining the amount of slip in deposits of different ages, we might identify recurrent movement, and, with appropriate age information on the deposits, we might estimate recurrence intervals and long-term slip rates.

Trench 1

Stratigraphy

Trench 1, 22 m long and about 2.5 m deep, was about 150 m east-southeast of Canyon Creek, a major drainage in the area. The scarp here is about 2.4 m

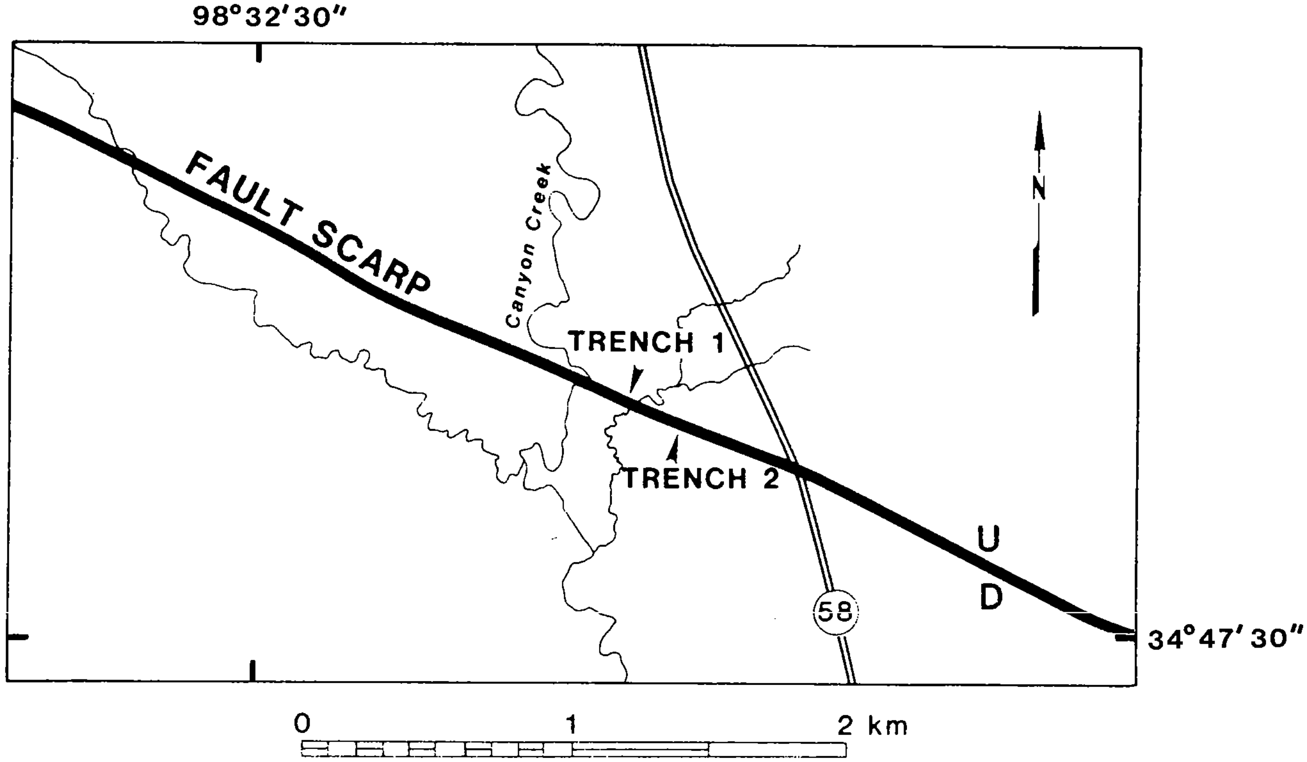

Figure 17. Locations of trenches across the Meers fault, Comanche County, Oklahoma.

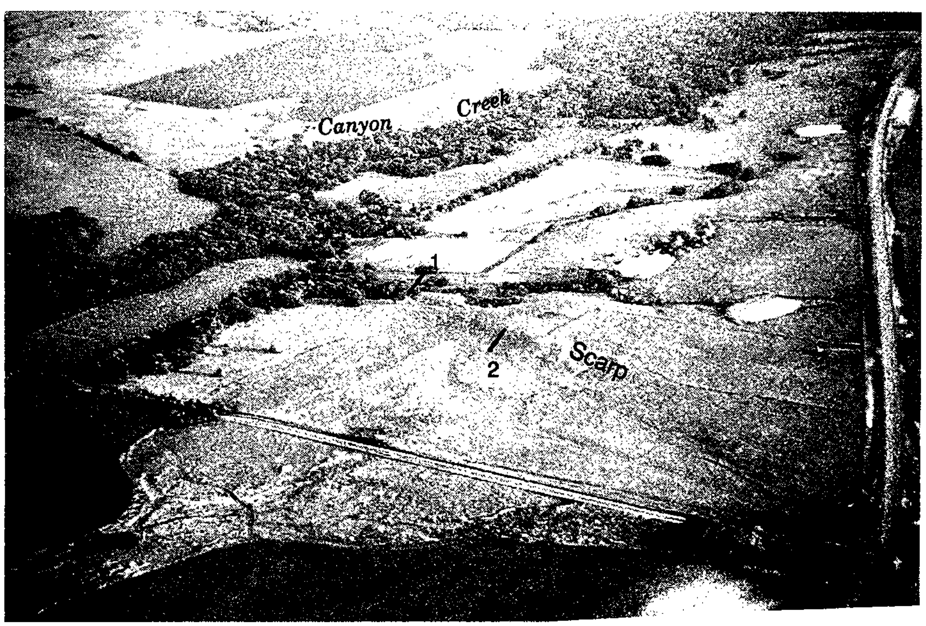

Figure 18. Aerial view of the Meers fault and trench locations. State Highway 58 on the right. Numbered lines are trenches as labeled in Figure 17. Photograph by D. B. Slemmons, 1983.

high, with a maximum slope angle of 9° 20'. The faulted deposits exposed in the trench are part of the Browns Creek Alluvium, believed to be late Pleistocene to early Holocene in age. In Canyon Creek and other nearby drainages, the Holocene East Cache Alluvium is not faulted. About 30 m east of the trench, a small ephemeral stream has incised a shallow gulley into the scarp.

At the bottom of the trench, weathered Hennessey Shale of Permian age was exposed on both sides of the fault (unit 15; Pl. 1). The shale is soft plastic, red (2.5YR 4/6), slightly silty clay. Near-surface weathering has obliterated all evidence of primary bedding. Small iron-reduction spots mottled the shale with orange, yellow, and gray colors. The most extensive area of iron reduction was adjacent to the fault, where the shale was light gray (5Y 7/2) and very calcareous (unit 15a; Pl. 1).

The Browns Creek Alluvium rests on the shale. The lower part of the alluvium is a generally fining-upward sequence of lenticular, interfingering sands, silts, clays, and pebble-cobble gravels (units 7-12, 14; Pl. 1); the lenticular deposits graded upward into a massive clayey silt (unit 6; Pl. 1). On the upthrown block, the silt is overlain by an organic-rich A horizon (unit 1; Pl. 1). The basal gravels are matrix-supported, strong brown (7.5YR 5/6) to yellowish red (5YR 4/6), and contain clasts that average 5-10 cm in size. The clasts are mainly rhyolite, with minor amounts of limestone and sandstone. The sands, silts and clays are strong brown (7.5YR 5/6) to yellowish brown (10YR 5/6), massive, calcareous, with scattered manganese concretions 2-3 mm in size. The sands, silts, clays, and gravels in the lower part of the Browns Creek Alluvium were deposited in relatively high-energy environments near the main channel of Canyon Creek.

The massive clayey silt in the upper part of the alluvium is strong brown (7.5YR 5/6), and also contains manganese concretions. It becomes less calcareous upward. This unit probably was deposited in a low-energy, flood-plain environment, and it may contain some loess. We suspect that the loess content increases upward and that much of the inorganic content of the A horizon may be loess.

A weak soil with a simple A/C profile has formed in the calcareous, clayey silt on the stable surface of the upthrown block. The brown to dark-brown (7.5 YR 4/4) A horizon is noncalcareous, massive, sandy silt. Calcium carbonate leached from the A horizon has started to accumulate in the underlying clayey silt; stage I+ soil carbonate morphology (Birkeland, 1984, p. 358) has started to develop in the lower part of the silt.

Following deposition of the Browns Creek Alluvium and formation of an A horizon, the scarp formed and warped the alluvium into a monocline. Extension cracks and small-displacement faults formed near the crest of the monocline. Details of the deformation will be described in the following section. After the scarp and faults formed, the nearby ephemeral stream flowed along the base of the scarp, eroded the A horizon and the massive clayey silt from the downthrown side of the fault, and deposited a sequence of interbedded fine gravel, sand, silt, and clay (units 2-5; Pl. 1). These fluvial deposits are overlain by a dark-brown (7.5 YR 3/2), cumulative, overthickened A horizon (unit 1; Pl. 1). The overthickened A horizon is mostly a colluvial (sheetwash) deposit that results from A-horizon material being stripped from the soil on upper part of the scarp and moved down the slope, where it has accumulated.

Deformation Characteristics

Nearly all of the deformation in trench 1 is a product of flexing and warping; there is only minor brittle deformation (cracking and displacement on faults). The actual displacement on faults in the trench accounts for only 8-13% of the total deformation. The faulting is expressed as a reverse fault and a normal fault near the midpoint of the scarp (Figs. 19,20). The total stratigraphic throw along the length of the trench was 2.7-2.8 m. This is a minimum value, because the fluvial gravels (unit 14; Pl. 1) on the downthrown side still had a tectonically induced, SW dip where they continued below the bottom of the trench. A slightly darker, organic-rich layer in the clayey silt (unit 10; Pl. 1) on both walls of the trench at (19.2 m; -1.5 m)[3] had a 17° SW dip. If the trench had extended farther to the southwest to where the beds were undeformed by the scarp, it is likely that the total stratigraphic throw would be 3 m or more.

The most significant fault in the trench is the reverse fault, even though it produced only 0.1 m of throw on the top of the Hennessey Shale (11.5 m; -0.5 m). This fault strikes N. 59° W. and dips 49° NE; the strike is compatible with the regional strike of N. 64° W. for the scarp. The narrow zone of deformed sediments associated with this fault near the bottom of the trench becomes wider upward. A distinctive feature of this zone is a finger like pod of A horizon that extends downward through the massive silt and into the

[3]Specific points on the trench logs in this report are located with respect to the metric horizontal and vertical scales shown on the plates. The first number in the notation is the location on the horizontal plane, and the second is the location on the vertical plane. Vertical points are measured from the datum; positive values are above and negative values are below the datum.

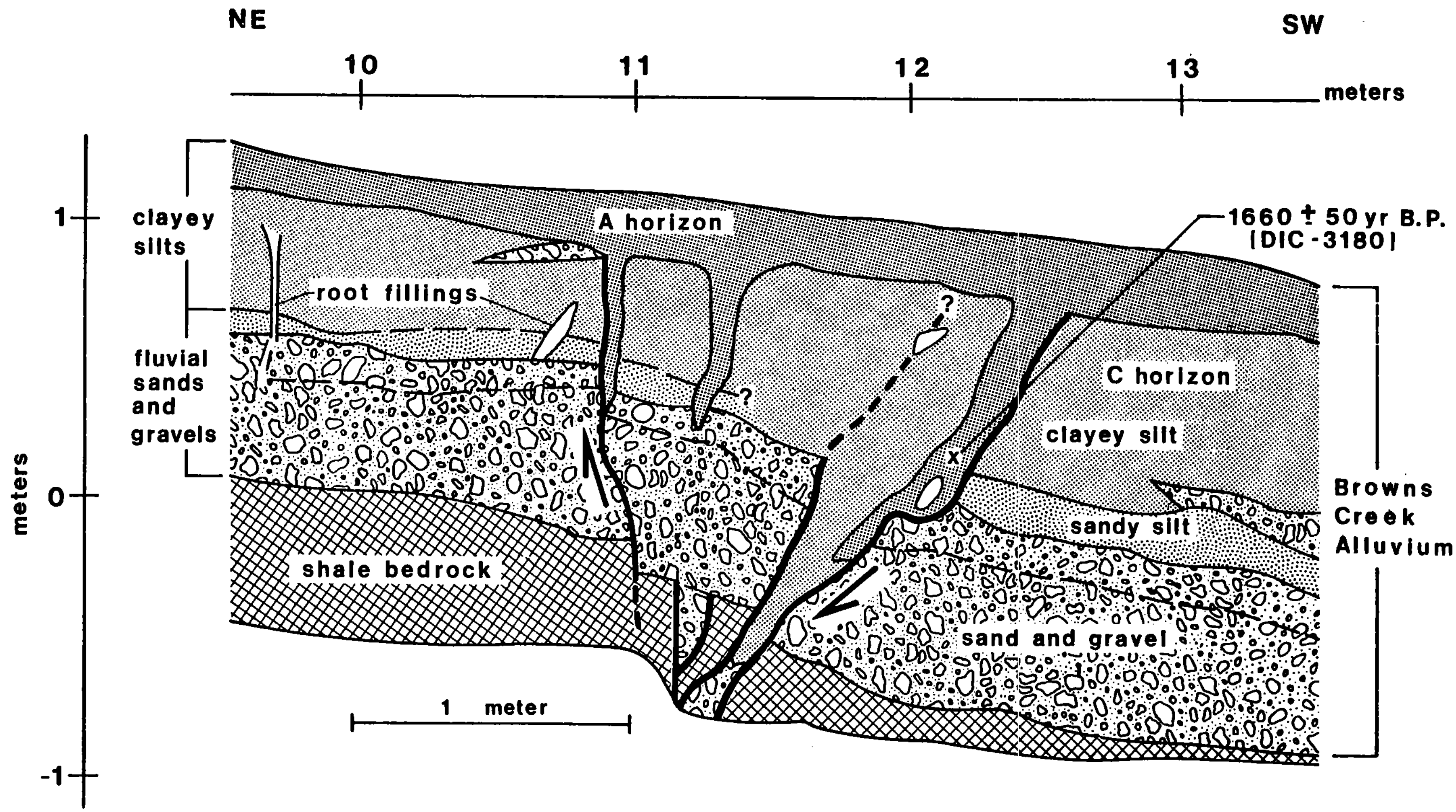

Figure 19. Part of the trench 1 log, showing stratigraphic relations near the main fault and location of ^{14}C age sample. Heavy lines are faults and edges of cracks that could be recognized by abrupt changes in the stratigraphy, dashed where inferred; arrows show general sense of displacement across the main fault zone. Fine lines are stratigraphic contacts, dashed where subtle. See Plate 1 for log of the entire trench.

Figure 20. Fault zone exposed in trench 1, looking east.

underlying gravel a distance of 1.15 m below the base of the soil horizon from which it was derived. Similar to the A-horizon material, a pod of the massive silt (unit 6; Pl. 1) extends about 0.8 m downward through the gravel (units 13 and 14; Pl. 1) and into the shale below. Beneath the silt in the fault zone, a small pod of gravel in the shale (11.3 m; - 0.7 m) is downdropped at least 0.40 m and is isolated from its source. Thus, the entire stratigraphic section of Browns Creek Alluvium is elongated downward in the deformed zone associated with this small fault.

Drag associated with displacement on the small fault cannot explain the downward movement of the sediments in this deformed zone. The dip-slip movement on this small fault is only about 0.1 m, as shown by the displacement of the top of the shale. Compared to the downdip displacement of the overlying sediments--0.40 m for the gravel to 1.15 m for the A horizon--the dip-slip movement on the fault is insufficient to produce the observed amount of downdip movement of the sediments.

The best explanation for the observed relationships is that a block of Browns Creek Alluvium collapsed into an open crack. During the early phases of deformation, an extension crack formed in the alluvium near the crest of the monocline. The crack, which was narrower at depth, originally dipped about 60-70° NE. This dip was estimated by restoring the warped beds in the alluvium to horizontal and measuring the attitude of the crack. As soon as the crack formed, a sliver of the alluvium from one wall collapsed into the opening. This collapse displaced the alluvial units more than the top of the shale. As warping of the monocline progressed, the originally near-vertical crack gradually rotated to a less-steep attitude. The small amount of reverse slip on this fault may be the result of near-surface compressional forces related to formation of the monocline.

Several pieces of evidence support this collapse interpretation. The extremely sharp contacts and the absence of slickenlines or severe disruption of the sediments at the edges of the deformed zone suggested limited differential movement at these boundaries. Furthermore, the sharp contacts between the stratigraphic units within the deformed zone indicated very little internal shearing. The relatively undeformed succession of the stratigraphic units in the deformed zone is consistent with the collapse interpretation. Finally, the original attitude of the fissure is nearly perpendicular to the bedding in the alluvium, as might be expected for an extensional crack.

The other significant fault in this trench is a small normal fault that also probably formed in response to tension near the crest of the monocline. The near-vertical, down-to-the-south fault vertically displaces both the tops of the shale (11.0 m; -0.25 m) and the gravel (10.9 m; 0.4 m) about 0.1 m. The position of this fault in the upthrown block of the reverse fault suggests that it is a secondary feature. An open fissure that extended down to the upper part of the gravel along the fault was infilled with A-horizon material.

The small, triangular-shaped pod of gravel in the shale (11.2 m; -0.5 m) between the two faults probably formed by gravel collapsing into an open tension crack. Projecting the top of the shale across the crack indicates no vertical displacement. Furthermore, a narrow finger of A-horizon material (11.3 m; 0.5 m) directly above the pod probably filled in the upper part of this crack; the crack does not vertically displace the contact between the fluvial sands and gravels and the overlying clayey silts.

Discussion

A portion of the fingerlike pod of A-horizon material (Fig. 19) was sampled for a radiocarbon age determination (12.2 m; 0.15 m). The soil humus has an age of 1,660 ± 50 yr B.P. (Sample DIC-3180). This ^{14}C date on the A-horizon material is a maximum for the time of the scarp formation (see page 44). The opening of the crack and the collapse of the A-horizon material coincided with the formation of the scarp.

Another radiocarbon date from the trench supports a late Holocene age for the scarp formation. Disseminated organic material in fluvial clayey silt (unit 4; Pl. 1) deposited after the scarp formed has a ^{14}C age of 1,730 ± 50 yr B.P. (Sample DIC-3266). This dated organic material is probably locally derived soil humus that was concentrated in the fine-grained fluvial sediment. Within the error limits of the date, this age is approximately the same as the age of the soil material in the crack. The similarity of these two dates suggests that the erosion and backfilling by the ephemeral stream on the downthrown side of the scarp occurred within a few decades of the scarp formation. A reconstruction of the pre-faulting stratigraphy on the downthrown side suggests that the ephemeral stream eroded about 0.6-0.8 m of sediment before backfilling began.

Even without the ^{14}C dates, other evidence indicates that the surface deformation at this site is geologically youthful. The A horizon of the modern soil (unit 1; Pl. 1) is the only deposit in the trench that is unbroken by faults. Secondly, the weak soil formed in the upper part of the Browns Creek Alluvium (an A horizon and a slightly oxidized C horizon) on the stable upthrown side of the fault suggests that the faulted alluvium is Holocene in age.

Most of the deformation at this site is expressed as monoclinal warp; therefore, the original scarp probably did not have a free face. Without a free face, erosion of the scarp would not produce a sequence of colluvial deposits typical of a degrading scarp. The absence of these colluvial deposits makes it difficult to determine if the scarp at the site results from a single faulting event or multiple events. However, evidence from the trench favors only one faulting event. The fluvial deposits on the downthrown side of the scarp (units 2-5; Pl. 1) are not warped, indicating no deformation since their deposition about 1,730 yr B.P. The similar ^{14}C dates for these fluvial deposits and for the collapsed soil material in the crack suggest that most of the warping was associated with the last deformational event. If there was an older event, it probably did not produce extensive open cracks. It is possible that deposits related to an older event could have been eroded by the nearby ephemeral stream prior to the most recent episode of deformation; however, we do not favor this interpretation, for two reasons. First, there is no stratigraphic or structural evidence (i.e., offset fault planes) of an earlier deformational event in this trench. Second, based on the youthful inferred age of the Browns Creek Alluvium, more than one deformational event would indicate a short recurrence interval during the late Holocene. A short recurrence interval, and therefore a high rate of deformation, is not supported by the amount of deformation found in older deposits (see discussion of trench 2).

The stratigraphic relationships in the trench neither support nor preclude a large amount of lateral slip on the fault. Abrupt changes in the thickness and character to the stratigraphic units across fault zones are commonly used as evidence to support significant amounts of lateral slip. The thickness and character of the stratigraphic units in the trench are remarkably consistent across the fault zone. The continuity of stratigraphic units does not support a major amount of lateral slip at this site; however, if stratigraphic units are a really uniform, moderate amounts of lateral slip are difficult to detect. Therefore, we cannot preclude the possibility of lateral slip on the fault in the trench. In fact, our continuing field studies suggest that lateral slip may be an important component of motion on the fault at a site about 3 km to the west (Crone and Luza, 1986).

Trench 2

Stratigraphy

Trench 2, about 200 m east-southeast of trench 1, was 19 m long. Here, the scarp is 3.4 m high, with a maximum slope of 9°. On the upthrown side of the scarp, the trench exposed about 2.5 m of Pleistocene Porter Hill Alluvium on weathered Hennessey Shale (Pl. 2). The lower part of the alluvium is fluvial pebble-cobble gravels (units 6-8; Pl. 2). The gravels are capped by as much as 60 cm of silty and clayey sand (units 1 and 2; Pl. 2) that may contain a large component of loess. A soil with an argillic (clay-rich) B horizon as much as 1 m thick has formed in the alluvium on the stable surface on the upthrown side of the fault. This soil and the position of the alluvium in the landscape both suggest that the Porter Hill Alluvium is much older than the alluvium in trench 1. The alluvium is believed to be middle to late Pleistocene(?) but detailed information on its age is not yet available.

In this trench, the Hennessey Shale was exposed only on the upthrown side of the fault; a high water table and ground water seeping from the shale-gravel contact prevented deepening the trench to bedrock on the downthrown side. The shale is bleached white (10YR 8/1) to light gray and calcareous; it contains numerous embedded gravel clasts in the upper part. Immediately upslope from the fault, a rounded boulder of dolomite about 1 m in diameter rests on the shale (8.4 m; -0.75 m). During deposition of the gravels, the shale downslope from the boulder was scoured and backfilled with gravel.

The gravels in the lower part of the Porter Hill Alluvium are divided into three units on the basis of the amount of matrix (Fig. 21). In ascending order, the units are a pebble-cobble gravel, a clay-enriched gravel, and a clay-plugged gravel (units 8, 7, and 6; Pl. 2). Typically, the contacts between the units are gradational, and in places the units are difficult to map because of the coarse texture of the gravels (Fig. 21).

The pebble-cobble gravel is massive to crudely stratified, clast-supported, and yellowish red (5YR 4/6) to dark red (2.5YR 3/6) (unit 8; Pl. 2). It contains angular to subrounded clasts of rhyolite and limestone that average 5-10 cm in size, with a maximum size of 20 cm. The lower contact of this unit with the shale is sharp; the upper contact with the clay-enriched gravel is gradational. This unit is the least-indurated of all three gravel units, because of its comparatively low matrix content. In places the matrix is mainly coarse sand, but usually it is a mixture of sand, silt, and clay. Much of the silt and clay was probably transported downward by infiltrating water through the originally porous overlying gravels. The silt and clay coats the surfaces of the clasts and partially fills the interstitial pores.

The clay-enriched gravel is a yellowish-red (5YR 4/6) to red (2.5YR 4/6), massive, matrix-supported pebble-cobble gravel (unit 7; Pl. 2). The clasts of angular to subrounded rhyolite and limestone are 5-10 cm in size. The upper and lower contacts are irregular and gradational. The slightly calcareous matrix is clayey, coarse to very coarse sand. Surfaces of the clasts and sand grains are covered by clay skins, and much of the interstitial pore space is filled with clay.

The clay-plugged gravel is massive, dark-red (2.5YR 3/6), poorly sorted, matrix-supported cobble and pebble gravel (unit 6; Pl. 2), with rhyolite and

Figure 21. Pebble-cobble gravels exposed in the east wall of trench 2. A, clay-plugged gravel; B, clay-enriched gravel; and C, pebble-cobble gravel. Distance between nails near A and C is 1 m.

limestone clasts similar to those in the underlying units. The upper contact is sharp to gradational. This unit is the most indurated of the gravel units, because of the relatively high silt and clay content in the matrix. Abundant matrix clay, interpreted to be pedogenic, completely fills most of the interstitial pores. The addition of this clay probably destroyed any primary stratification and changed the gravel fabric from clast-supported to matrix-supported.

On the upthrown side of the fault, the gravels are overlain by silty and clayey sand in which a soil with an organic-rich A horizon (unit 1; Pl. 2) and argillic B horizon (unit 2; Pl. 2) has formed. The dark-brown (7.5YR 3/4) to dark-reddish-brown (5YR 3/3) A horizon is noncalcareous, massive, silty sand, with abundant roots and a few cobbles up to 20 cm in size. The dark-red (2.5YR 3/6) to reddish-brown (5YR 4/4) B horizon is noncalcareous clayey sand with a few cobbles up to 15 cm in size. Cobbles are more abundant in the lower third of the B horizon. The B horizon has a massive to blocky structure and contains abundant clay that coats the sand grains.

The B horizon thins toward the fault zone and could not be identified downslope from station 10.1 m; 0.9 m. Downslope from station 10.1 to a point above the fault zone (12.5 m; 0.5 m), the A horizon rests directly on the clay-plugged gravel or gravel in the fault zone. The original A horizon and the B horizon found on the upthrown side of the fault were probably eroded in this area (between 10.1 m; 0.9 m and 12.5 m; 0.5 m) after the scarp formed. The A horizon that now rests directly on the gravels is mainly redeposited A-horizon material eroded from the upper part of the scarp.

On the downthrown side of the fault, the clay-plugged gravel was overlain by a 1.2-m-thick sequence of interstratified silty and clayey sands, and sandy silt. The clayey sand (unit 5; Pl. 2) above the gravel and the overlying sandy silt (unit 4; Pl. 2) are interpreted as a buried argillic B horizon and buried A horizon, respectively, formed in silty and sandy alluvium. The dark-reddish-brown (5YR 3/4) B horizon is noncalcareous and has massive to blocky structure; it contains a few pebbles and cobbles as much as 12 cm in size. Clay fills most of the pores in the B horizon and coats most of the sand grains. The dark-reddish-brown (5YR 3/3) A horizon is also noncalcareous, has a massive to granular structure, and contains a few pebbles 1-2 cm in size. The A horizon is darker (from a higher organic-matter content) and contains less clay than the underlying B horizon. Organic material from the buried A horizon has a ^{14}C age of 1,360 ± 50 yr B.P. (Sample DIC-3183). Generally, sand grains are not coated with clay. The top of this buried soil marks the pre-faulting ground surface which was buried by colluvium derived from erosion of the scarp.

A modern soil (post-faulting) composed of an A and a C horizon is forming on the colluvium that has accumulated on the downthrown side of the fault. The modern C horizon (unit 3; Pl. 2) is dark-reddish-rown (5YR 3/4), noncalcareous, clayey sand, with massive to blocky structure; it contains a few pebbles as much as 1.5 cm in size. Clay coatings on the sand grains are abundant. The C horizon is only about 5 cm thick at the fault zone (near station 12.5), but is more than 40 cm thick within a short distance downslope (near station 14). This abrupt increase in thickness marks the approximate location of the free face of the fault scarp. Upslope from the free face, erosion dominated, stripping sediment from the upthrown side of the fault; downslope, colluvium accumulated and buried the pre-faulting ground surface on the downthrown side.

The modern A horizon on the downthrown side of the fault zone (unit 1; Pl. 2) is dark-reddish-brown (5YR 3/3), noncalcareous, silty sand. It also contains a few pebbles as much as 1-2 cm in size. This horizon probably includes soil components that formed *in situ*, as well as components that formed on the upper part of the scarp and moved downslope.

Deformation Characteristics

A fault zone with a reverse sense of slip vertically displaces the gravel units in the trench (Fig. 22). The fault zone strikes N. 64° W. and dips 56° NE; the strike of the fault zone is identical to the regional strike of the scarp. Differential shearing in the fault zone has mixed the gravels of units 6, 7, and 8 (Pl. 2) into a dark-red (2.5YR 3/6), poorly sorted, matrix-supported gravel. The shearing also reoriented a few elongate rhyolite clasts such that their long axes are subparallel to the boundaries of the fault zone. We could not identify discrete slip planes or find features that showed net slip directions in the coarse gravels.

The boundaries of the fault zone are subtle and generally difficult to identify except where the pebble-cobble gravel (unit 8; Pl. 2) on the upthrown block bounds the fault zone. At this boundary, the crude stratification in the pebble-cobble gravel ends, and the clayey texture of the fault-zone gravel is obviously different from the texture of the pebble-cobble gravel.

The clay-plugged and clay-enriched gravels (units 6 and 7; Pl. 2) are exposed on both sides of the fault zone and can be used to measure the stratigraphic throw. The throw across the fault zone is only 0.6-1.0 m compared to the total stratigraphic throw of 3.2-3.3 m along the length of the trench. The stratigraphic throw is probably a minimum value, because the gravels are still slightly warped where they extend beyond the southwest end of the trench. However, a profile of the scarp indicates that the stratigraphic throw is a good estimate of the net throw on the scarp. The scarp height is

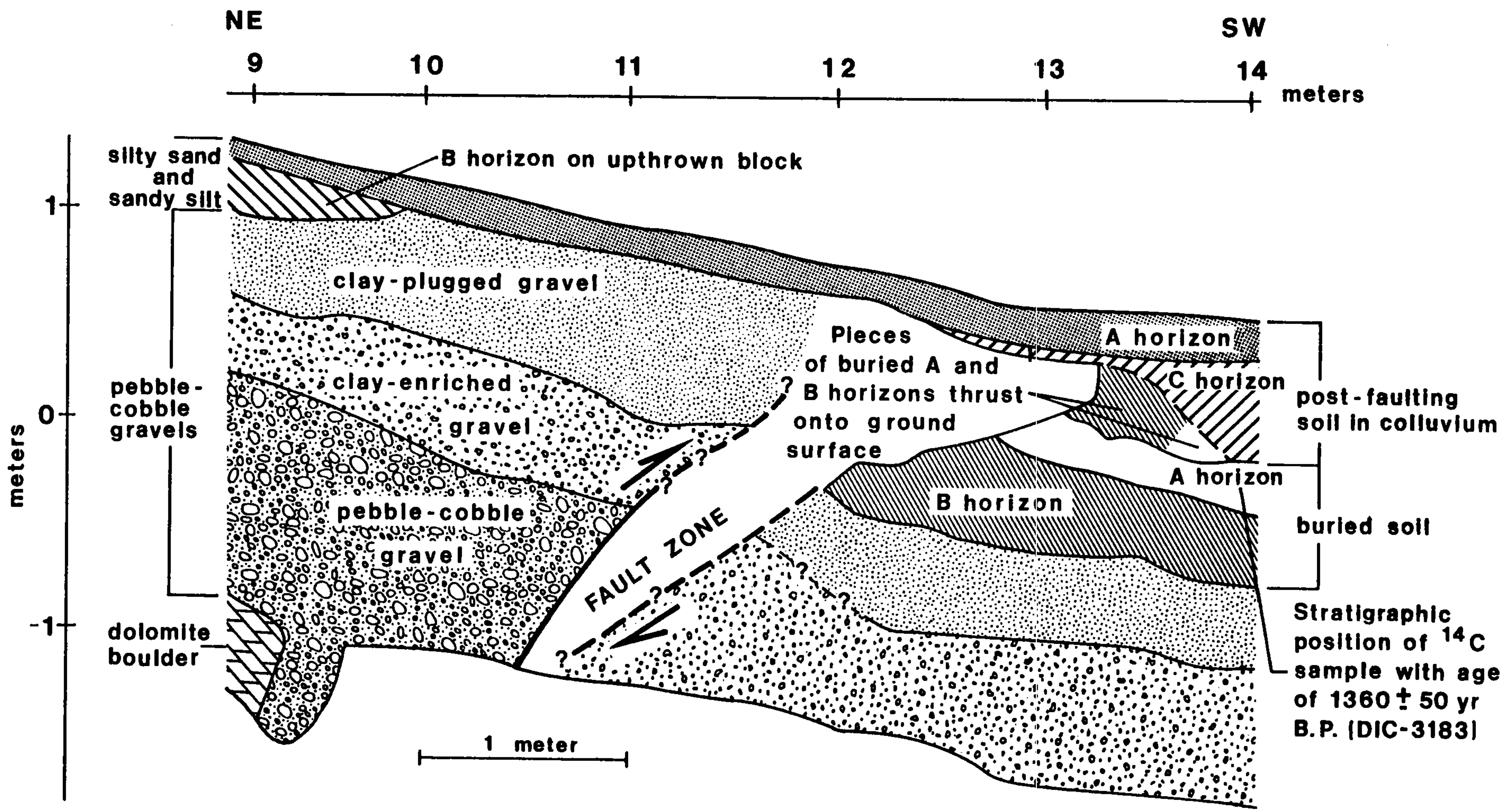

Figure 22. Part of trench 2 log, showing stratigraphic relations near the main fault zone. Heavy lines are faults that could be recognized by abrupt changes in the stratigraphy (dashed where inferred); arrows show general sense of displacement across the main fault zone. Fine lines are stratigraphic contacts (dashed where subtle). See Plate 2 for log of the entire trench.

3.4 m, and the surface offset, which approximates the net throw on this scarp, is 3.0 m (Bucknam and Anderson, 1979). Thus, from the stratigraphic data and the scarp profile, we estimate the net throw on the scarp to be slightly more than 3 m.

The difference between the net throw (about 3 m) and the throw across the fault zone (0.6-1.0 m) is the amount of deformation caused by warping. In this trench, only about one-quarter of the relief on the scarp results from displacement on the fault zone. Thus, in this trench as in trench 1, much of the relief on the scarp is the product of warping.

Discussion

The stratigraphy of colluvial deposits in the trench supports only one major surface-faulting event. On the downthrown side of the fault, the buried soil and alluvial gravels (units 4-7; Pl. 2) are truncated by the fault zone. The blocks of the buried B and A horizons (units 4a and 5a; Pl. 2) resting on the buried soil were either thrust upward and onto the ground surface during the faulting or they broke off from the free face shortly after the scarp formed. As the scarp continued to erode, the clayey and silty sand of units 1 and 2 (Pl. 2) on the upthrown side of the fault moved downslope and buried the soil on the downthrown side. Erosion also stripped some of the clay-plugged gravel (unit 6; Pl. 2) from the upthrown side immediately adjacent to the fault zone. The modern soil (units 1 and 3; Pl. 2) is forming in the post-faulting deposits that have accumulated on the downthrown side.

The faulting at trench 2 is late Holocene in age. The radiocarbon date of 1,360 ± 50 yr B.P. (Sample DIC-3181) for the buried A horizon (unit 4; Pl. 2) is a minimum age for the time of faulting. The radiocarbon date approximates the time when the A horizon was buried by scarp-derived colluvium and younger organic matter was no longer added to the soil. Studies of scarp degradation suggest that the actual time between the formation of the scarp and the burial of the soil could range from several decades to a few centuries. Thus, the age of the faulting indicated by the ^{14}C date from trench 2 is consistent with the age indicated by the dates from trench 1.

As in trench 1, the only unfaulted deposit in this trench is a 15 to 20-cm-thick mantle of the modern A horizon (unit 1; Pl. 2) that is continuous across the fault zone. Following the same reasoning as for trench 1, the A horizon at this position on the slope can form in a short time (possibly decades) and does not indicate a long period (thousands of years) of stability.

The modern soil in the post-faulting colluvium on the downthrown side contains slightly less clay than the buried soil, even though the relatively clay-rich soil on the upthrown block was a major source for the colluvium. The lower clay content in the modern soil suggests that there has been insufficient time for pedogenesis to substantially modify it. We do not yet have sufficient data to accurately estimate the rates of the soil formation in the study area, but the weak development of the soil on the post-faulting colluvium suggests that the colluvium is probably only a few thousand years old.

The stratigraphy in trench 2 provides little information about the significance of lateral slip during the last surface faulting. The gravel units that can be correlated across the fault show minor changes in thickness and no significant changes in character on either side of the fault zone. These gravel units are defined on the basis of varying amounts of silt and clay matrix. The variation in the matrix content is believed to be partly the result of pedogenesis; therefore, the boundaries between the gravel units are typically irregular, gradational, and, in places, subtle and difficult to identify. Because of this variability, the small changes in the thickness of the gravel units on either side the fault zone are not conclusive proof of strike-slip movement. Conversely, we cannot eliminate the possibility of some strike-slip motion during the last surface-faulting event.

SUMMARY AND CONCLUSIONS

The Meers fault is part of a major zone of NW-trending faults that form the boundary between the Wichita Mountains and the Anadarko basin (Harlton, 1951,1963). Much of the movement along the Wichita frontal fault system occurred in Pennsylvanian to Early Permian time. The net result created a vertical stratigraphic offset of several kilometers, with an overall vertical down-to-the-north sense of displacement.

At depth, the Meers fault appears to be a reverse fault (Brewer, 1982). Walper (1970), Donovan (1982), Donovan and others (1982), and most recently Ramelli and Slemmons (1985) and Crone and Luza (1986) have provided evidence for some left-lateral movement along the frontal fault system.

The frontal fault system is overlain by the Post Oak Conglomerate and Hennessey Shale in the vicinity of the Meers fault. In Comanche County, between East Cache Creek and Saddle Mountain, the Meers fault offsets conglomerate and shale at the surface for a distance of at least 26 km. These units are consistently displaced down to the south. The maximum topographic offset is 5 m near the center of the exposed fault trace.

The topographic displacement across the fault was initially interpreted as a fault-line scarp. The date of the last movement was thought to be Permian, representing the last adjustment between the Anadarko basin on the north and the Wichita uplift on the south. However, recent mapping has indicated that Quaternary alluvial deposits are offset by the fault.

Quaternary stratigraphic relationships and 10 ^{14}C age dates demonstrate that the last movement on the Meers fault is late Holocene in age. The last movement postdates the Browns Creek Alluvium, which began to be deposited about 13,000-14,000 yr B.P., and predates the East Cache Alluvium, which was deposited between 800 and 100 yr B.P. The topographic offset caused by faulting produced local stream incision on the upthrown side and deposition of sheetwash and fan alluvium on the downthrown side. Three ^{14}C ages of material buried by fan alluvium date the time of faulting. These ages indicate that faulting and deposition of fan alluvium probably occurred between 1,400 and 1,100 yr B.P. The soil formed in fan alluvium is only slightly more developed than that in the East Cache Alluvium, and the weak development of both soils indicates a geologically recent age that is consistent with the radiocarbon ages obtained for these deposits.

The two trenches provide important information about the age and characteristics of the deformation associated with Meers fault scarp. In both trenches, the dominant mode of deformation is warping and flexing of the alluvium. Brittle deformation expressed as discrete faults accounts for about one-tenth of the total deformation in trench 1 and about one-quarter of the total in trench 2. The difference in the amount of brittle deformation in the two trenches may be related to the degree of induration of the sediments at each site. The soft, porous, completely unconsolidated Browns Creek Alluvium in trench 1 deformed as an incompetent, plastic material. The high clay content in Porter Hill Alluvium in trench 2 partially indurated the gravels, and, as a result, the gravels behaved more competently and deformed in a more brittle fashion.

The surface faulting that formed the scarp on this part of the Meers fault is late Holocene in age. The ^{14}C trench dates suggest that the scarp formed about 1,700-1,300 yr ago. The age of the faulting from our trenching study is consistent with the age determined from regional Quaternary stratigraphic studies. The Meers fault, in the opinion of the authors, is clearly a capable fault (moved in the last 35,000 yr) as defined by Nuclear Regulatory Commission standards in Appendix A of part 100, Reactor Site Criteria.

The stratigraphy in the trenches and scarp profiles suggests that the net tectonic throw at both trench sites is about 3 m. Post-faulting erosion, backfilling, and gradational stratigraphic contacts introduce uncertainty in the net throw measured at the trench sites, but, considering these uncertainties, the values of net throw at both sites are similar. The similar amounts of throw and the stratigraphy at each site suggest that the alluvium exposed in each trench was deformed by one surface-faulting event with a major amount of vertical displacement. If this interpretation is correct, major surface faulting has occurred only once since depostion of the gravel in trench 2. Although their age is poorly constrained, these gravels are thought to be middle to late Pleistocene in age. This implies a lengthy recurrence interval (tens of thousands of years) for surface faulting on this part of the Meers fault. This conclusion assumes that the motion on the fault is consistent during succeeding events; that is, the amount of vertical and lateral slip per event is relatively uniform. An event with mainly lateral slip could be difficult to detect in the gravels in trench 2. If present, an undetected event in the gravels would reduce the inferred recurrence interval.

Long-term slip rates computed from the available data have large uncertainties and therefore seem to be of limited value in characterizing the rate of strain accumulation on the fault. Without reliable information about the timing of successive events, the amount of lateral slip, and the age of the Porter Hill Alluvium, calculated slip rates are, at best, general estimates. Using 125,000 yr B.P. for the age of the Porter Hill Alluvium and 3.0 m for the net slip, the resulting slip rate is 0.02 mm/yr. In spite of the uncertainty, of the age of the Porter Hill Alluvium, this calculated slip rate is consistent with slip rates expected in intraplate environments.

Although the Quaternary-stratigraphy studies and trench data provide valuable insight into the age of the last surface-faulting event and the mode of deformation, many questions remain unanswered. Westen (1985) and Ramelli and Slemmons (1985) reported evidence of multiple recent fault movements. At the trench locations, only one event was observed. Surface offset measurements by Ramelli and Slemmons (1985) indicate a left-lateral, reverse-oblique sense of displacement, with a dominant horizontal component. Westen (1985) and the trench data suggest that the displacement is primarily vertical. Additional work is needed to resolve these inconsistencies.

An important aspect in evaluating the seismic hazards associated with the Meers fault is understanding the relationship between the fault at the surface and faults that extend to seismogenic depths. In the shallow subsurface, the fault responsible for the scarp is probably a reverse fault that dips NE. Establishing the relationship between the fault scarp and deeply penetrating faults that are suitably oriented for slip within the contemporary regional stress field should be an important goal of future studies.

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