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DEPARTMENT OF THE INTERIOR
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PRELIMINARY REPORT ON LATE CENOZOIC FAULTING AND STRATIGRAPHY IN THE VICINITY OF YUCCA MOUNTAIN, NYE COUNTY, NEVADA

By

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Open-File Report 84-788

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Errata for U.S. Geological Survey Open-File Report 84-788

On Plate 1, the fault shown at D should be changed to a stratigraphic contact. The letter designation D should be deleted at that site. All subsequent letters designating faults should be changed to reflect the deletion. Fault E should be redesignated fault D; similar changes should be carried through the letter designations to fault Z. Letter designations in the text correspond to the relettered fault symbols.

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ABSTRACT

Mapping of surficial deposits and examination of faults in natural and trenched exposures in a 1100 km^2 area around the site of a potential repository for radioactive waste at Yucca Mountain have identified 32 faults that offset or fracture Quaternary deposits. Where the amount of Quaternary offset can be estimated, dip-slip movement is on the order of 3 m or less on faults in and near Yucca Mountain. Maximum Quaternary offset within the study area may be as much as 30 m. No strike-slip movement was demonstrated nor can it be ruled out.

Based on radiometric ages, correlations of stratigraphic units, and field observations, Quaternary faults are divided into three broad age groups: five faults moved between about 270,000 and 40,000 years ago; four faults moved about 1 m.y. ago; and 23 faults moved probably between 2 m.y. and more than 1.2 m.y. ago. Offset of Holocene deposits has not been demonstrated.

INTRODUCTION

Geological and hydrological investigations to evaluate Yucca Mountain in southern Nye County, Nevada (fig. 1), as the possible site for an underground radioactive waste repository were begun by the U.S. Geological Survey in 1978. These studies are being conducted in cooperation with the U.S. Department of Energy Nevada Nuclear Waste Storage Investigations. This report summarizes a reconnaissance study of late Cenozoic faulting in the vicinity of Yucca Mountain. Detailed investigations of faults in the Yucca Mountain area are continuing, but data and preliminary conclusions are presented at this time for use by the U.S. Department of Energy and others involved in evaluating the Yucca Mountain site.

The purposes of this fault study were to determine the location and extent of faults in the Yucca Mountain area that displace late Pliocene and Quaternary deposits and to make a preliminary assessment of the amount and age of fault displacements on which to base more detailed investigations.

This report is based on published and unpublished surficial maps of the Yucca Mountain area by Swadley and Hoover. Uranium-trend isotopic dates were determined by Rosholt. Preliminary analysis of trenches excavated across faults in the study area were by Swadley and Hoover unless noted otherwise.

GEOLOGIC SETTING

Yucca Mountain is in the southern Great Basin, an area chiefly characterized by north-trending linear mountain ranges that are flanked by extensive alluvial fans and separated by broad alluvial basins. Most ranges are deeply incised by narrow stream valleys. The climate is arid and vegetation is limited to sparse desert plants.

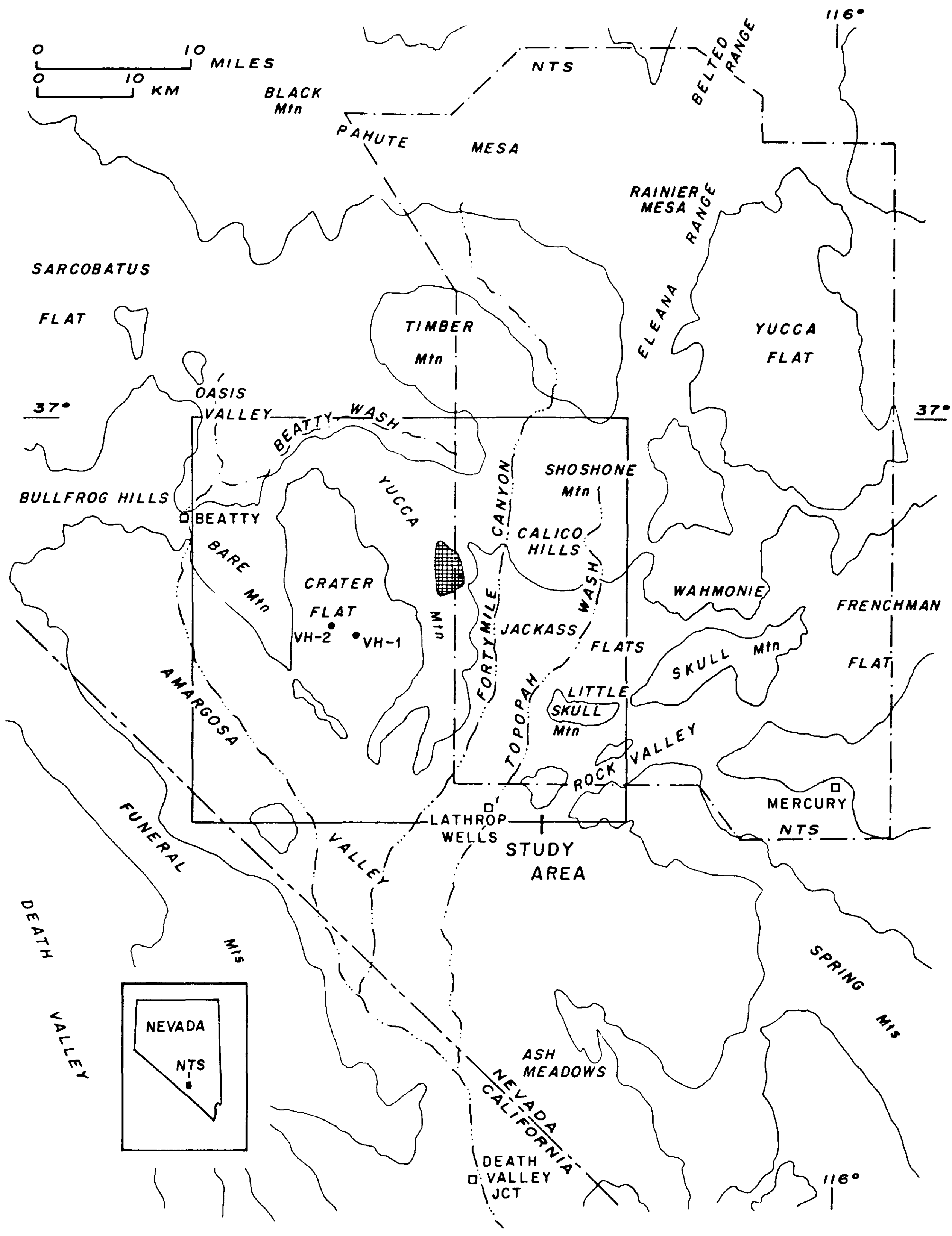


Figure 1.--Map of Nevada Test Site area showing location of Yucca Mountain and site of potential waste repository (shaded area).

The exposed bedrock in the vicinity of Yucca Mountain consists of Precambrian and Paleozoic quartzite, shale, and carbonate rocks and Tertiary volcanic rocks (fig. 2) (Stewart and Carlson, 1978). These rocks locally are overlain by late Tertiary and Quaternary surficial deposits. The area lies within a major Miocene volcanic field and contains several calderas, which produced voluminous pyroclastic deposits including the tuffs that underlie Yucca Mountain (Byers and others, 1976). Small basalt lava flows and cinder cones erupted in the Crater Flat area during the late Pliocene and Pleistocene.

Yucca Mountain consists of a series of subparallel ridges that are formed by blocks of resistant Tertiary volcanic rocks, mainly densely welded tuffs, which dip gently eastward and are bounded by north-trending faults. The areas bordering Yucca Mountain and the valleys between the ridges making up Yucca Mountain are underlain by alluvial gravels and, locally, by eolian deposits. The bedrock geology of Yucca Mountain is shown on maps by Christiansen and Lipman (1965), Lipman and McKay (1965), and Scott and Bonk (1984). The geology of the Bare Mountain quadrangle, west of Yucca Mountain, was mapped and described by Cornwall and Kleinhampl (1961). The volcano-tectonic history of Crater Flat (fig. 1) is discussed by Carr (1982).

METHODS

Late Cenozoic surficial deposits in the vicinity of Yucca Mountain were mapped on the basis of stratigraphy described by Hoover and others (1981). Mapping in the field was supplemented by the interpretation of conventional aerial photography. The locations of faults that offset the surficial deposits are shown on plate 1 along with the areal distribution of generalized time-stratigraphic surficial units.

Twenty-three trenches (pl. 1) were excavated in the Yucca Mountain area to evaluate Quaternary fault movement. Fourteen trenches are on Yucca Mountain or in valleys that border it; six trenches are on adjacent ridges that parallel Yucca Mountain; and the remaining three trenches are in the eastern part of Crater Flat, southwest of Yucca Mountain. Some trenches were excavated across recognized fault scarps, and others were placed in surficial deposits across the projection of a known bedrock fault.

Trenches were excavated using bulldozers to depths of 2 to 4 m and lengths of 20 to 40 m. The trenches were mapped by establishing a level line and a 2-m reference grid from which readily recognized stratigraphic units, sedimentary features, soil horizons, faults, and fractures were plotted. (The term fracture, as used in this report, refers to planar breaks in the deposits along which there is no demonstrable offset.) Diagrams of one wall of each trench illustrating these features are included in an appendix. More detailed logging of fault trenches is in progress.

Data obtained from the study of the trenches are summarized in table 1. Trenches 1, 15, GA1A, and GA1B exposed faulted Tertiary bedrock at shallow depths and Quaternary deposits were thin or absent; these trenches were abandoned and are not reported in table 1. Nineteen trenches exposed surficial deposits that are believed to range in age from 7,000-9,000 years old (unit Q1c) to as much as 2 m.y. old (unit QTa) (Hoover and others, 1981). Six of these trenches also exposed Tertiary volcanic rocks.

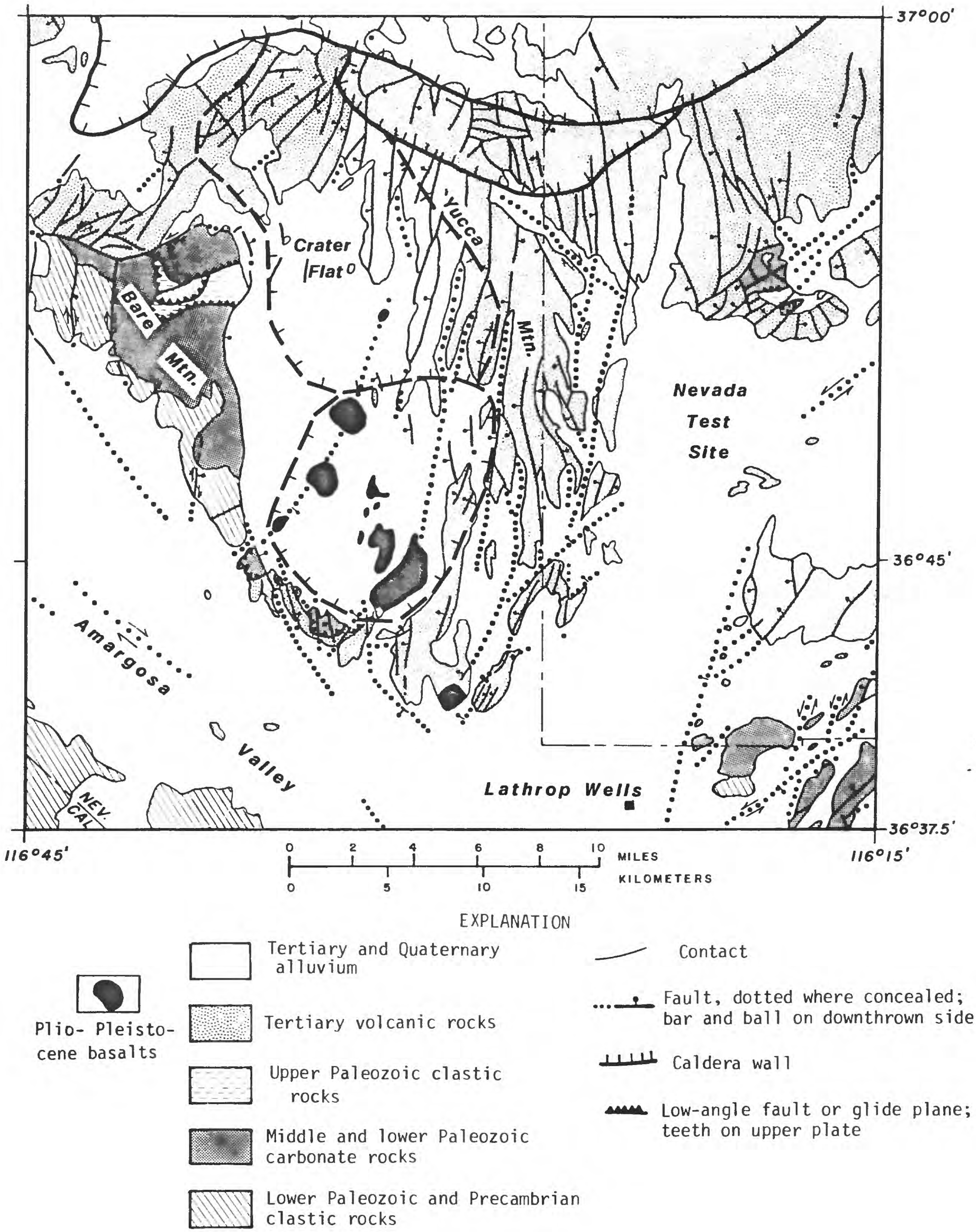


Figure 2.--Generalized geologic map of the Yucca Mountain area. Modified from Snyder and Carr, 1982.

Table 1.--Data from trenches across faults in the Yucca Mountain area

Trench no.	Fault	Trench location	Surficial units exposed in trench	Bedrock exposed in trench	Tectonic features that affect surficial deposits	Inferred age of tectonic feature	Remarks
2	G	On projection of bedrock fault	Q1c, Q2a, Q2b, Q2c	No	None		Indicates no fault movement after 270,000 yr
4	F	do.	Q1c	No	do.	None	Indicates no fault movement after 7,000 yr
6	F	do.	Q1c	In trench floor	do.	None	Do.
8	Solitario Canyon	On QTa - bedrock contact	Q1c, QTa	In upthrown block	Faults cut QTa; fractures cut QTa and QTa soil	1.2 m.y.	Fault movement dated by basaltic ash in fault zone
9	F	On projection of bedrock fault	Q1c, Q2c	In upthrown(?) block	None	None	Indicates no fault movement after 270,000 yr
10A	Solitario Canyon	do.	QTa	No	do.	None	Probably not located on fault
10B	Solitario Canyon	On QTa - bedrock contact	Q2c, QTa	In upthrown block	QTa faulted against Tv; QTa soil and Q2c not faulted	<2 m.y.; >270,000 yr	-----
11	D	On projection of bedrock fault	Q2b, Q2c, QTa	No	None	None	Indicates no fault movement after 270,000 yr
12	E	On trace of bedrock fault	Q2 soil	In upthrown and downthrown block	Q2 soil buries fault scarp in bedrock	<40,000 yr	Indicates no fault movement after 40,000 yr
13	H	On projection of bedrock fault	Q2b, Q2c	No	None	None	Indicates no fault movement after 270,000 yr
14	C	On Q2 - bedrock contact	Q2a, Q2s	In upthrown block	Fractures cut Q2s and Q2s soil; do not cut Q2a	$<270 \pm 90 \times 10^3$ yr; $>30 \pm 10 \times 10^3$ yr	Ages of Q2s and Q2a by uranium-trend method
16	Paintbrush Canyon	On projection of bedrock fault	Q2e	No	None	None	Probably not located on fault
16B	Paintbrush Canyon	do.	Q2e, Q2s	In upthrown block	Fractures cut Q2e; do not cut Q2s	<700,000 yr; >270,000 yr	-----
17	Paintbrush Canyon	do.	Q2e	do.	None	None	Indicates no fault movement after 700,000 yr
A1	Paintbrush Canyon	do.	Q2e, Q2h	No	Fractures cut Q2e and Q2e soil; do not cut Q2b	<about 700,000 yr; >160,000 yr	-----
A2	Paintbrush Canyon	do.	Q2b, Q2c	No	Fractures cut Q2c, not Q2c soil or Q2b	<800,000 yr; >270,000 yr	-----
CF1	M	On scarp in QTa	Q2, QTa	No	Faults cut QTa; do not cut some QTa soil horizons of Q2	1.2 m.y.	Fault movement dated by by basaltic ash in fault zone
CF2	Q	do.	Q2, QTa	No	3 faults cut QTa and lower part of QTa soil, 1 fault cuts entrie QTa soil; Q2 not cut	<2 m.y.; >40,000 yr	Two periods of faulting likely
CF3	Q	On projection of scarp in QTa	Q2a, Q2c	No	Faults cut Q2c and Q2c soil; not Q2a	$<270 \pm 30 \times 10^3$ yr; $>40 \pm 10 \times 10^3$ yr	Ages of Q2c and Q2a by uranium-trend method

Five trenches (8, 10B, CF1, CF2, and CF3) exposed evidence of Quaternary offset and four other trenches (14, 16B, A1, and A2) exposed fractures in Quaternary units. These fractures parallel the faults on which the trenches are located, and are interpreted as fault related. The remaining 10 trenches showed no indication of Quaternary faulting. The evidence for Quaternary faulting derived from the trench studies is discussed in more detail below.

Where the trace of a fault plane was exposed in a trench wall, it was excavated by hand to search for slickensides and other directional features. None, however, were found. Neither the poorly consolidated Quaternary units nor the secondary carbonate deposits that commonly occur along the faults appeared to preserve such features. Slickensides associated with Quaternary faulting were observed only in an abandoned prospect pit along the Bare Mountain fault zone.

Stratigraphic units and post-fault carbonate and silica deposits were sampled in six trenches for isotopic age determinations. Sample locations are shown on trench diagrams in the appendix. Surficial deposits were dated by the uranium-trend method (Rosholt, 1980). This method is experimental but was used because materials needed for more conventional radiometric dating methods are sparse in the Yucca Mountain area. Dates determined by the uranium-trend method theoretically indicate the minimum age for deposition of surficial deposits (Rosholt, 1980). The technique is considered to be applicable for deposits that range in age from 5,000 to 900,000 years and has a potential estimated accuracy of about ±10 percent. Uranium-trend dates have been used in an attempt to determine minimum ages for deposits that structurally and stratigraphically bracket the age of fault related features in trenchs 2, 13, 14, and CF3. Approximate limits on the absolute age of faulting are inferred on the basis of these dates. The accuracy of the absolute ages derived by this method is not known, but ages determined for some stratigraphic units are reasonably consistent over the study area and are consistent with the broad limits on the ages of stratigraphic units in the study area inferred on the basis of correlations with better dated sequences from the surrounding region.

The uranium-series method (Szabo and others, 1981) was used to date deposits of carbonate or silica in trenches 14, CF1, and GA1A, interpreted as post-fault deposits. Uranium-series dates theoretically indicate the minimum age for the dated deposit, but the method only is considered to be accurate if the chemical system is closed. Most samples dated by this method yielded dates that appear to be inordinately young, but which can be considered as minimum ages (Szabo and others, 1981, p. 32). The dated samples from Yucca Mountain may not be from chemically closed systems, and the effect of this on the age determinations is not known. Dates determined by the uranium-series method are summarized in table 2.

Topographic profiles were measured across a number of fault scarps in the Crater Flat area, west of Yucca Mountain, to help characterize the scarps and possibly to provide a relative indicator of scarp age. Terms used in scarp descriptions are as defined by Bucknam and Anderson (1979).

LATE CENOZOIC STRATIGRAPHY

The late Tertiary and Quaternary deposits of the study area consist of alluvium, eolian sands, colluvium, lake sediments, and volcanic deposits.

Table 2.--Radiometric age data for fault-related secondary deposits exposed in trenches in the Yucca Mountain area

[Age determination by uranium-series method by P. O'Malley and B. Szabo, U.S. Geological Survey, written commun., 1982.]

Trench no.	Sample no.	Type of deposit	Age (in 10^3 yr)
14	TSV-412-1	Carbonate from K horizon Q2s soil	>400
		Opal from K horizon of Q2s soil	>350
	TSV-412-3	Opal from K horizon of Q2s soil	>550
	TSV-412-7	Opal from K horizon of Q2s soil	>400
CF1	TSV-386	Secondary carbonate along fault	27 ± 3
	TSV-387	K horizon of QTa	33 ± 4
GA-1A	TSV-395	Undisturbed carbonate deposit above fault	>32

These range in age from greater than 3 m.y. old for some of the lake sediments to less than about 150 years old for the youngest alluvial unit (Hoover and others, 1981). Hoover and others (1981) described the stratigraphy of these deposits (fig. 4) and defined characteristics by which they can be mapped and correlated across the region on the basis of age, lithology, and depositional environment. The following brief descriptions of the map units are based mainly on their work. More recently determined isotopic ages used to refine the stratigraphy reported by Hoover and others (1981) are summarized in table 3. The deposits are grouped herein into four major units: (1) late Pliocene and Pleistocene, (2) early Pleistocene and Pliocene(?), (3) middle and late Pleistocene, and (4) Holocene. The distribution of these units over the study area is shown on a generalized surficial map (pl. 1, in pocket).

Late Pliocene and Pleistocene Deposits

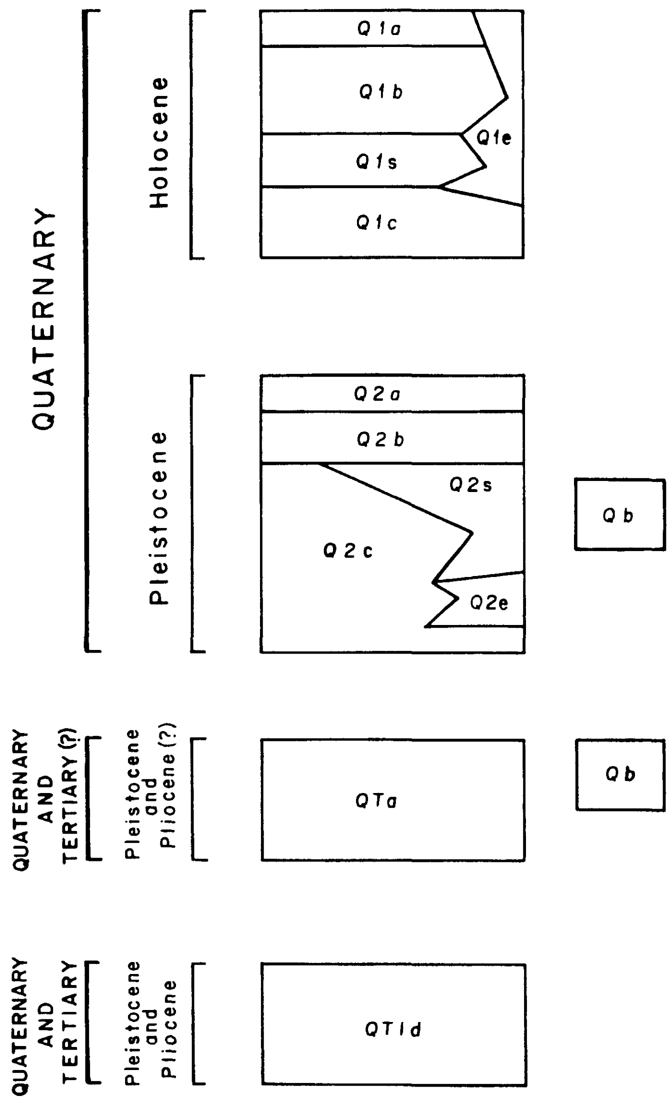
The oldest surficial deposits of the study are predominantly of late Pliocene age and consist of lacustrine sediments (fig. 4). These lacustrine deposits (unit QTld) are mainly unconsolidated to moderately indurated marl and silt that locally contain beds of limestone, sand, and fine-grained volcanic ash. They were deposited in Lake Amargosa, which occupied much of what is now the Amargosa Valley (fig. 1) during the late Pliocene; remnants of the lake probably persisted into the early Quaternary.

The age of unit QTld is not precisely known; however, an ash bed near the middle of the unit yielded radiometric ages that ranged from about 3 m.y. (fission-track method; C. W. Naeser, U.S. Geological Survey, written commun., 1980) to 3.8 m.y. (K-Ar method on biotite; R. L. Hay, University of California, Berkeley, written commun., 1979). A second ash bed near the top of the unit was dated at 2.1 ± 0.4 m.y. by the fission-track method (C. W. Naeser, written commun., 1982). A slightly younger age is suggested for the upper part of unit QTld by mammoth remains that are considered to be less than 2 m.y. old (C. A. Repenning, U.S. Geological Survey, written commun., 1982).

Early Pleistocene and Pliocene(?) Deposits

These deposits consist of alluvium that mainly is early Pleistocene but in some areas may be as old as latest Pliocene. The alluvium (unit QTa, fig. 3) consists of debris flows with sparse bedded fluvial sediments; it occurs as dissected fans and fan remnants that are adjacent to bedrock ranges and, less commonly, as isolated outcrops several kilometers from the ranges. Unit QTa typically is moderately indurated, coarse, angular, unsorted gravel with minor amounts of sand- to clay-size material. In most exposures, QTa is partly cemented with calcium carbonate.

The approximate age of unit QTa is limited by the ages of enclosing units; there are no dated materials within the unit. QTa unconformably overlies QTld at several localities in the Lathrop Wells quadrangle (Swadley, 1983), indicating that QTa deposits are less than 2 m.y. old in that area. Unit QTa is overlain by unit Q2e, that locally contains lenses of volcanic ash correlated with the Bishop ash by Izett (1982) on the basis of their similar chemistry. Radiometric dates for samples from the Bishop ash indicate that it is 0.74 m.y. old (Izett, 1982). The lower part of unit Q2e is considered approximately 0.74 m.y. old on the basis of the correlation with the Bishop ash. A period of erosion and weathering occurred following the deposition of QTa but prior to depostion of Q2e (Hoover and others, 1981), suggesting that



UNIT	ESTIMATED AGE RANGE (in years)
Holocene Deposits	
Q1a - Fluvial deposits	present to 150
Q1b - Fluvial deposits and debris flows	150 to 4000
Q1e - Eolian dunes and sheets	present to 8000
Q1s - Fluvial sand sheets	4000 to 7000
Q1c - Coarse fluvial deposits	7000 to 9000
Middle and Late Pleistocene Deposits	
Q2a - Local debris flows	≈40,000
Q2b - Fluvial deposits	160,000 to 250,000
Q2s - Fluvial sand sheets	270,000 to 700,000
Qb - Basalt flows and cinders	230,000 to 300,000
Q2e - Eolian dunes and sheets	700,000 to 750,000
Q2c - Coarse fluvial deposits	270,000 to 800,000
Early Pleistocene — Pliocene (?) Deposits	
QTa - Debris flows, minor fluvial deposits	1.1×10^6 to 2×10^6
Qb - Basalt flows and cinders	1.1×10^6 to 1.3×10^6
Pliocene — Pleistocene Deposits	
QTld - Lacustrine deposits	$< 2 \times 10^6$ to 4×10^6

Figure 3.--Surficial units present in the NTS region. Modified from Hoover and others (1981). Estimated age ranges are based in part on radiometric data. Where data are not available, age limits have been estimated based on field relations, reconstruction of the depositional history, and correlations with dated units outside the NTS area.

Table 3.--Radiometric age data for stratigraphic units of the NTS region

[Ages shown are ± one standard deviation. Determinations by uranium-trend method by J. N. Rosholt except where otherwise indicated.]

Stratigraphic unit	Material	Sample location	Age (in 10^3 yr)
[1]Q1c	Charcoal in fluvial gravel	Amargosa River bank, 2 km SE of Beatty, NV	8.3 ± .075
Q	Clayey silt of eolian A horizon of Q2 soil	SW Frenchman Flat	30 ± 30
[2]Q2	Loess	Basalt cinder cone, 11 km NW of Lathrop Wells, NV	25 ± 10
Q2a(?)	Slope wash sand	Trench 14	38 ± 10
	Slope wash below fault scarp	Trench CF3	40 ± 10
	Slope wash	Trench 13	41 ± 10
	Fluvial gravel	Trench 2	47 ± 20
	Slope wash sand	Trench 14	90 ± 50
Q2b	Fluvial gravel	Trench 2	145 ± 25
	Fluvial gravel	Gravel pit near Shoshone, CA	160 ± 18
Q2s	Fluvial sand	Jackass Flats	160 ± 90
	Fluvial sand	Trench 14	270 ± 90
	Fluvial sand	Trench 14	420 ± 50
	Fluvial sand	Trench 14	480 ± 90
Q2c (younger soil)	Fluvial gravel	Trench 13	240 ± 50
	Fluvial gravel	Trench CF3	270 ± 30
	Fluvial gravel	South Crater Flat	260 ± 140
	Fluvial gravel	Jackass Divide	270 ± 35
	Fluvial gravel	Rock Valley	310 ± 30
Q2c (older soil)	Fluvial gravel	Jackass Divide	430 ± 40
	Fluvial gravel	South Crater Flat	430 ± 60
[3]Q2e	Eolian sand containing volcanic ash	Striped Hills	730
[4]QTld	Volcanic ash bed near top of lake beds	Carson Slough, south Amargosa Desert	2.1 ± 0.4 m.y.

1 ^{14}C analysis by S. W. Robinson, U.S. Geological Survey.
2 Uranium-series analysis by B. J. Szabo, U.S. Geological Survey.
3 Correlation on basis of trace element chemistry to Bishop ash; analysis by G. A. Izett, U.S. Geological Survey.
4 Fission-track analysis by C. W. Naeser, U.S. Geological Survey.

QTa deposits may be substantially older than the 0.74 m.y. old limit implied by its stratigraphic position below Q2e deposits. Basalt ash deposits in fractures within unit QTa exposed in two fault trenches in eastern Crater Flat are inferred to be approximately 1.2 m.y. old on the basis of complex geological relationships discussed below, possibly restricting further the upper limit for the age of unit QTa (see discussion of trenches 8 and CF1).

Middle and Late Pleistocene Deposits

Middle and late Pleistocene deposits (unit Q2, fig. 3) consist of fan alluvium, fluvial and eolian sands, and volcanic deposits. These deposits have been subdivided into five mappable units on the basis of relative age and lithology: three alluvial units, Q2c, Q2b, and Q2a (in order of decreasing age); eolian dunes and sand sheets, Q2e, and fluvial sand sheets, Q2s (fig. 4). The lithologies, stratigraphic relations, and soil development of these units are described in more detail by Hoover and others (1981, p. 15).

Unit Q2c consists of fluvial fan deposits and some debris flows. These deposits typically are unconsolidated, poorly to well-sorted, nonbedded to well-bedded, angular to rounded gravel with sand and silt in the matrix. Interbeds of silty sand are locally common. Alluvial fans of Q2c are generally deposited on unit QTa on the middle and upper valley slopes; Q2c also occurs as terrace deposits in larger stream valleys.

Eolian deposits of unit Q2e occur as dunes and sand sheets in and adjacent to the Amargosa Valley. Ramps of fine, well-sorted sand as much as 50 m thick flank many of the hills bordering the Amargosa on the north. Unit Q2e is locally interbedded with the lower part of Q2c and is clearly older than Q2b.

Fluvial sand sheets of unit Q2s occur along major streams and along drainages downstream from dunes. The sheets consist of water-laid fine to medium gravelly sand or stream-reworked windblown sand and commonly rest on Q2c fans.

Unit Q2b is similar to Q2c in depositional environment and lithology. It occurs as terrace deposits that are inset in Q2c and underlies lower slope fans. These Q2b fans commonly merge upslope with Q2c fan deposits.

The youngest Q2 fluvial unit, Q2a, consists of debris flow deposits that are large enough to be mapped at only three localities. Q2a is poorly sorted, unconsolidated sand- to clay-size material that contains some gravel.

The inferred age of 0.74 m.y. old for lenses of volcanic ash in the lower part of unit Q2e discussed above is considered the approximate lower age limit for both units Q2e and Q2c. Younger Q2c gravels locally overlie and contain reworked cinders from a small basaltic volcano 11 km northwest of Lathrop Wells (fig. 1), which has yielded K-Ar dates ranging from 230,000 to 300,000 years old (Vaniman and others, 1982), indicating the approximate age for the younger part of Q2c deposition. A uranium-trend date of $270 \pm 30 \times 10^3$ years old was determined for a sample of Q2c from a soil horizon developed in the upper part of the unit. This date, which theoretically indicates the minimum age of Q2c deposition is consistent with the approximate age for the younger part of Q2c indicated by the relationship with the volcanic center near Lathrop Wells.

Uranium-trend dates determined for samples of Q2s in the Yucca Mountain area range from 480 ± 90 x 10^3 years to 270 ± 90 x 10^3 years. Stratigraphic relationships demonstrate that unit Q2s is equivalent in age to upper Q2c, in part equivalent to Q2e, and is older than Q2b. The minimum ages inferred from the uranium-trend dates are generally consistent with these stratigraphic relationships.

Samples of Q2b from the Yucca Mountain area have yielded uranium-trend dates that range from 145 ± 25 x 10^3 years to 160 ± 18 x 10^3 years (table 3). A minimum age of about 160,000 years for Q2b is preferred on the basis of the reliablity of laboratory results. Samples from four exposures of slope-wash and fluvial deposits that have been correlated with Q2a yielded uranium-trend dates that range from 38 ± 10 x 10^3 to 47 ± 20 x 10^3 years (table 3).

Holocene Deposits

Holocene deposits in the study area consist of fluvial sands and gravels and eolian sand. These deposits have been subdivided on the basis of relative age and lithology into five mapping units: three units of fluvial gravel, Q1c, Q1b, and Q1a (in order of decreasing age); fluvial sand sheets, Q1s; and dunes and eolian sand sheets, Q1e (fig. 4).

Unit Q1c consists of unconsolidated fluvial gravel and minor debris flows that typically are poorly to well-bedded, moderately well-sorted gravel having a sandy matrix; Q1c locally contains numerous thin beds of sand. Q1c occurs as thin, broad fans on Q2c downstream from the incised parts of stream channels on valley slopes and underlies terrace remnants along larger drainages. Charcoal fragments from Q1c fluvial sand and gravel near Beatty, Nevada (fig. 1), yielded a ^{14}C age of 8,300 ± 75 years (S. Robinson, U.S. Geological Survey, written commun., 1981).

Q1e consists of well-sorted fine sand that occurs as small dunes and irregularly shaped sheets over much of the Amargosa Valley. It has been observed overlying all other units. Unit Q1s consists of thin sheets of fine moderately well-sorted gravelly sand and commonly overlies Q1c. Q1b and Q1a consist of unconsolidated fluvial gravel and sand and are confined to the channels of active washes. The subunits of Q1 are described in more detail by Hoover and others (1981, p. 20).

LATE CENOZOIC FAULTING

Thirty-two faults with associated offsets or fractures in late Cenozoic deposits were indentified in the Yucca Mountain area on the basis of mapping and trench studies. The traces of faults that involve Quaternary deposits and their extentions in bedrock are shown on plate 1, along with several fault traces across which trenches were excavated but no disturbance of Quaternary deposits was recognized. The length of fault segments that have Quaternary offset cannot be determined in most cases, because materials necessary to demonstrate Quaternary offset are not present where faults extend into bedrock. The faults are described from east to west across the area; they are referred to by fault names where such names exist, otherwise a letter designation has been used to identify each fault or group of adjacent faults.

In the Calico Hills, in the northeastern part of the study area, four probable faults, collectively designated A on plate 1, form distinct linear features on aerial photographs and appear to offset unit QTa in outcrop. Three of these faults trend northeast and one trends eastward. The lineaments can be traced on aerial photographs across deposits of Q2c in some places, but do not cross Q1c deposits. No definite scarps were observed and offset of QTa is probably a half meter or less. It was not determined whether the lineaments in Q2c reflect vegetation growth controlled by fractures in QTa beneath undisturbed Q2c or offset of Q2c. None of the faults at this location were trenched.

Fault B, also in the Calico Hills, trends northeast and is exposed for less than 0.2 km in Paleozoic sedimentary rocks. It locally offsets deposits of QTa and Q2c, which are too small to show on plate 1. Offset, down to the southeast, is 2 m in QTa at the northeast end of the fault and about 0.5 m in Q2c at the southwest end. Fault B was not trenched, and it is not known whether the difference in the amount of offset is because of recurrent movement or a decrease in throw to the southwest.

The Paintbrush Canyon fault trends northward for 18 km in the eastern part of Yucca Mountain and continues to the north beyond the study area. Where it offsets Miocene volcanic rocks, the displacement is normal and down to the west. Although surficial mapping did not indicate Quaternary offset, evidence for disturbance of Pleistocene deposits was discovered in three trenches excavated across the fault (pl. 1). Trench A1 (fig. A15) exposed fractures in unit Q2e. These fractures do not appear to offset unit Q2b. In trench A2 (fig. A16), similar fractures cut unit Q2c but not the soil developed in Q2c or the overlying Q2b deposits. Because bedding features are scarce in these unconsolidated units, offset along the fractures was difficult to assess, but the lack of apparent disturbance adjacent to the fracture suggests any offset was minor, less than a few centimeters. Trenches 16 and 16B were cut near the southern end of the fault zone (north end of the Fran Ridge fault of Scott and Bonk, 1984) in deposits of unit Q2e. Trench 16 (fig. A12) showed no faults or fractures, but 16B (fig. A13) exposed carbonate-coated west-dipping fractures that cut Q2e but not overlying deposits of Q2s(?). The fracturing is interpreted as indicating minor offset on the fault in the underlying bedrock that produced fractures with no visible offset in the unconsolidated sand of unit Q2e.

Fault C (Bow Ridge fault of Scott and Bonk, 1984) parallels the Paintbrush Canyon fault (pl. 1) and also offsets Tertiary rocks down to the west. The fault trends northward for at least 6 km from the trench 15 site. It does not appear to cross Yucca Wash to the north, and its extent south of trench 15 is not known. No indication of Quaternary offset was detected by mapping of surficial deposits, but trench 14 exposed a fault in Tertiary volcanic rocks and fractures that cut across but do not appear to offset unit Q2s and the K horizon of the soil developed in it. These fractures do not cut the overlying Q2a (fig. A11). Uranium-trend dates determined for samples from units Q2s and Q2a in this trench are $270 \pm 90 \times 10^3$ years and $38 \pm 10 \times 10^3$ years respectively (table 3). Minor offset on fault C that produced the fractures in unit Q2s is inferred during the time interval between these dates. Uranium-series dates ranging from 350×10^3 to 550×10^3 years were determined for samples of carbonate and opal deposits (table 2) that extend across the faulted volcanic rocks without offset.

Along the northeast side of Yucca Mountain, four faults, D, E, F, and G, cut Tertiary volcanic rocks but, no offset of Quaternary deposits was observed. Each fault was investigated by one or more trenches (pl. 1). No evidence of Quaternary faulting was found. Data from these trenches are summarized in table 1 and trench wall diagrams appear in the appendix.

Fault I, near the south end of Yucca Mountain, cuts QTa and locally faults it against older Tertiary rocks. The fault strikes northeast and is down to the west; it was not trenched, and the amount of displacement is unknown. The fault is exposed for a distance of 2.4 km and appears to be covered by younger Q2 deposits to the north and south. A low northwest-facing scarp is exposed along part of the fault, but for most of its length, the downthrown block and the scarp are masked by windblown sand (Q2e) that locally extends across the fault without demonstrable offset.

The Solitario Canyon fault zone is one of the major structures of the Yucca Mountain area and marks the west boundary of the potential repository. The fault zone strikes northerly and extends for at least 12 km. Although the fault zone is complex, the net offset is normal and down to the west. Mapping of surficial deposits indicated several fault segments where QTa is faulted against Tertiary volcanic rocks for a total distance of 4.5 km (pl. 1).

Three trenches (8, 10A, and 10B) were cut in Quaternary deposits across the Solitario Canyon fault zone. Trench 8 exposed unit QTa displaced downward on the west against Tertiary volcanic rocks (fig. A4). The amount of offset is unknown. Reworked basaltic ash occurs in a fracture zone in unit QTa on the south wall of trench 8. Known late Cenozoic basaltic centers in the Crater Flat area, which are potential sources for the basaltic ash in trench 8, fall into three age groups on the basis of K-Ar dates. Basalt centers of the oldest group, approximately 3.75 m.y. old (Carr, 1982), are older than the maximum age for QTa interpreted from stratigraphic relations and isotopic dates from the Amargosa Desert and are not considered a possible source for the reworked ash. Differences between phenocryst compositions determined by microprobe analyses of samples of the 3.75 m.y.-old basalt and ash from trench 8 and a similar ash from trench CF1, 2 km to the west (pl. 1), also suggest that the 3.75 m.y.-old basalt eruptions were not the source of the ash in the trenches (Wolfsberg and Vaniman, 1984). The younger basalt centers in Crater Flat, approximately 1.2 and 0.24 m.y. old (B. M. Crowe, Los Alamos National Laboratory, written commun., 1984), cannot be distinguished by their phenocryst compositions, which are similar to compositions of reworked ash samples from both trenches (B.M. Crowe, Los Alamos National Laboratory, written commun., 1984). The reworked ash deposits in the fault trenches, therefore, cannot be uniquely correlated with either the 1.2- or 0.24 m.y.-old basalt sources on the basis of their phenocryst compositions.

The faulting and emplacement of the basaltic ash in trench 8 seem to have preceded the development of the K horizon of the QTa soil because the fault at the west edge of the fault zone does not offset the K horizon and the fracture that contains the ash appears to be sealed by carbonate where the fracture intersects the overlying K horizon. Fractures within the fault zone that cut across the K horizon without visible offset are probably related to later minor offset on the fault in the underlying bedrock. No deposits exposed establish a minimum age for these fractures.

Trench 10B, 3.3 km north of trench 8, exposes QTa faulted against Tertiary volcanic rocks (fig. A7). The amount of displacement of unit QTa is unknown. The K horizon of the QTa soil and the overlying Q2c deposit extend across the fault without offset. No displaced or fractured Quaternary deposits were exposed in trench 10A (fig. A6).

Uranium-series dates for unfractured calcrete deposits from the Solitario Canyon fault zone, where QTa is faulted against Tertiary volcanic rocks (sample localities 113 and 115, plate 1), were reported by Szabo and others (1981, p. 21-22), who interpreted the ages of the calcrete as greater than 5,000 years for locality 113 and greater than 20,000 and 70,000 years for two samples from locality 115). If this interpretation is correct, these dates could also represent minimum ages for lastest movements along parts of the fault zone because the calcrete was not fractured.

A fault designated H that is aligned with the Solitario Canyon fault zone, but is downthrown to the east, was investigated at the north edge of Yucca Mountain by trenches 13, GA1A and GA1B (pl. 1). Deposits of Q2c in trench 13 are not faulted (table 1). Carbonate deposits from an unfaulted soil overlying faulted Tertiary volcanic rocks in trench GA1A yielded a minimum uranium-series age of 32,000 years (table 2). No evidence confirming Quaternary movement was found.

Near the southern end of the Solitario Canyon fault zone, a possible fault, J, forms a northeast-trending 0.5-km-long lineament between QTa and Tertiary volcanic rocks. No offset could be demonstrated and no scarp is present where the lineament crosses QTa.

West of the Solitario Canyon fault zone, two parallel faults, K and N, trend generally north-northeast and are 7.5 and 6 km long, respectively. Both fault QTa down to the west against Tertiary volcanic rocks and are overlain locally by unfaulted deposits of Q1c. These faults were not trenched, and no data are available on the amount of Quaternary offset.

Fault L is exposed for less than 0.5 km in QTa along the east side of Crater Flat. The fault is marked by a north-northwest-trending brush line but does not display a scarp; it was not trenched and the direction and amount of offset are unknown.

Fault M consists of two segments that are not continuous on aerial photographs but are considered to be one fault because of alignment and similarities in the scarps. The northern segment trends north-northwest and is about 1 km long. It displaces QTa down to the west. The scarp is 1.5 m high and has a maximum slope angle of 7°. The southern segment cuts unit QTa for a distance of 1.5 km, trends north and northwest and is marked by a west-facing scarp 1.5 m high. The scarp has a slope of 9° and a surface offset of 1 m. Trench CF1, excavated across the scarp, exposed three faults that offset a QTa soil horizon about 2.5 m down to the west adjacent to the fault zone (fig. A17).

Basaltic ash occurs along one of the faults in trench CF1 and appears to have been emplaced in an open fracture that formed at the time of faulting. Because near-surface open fractures in poorly consolidated alluvial deposits are assumed to be short-lived features, it is probable that faulting of unit

QTa, the eruption of the basalt ash, and deposition of the ash in the open fracture essentially were contemporaneous. As discussed above, this ash is similar in composition to both the 1.2- and 0.24-m.y.-old basalts in the Crater Flat area. Although it was not possible to correlate uniquely the basaltic ash from the trench with basalt sources of either age on the basis of their composition, stratigraphic and structural relations suggest that the ash present in the fault zone is from the 1.2-m.y. old eruptions. A 1- to 2-m-thick K horizon (K_1 on fig. A17) interpreted by Swadley and Hoover (1983, p. 7-8) as post-dating the offset along the fault zone in trench CF1 contains stage III to stage IV carbonate development. A 1-m-thick pedogenic carbonate horizon developed on unit Q2c gravel exposed in nearby trench CF3 (fault Q, 2.5 km south of CF1) contains only stage II carbonate. The stage III to IV carbonate developed across the fault zone in trench CF1 is considered to be significantly older than the stage II carbonate on Q2c in trench CF3. A date of 0.27 $\pm$ 0.03 m.y. determined by the uranium-trend method for samples from the carbonate horizon developed on Q2c in trench CF3 theoretically indicates the minimum age for the deposition of the Q2c deposit (Swadley and Hoover, 1983). The K horizon thought to post-date the fault in trench CF1 is interpreted as older than the Q2c deposit in trench CF3 and, therefore, older than the 0.24 m.y.-old basalts. It is concluded on the basis of these relationships that the ash in the fault zone in trench CF1 was erupted during the 1.2 m.y.-old basalt cycle and faulting in trench CF1 is coeval with these eruptions. It can be concluded through a similar line of reasoning that the unfaulted K horizon exposed in trench 8 on the Solitario Canyon fault also is older than the 0.24 m.y.-old basalt, and the ash and fault zone exposed in that trench are also approximately 1.2 m.y. old.

To the west the short, poorly defined fault O cuts QTa and can be traced across an adjoining area of QTa that is thinly covered with Q2c gravel. The fault is indicated by a 0.5-km-long north-northwest-trending brush line, but does not form a scarp. No stratigraphic data are available on the amount of offset because the fault was not trenched.

Approximately 2 km southwest of fault M, two intersecting faults, designated P and Q occur chiefly in unit QTa. Fault Q, to the west, extends for 0.9 km in a north-northeast direction. It is marked by a scarp 1 to 4 m high where it crosses QTa. Two trenches, CF2 and CF3, were excavated across this fault. Trench CF2 (fig. A18), cut across the scarp, exposed the main fault and three minor faults. The amount of offset on these faults could not be determined because of a lack of bedding features in QTa. Three faults offset QTa but do not offset the upper part of the K horizon developed in QTa. A minor fault, 1 m east of the main fault, cuts the upper part of the K horizon and indicates a period of faulting younger than that of the main fault. A topographic profile measured near trench CF2 gave a maximum scarp slope angle of 12°, a scarp height of 4 m, and a surface offset of 1.5 m. Trench CF3 was excavated 300 m south of CF2 in Q2 deposits where no scarp is present but the fault is marked by a poorly developed brush line. CF3 revealed three small faults that offset Q2c less than 1 m down to the west but do not offset an overlying Q2a deposit (fig. A19). Uranium-trend dates determined for samples from this trench are 270 $\pm$ 30 x 10^3 years for unit Q2c and 40 $\pm$ 10 x 10^3 for Q2a, suggesting that movement occurred during the time interval between these two dates.

Fault P, to the east, trends northwest across QTa for 0.35 km and is recognized by the presence of a subtle brush line; no fault scarp was found. The fault trace is concealed by Q2 deposits to the north and south, and fault P may be somewhat longer than indicated by surface expressions. The fault was not trenched and the amount of offset is unknown.

At the southwest end of Yucca Mountain, fault R offsets QTa against Tertiary volcanic rocks for a distance of 1.3 km. The fault continues to the south for about 2.5 km where it offsets Tertiary volcanic rocks or is concealed by Q2 deposits. The segment that offsets Quaternary deposits strikes north-northeast and is downthrown to the west. The fault was not trenched.

Fault segment S probably connects with a fault that extends for 11 km to the north through Tertiary volcanic rocks. The segment that cuts Quaternary deposits is 1.1 km long and offsets only unit QTa. This segment is marked by a poorly developed brush line. Although no definite scarp was found where the fault trace crosses QTa, deposits of Q2c, which are too small to show on page 1, appear to have been deposited along the east side of the fault against an east-facing scarp. If this interpretation is correct, it suggests that the Quaternary offset on this segment of the fault is down to the east, which is the opposite of the offset demonstrated by Tertiary volcanic rocks exposed along the fault to the north (pl. 1). The fault was not trenched, and the amount of offset is unknown.

Northeast of fault S, a north-northeast-trending fault, designated T, faults QTa and also displaces QTa against Tertiary volcanic rocks. It is 7 km long and is downthrown to the west. The fault was not trenched, and the amount of offset is unknown. A profile measured where the fault offsets QTa gave a maximum scarp slope angle of 11°, scarp height of 1 m, and a surface offset of 0.7 m.

A short northeast-trending fault segment, designated U, near the southwest end of Yucca Mountain appears to displace QTa down to the west against Tertiary volcanic rocks although actual displacement of QTa could not be determined. The scarp is exposed for only 0.2 km but the fault can be traced on areal photographs for another 0.3 km to the southwest where it is partly obscured by Q1c deposits (pl. 1). The fault was not trenched; and no data are available on the amount of throw.

Fault V, located 1.5 km northeast of Black Cone in Crater Flat, has a north-northwest trend and extends for 1 km across an area of QTa. A very low east-facing scarp that is present only along part of the fault suggests that offset is down to the east. Where the fault trace crosses thin terrace deposits of subunit Q2c (pl. 1) the trace is visible on aerial photographs. It is not known whether this lineament reflects plant growth controlled by fractures in the underlying QTa or faulting in Q2c. The fault was not trenched, and the amount of Quaternary offset is unknown.

Near the north end of Bare Mountain there is a group of seven short, subparallel faults with a north-northeast trend. These faults collectively designated W on plage 1, cut QTa or offset QTa against an older Tertiary gravel unit. They range in length from 0.2 to 1.0 km, and several can be traced on aerial photographs across areas where QTa is covered by thin deposits of Q2c that do not appear to be offset. These faults were not trenched, and there are no data on the amount of offset; for most the sense of motion is unknown.

Northwest of location W an arcuate fault, designated X, is exposed chiefly in an area underlain by Tertiary gravel but locally cuts a narrow deposit of QTa. The fault is 2.5 km long. The southern part trends east-west and swings sharply to a north-northeast trend. No scarp was observed where the fault cuts QTa.

Fault Y, near the western edge of Crater Flat, is exposed for only 0.2 km in unit QTa. The fault trends north-northeast and is recognized by a brush line. No scarp is present but a cutbank exposure indicates that the offset is down to the east. The fault trace is concealed to the south by deposits of Q2c.

The Bare Mountain fault zone is a major structural feature of the area and marks the western edge of Crater Flat. It trends generally north and is about 20 km long. Although the fault is concealed for much of its length, evidence of Quaternary offset is exposed at several locations. Along the northern segment of the zone (BM-1, plate 1) QTa is faulted down against Paleozoic rocks. Locally Q2c fan deposits appear to cross the fault without offset. A prospect pit in dense secondary carbonate and opal deposits along the fault zone exposed a number of subparallel fault planes that dip 50° to 60° east. Slickenslides on one of these planes showed only dip-slip movement. A scarp profile measured near the southern end of this segment where the fault trace crosses an area of QTa, gave a slope angle of 10°, a height of 1 m, and a surface offset of 0.8 m.

To the south (segment BM-2) the fault trace can be identified only where it crosses two small areas of QTa. The fault is recognized by a brush line but no scarp is present. A cut bank exposure in QTa revealed that the fault plane dips 75° to the east.

The southern segment, BM-3, exposes faulted QTa at two locations and also exhibits geomorphic evidence of Quaternary movement. At the southern location the fault has formed a well-defined scarp in QTa. A scarp profile measured here gave a slope angle of 20°, a height of 4 m, and a surface offset of 1.7 m. At the second location, an area of QTa is truncated by the fault but the downthrown block is covered by Q1 age deposits and no scarp was observed.

Along the southern segment of the fault zone, fans composed of Q1c fluvial gravel at several locations occur adjacent to but 10 to 30 m above small remnants of Q2c fans that appear to be faulted against Paleozoic bedrock. Commonly Q1c overlies Q2c or is inset into Q2c fans. The juxtaposition of Q1c deposits well above Q2c fans is interpreted as indicating uplift along this segment of the fault zone after Q2c deposition. The uplift elevated the bedrock valleys that were the source of the Q1c gravels and resulted in deposition of fans at elevations above the older Q2c deposits. These Q1c fans extend into the bedrock valleys on the upthrown side of the fault and cross the fault without offset. The fault has not been trenched, but the relative positions of Q1c and Q2c deposits indicate Quaternary uplift could be in the range of 10 to 30 m along the southern part of the Bare Mountain fault zone.

SUMMARY AND DISCUSSION

Offset or fracturing of Quaternary deposits was demonstrated for 32 faults within the Yucca Mountain study area. The fault segments for which Quaternary offset can be demonstrated range in length from 16 km, the Bare Mountain fault zone, to less than 0.5 km. The longest continuously exposed scarp in Quaternary deposits is a 4-km segment located near the south end of the Solitario Canyon fault zone.

For most faults the amount of Quaternary offset has not been determined. Where offset can be measured or where fault scarps are preserved, dip-slip movement on the order of 3 m or less is indicated. The one exception is the southern segment of the Bare Mountain fault zone where geomorphic evidence suggests Quaternary offset may be in the range of 10 to 30 m.

Strike-slip movement could not be demonstrated nor could such movement be ruled out. The poorly consolidated surficial deposits exposed in the trenches and the secondary carbonate deposits along the trace of faults are poor mediums for the preservation of slickensides and other small-scale directional features. Strike-slip offset on the order of tens of meters would probably be detected by geomorphic evidence such as offset of streams or other linear features, whereas offset of a few meters or less probably could not be detected.

Although absolute age data are limited, faults with Quaternary displacement can be divided into three broad age groups. The youngest group consists of faults B, C, Q, the Paintrbrush Canyon fault, and the Bare Mountain fault zone; these faults offset or produced fracturing in deposits of Q2 age. Based on uranium-trend age determinations as discussed above, age brackets of less than 270,000 $\pm$ 90,000 yr and greater than 38,000 $\pm$ 10,000 yr and less than 270,000 $\pm$ 30,000 yr and greater than 40,000 $\pm$ 10,000 yr have been inferred for faults C and Q, respectively. Offset on the Paintbrush Canyon fault after about 700,000 yr and before 270,000 yr is suggested by correlation of stratigraphic units where fracturing is exposed in trenches A1 and A2. Quaternary offset on the southern part of the Bare Mountain fault zone is inferred during the interval between 270,000 and 9,000 yr ago based on geomoprhic evidence and stratigraphic correlations. Movement on fault B after 270,000 yr is inferred from the minimum age of the youngest offset unit, Q2c; no minimum age of offset has been determined for this fault.

Faults of the intermediate age group offset only QTa and older units; where these faults are exposed in areas of QTa, a distinct scarp is commonly observed. Only general age constraints can be inferred for Quaternary offset along faults of this group. Quaternary movement of the Solitario Canyon fault zone and fault M has been tentatively dated at about 1.2 m.y. ago based on occurrences of basaltic ash in the fault zones as discussed above. Inferred age brackets for Quaternary offset on fault I are less than 2 m.y., based on the maximum age inferred for unit QTa and greater than about 700,000 yr, the approximate minimum age inferred for Q2e deposits that appear to extend across the fault scarp without offset. Fault T is included in the intermediate group because the height and slope angle of the scarps of faults T and M are similar. Based on preliminary scarp measurements, faults in Crater Flat have been classified as significantly older than 1.2 m.y. where no scarp is preserved or about 1 m.y. old or younger for faults that exhibit scarps similar in height and slope angle to fault M, tentatively dated at 1.2 m.y. old. In this preliminary study, comparisons have been limited to scarps of similar height (1-2 m) and scarps formed in the same rock type (unit QTa). For these comparisons it is assumed that the fault offset included some scarp-forming component.

The 23 faults of the oldest group offset QTa and older units, but no scarps are preserved. General age limits for Quaternary offset on faults of this group are younger than 2 m.y., the maximum age inferred for unit QTa, and older than about 1.2 m.y., inferred from the lack of preserved scarps. Minimum age constraints are demonstrated for some faults of the oldest group where stratigraphic units younger than QTa overlie a fault without offset. Faults S, V, and Y and faults P and R are locally overlain by apparently unfaulted deposits of Q2c and Q2b, respectively. Minimum age limits for Quaternary offset of greater than 270,000 yr and greater than 160,000 yr are inferred for these two groups of faults from the minimum ages of the overlying stratigraphic units. Fault group A and faults K, N and U are overlain in places by unfaulted Q1c deposits and a minimum age limit for Quaternary offset of greater than 7,000 yr is inferred. No minimum age limit can be demonstrated by this method for faults J, L, X, and fault group W. Table 4 summarizes the data on each fault and the inferred ages of offset.

Where age constraints have been inferred from radiometric dating and from stratigraphic correlations of faulted and unfaulted deposits at a trenched site, no offset younger than about 40,000 yr has been demonstrated. Holocene offset has not been demonstrated in the study area nor can it be ruled out.

Table 4.--Summary of Quaternary faulting in the Yucca Mountain area

Fault or fault group[1]	Trench number	Youngest unit faulted or fractured[2]	Oldest unit not faulted or fractured	Inferred age of last movement	Method of dating	Remarks
A (4)	not trenched	QTa	Q1c	$<2 \times 10^6$ >7,000	Correlation of stratigraphic units	-----
B	do.	Q2c	Unknown	<270,000	do.	No minimum age determined
Paintbrush Canyon fault	A1, A2, 16, 16B	Q2e (fractures in trench A2)	Q2c soil (in trench A1)	<700,000 >270,000	do.	----- -----
C	14	Q2s (fractures in trench 14)	Q2a	$<270 \pm 90 \times 10^3$ $>38 \pm 10 \times 10^3$	Uranium-trend	-----
D	11	No Quaternary offset found	QTa	-----	-----	No evidence of Quaternary offset
E	12	do.	Q2 soil	-----	-----	Do.
F	4, 6, 9	do.	Q2c	-----	-----	Do.
G	2	do.	Q2c	-----	-----	Do.
Solitario Canyon fault zone	8, 10, 10B	QTa	QTa soil	1.2×10^6	Petrographic correlation of of basalt ash; correlation of stratigraphic units	-----
H	13, GA1A, GA1B	No Quaternary offset found	Q2c	-----	-----	-----
I	Not trenched	QTa	Q2e	$<2 \times 10^6$ >700,000	Correlation of stratigraphic units	-----
J	do.	QTa	Unknown	$<2 \times 10^6$	do.	>1.2 m.y. age inferred from lack of scarp
K	do.	QTa	Q1c	$<2 \times 10^6$ >7,0000	do.	Do.
L	do.	QTa	Unknown	$<2 \times 10^6$	do.	>1.2 m.y. age inferred from lack of scarp
M	CF1	QTa	Q2 soil	1.2×10^6	Petrographic correlation of basalt ash; correlation of stratigraphic units	-----
N	Not trenched	QTa	Q1c	$<2 \times 10^6$ >7,000	Correlation of stratigraphic units	>1.2 m.y. age inferred from lack of scarp
O	do.	QTa	Q2c(?)	$<2 \times 10^6$ >270,000(?)	do.	Do.
P	do.	QTa	Q2b(?)	$<2 \times 10^6$ >160,000(?)	do.	Do.
Q	CF2, CF3	Q2c	Q2a	$<270 \pm 30 \times 10^3$ $>40 \pm 10 \times 10^3$	Uranium-trend	Two episodes of faulting; younger episodes dated in trench CF3
R	Not trenched	QTa	Q2b(?)	$<2 \times 10^6$ >160,000(?)	Correlation of stratigraphic units	-----
S	do.	QTa	Q2c	$<2 \times 10^6$ >270,000	do.	-----
T	do.	QTa	Unknown	$<2 \times 10^6$	do.	1 m.y. or younger age inferred from scarp
U	do.	QTa	Q1c	$<2 \times 10^6$ >7,000	do.	>1.2 m.y. age inferred from lack of scarp
V	do.	QTa	Q2c(?)	$<2 \times 10^6$ >270,000(?)	do.	Do.
W (7)	do.	QTa	Unknown	$<2 \times 10^6$	do.	Do.
X	do.	QTa	Unknown	$<2 \times 10^6$	do.	Do.
Y	do.	QTa	Q2c	$<2 \times 10^6$ >270,000	do.	Do.
Bare Mountain fault zone	do.	Q2c	Q1c	<270,000 >9,000	Correlation of stragigraphic units and geomorphic evidence	-----

1 Number of faults in group shown in parenthesis.
2 Unit shown is faulted except where fractures are indicated.

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APPENDIX

Preliminary diagrams of nineteen trenches excavated in the Yucca Mountain area to evaluate Quaternary fault movement.

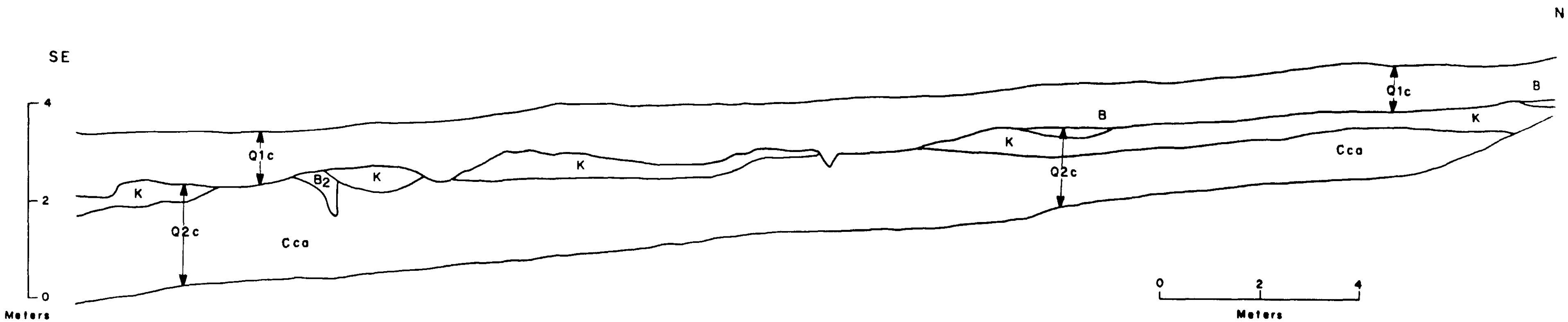

Figure A1.--Diagram of south wall of trench 2. Trench trends N. 60^{o} W. across the projection of fault G. Mapped in May 1982 by Swadley, L. D. Parrish and H. E. Huckins, Fenix & Scisson (F&S). Samples of Q2a and Q2b dated by uranium-trend method (table 1) were collected from north wall from strata not preserved in south wall. Sample location is opposite southeast end of diagram.

Unit	Description
Q1c	Gravel, sandy, unconsolidated, mostly pebbles with scattered cobbles; poorly bedded to nonbedded
Q2c	Gravel, mostly pebbles and cobbles with scattered boulders, poorly sorted, poorly bedded. Soil developed in Q2c consists of B, B2, K, and Cca horizons
B	B horizon, light-brown, cambic, developed in poorly sorted gravel
B2	Similar to B with threads and filaments of carbonate minerals
K	K horizon--poorly sorted gravel with stage III carbonate development
Cca	Cca horizon--poolry sorted gravel with stage I carbonate development

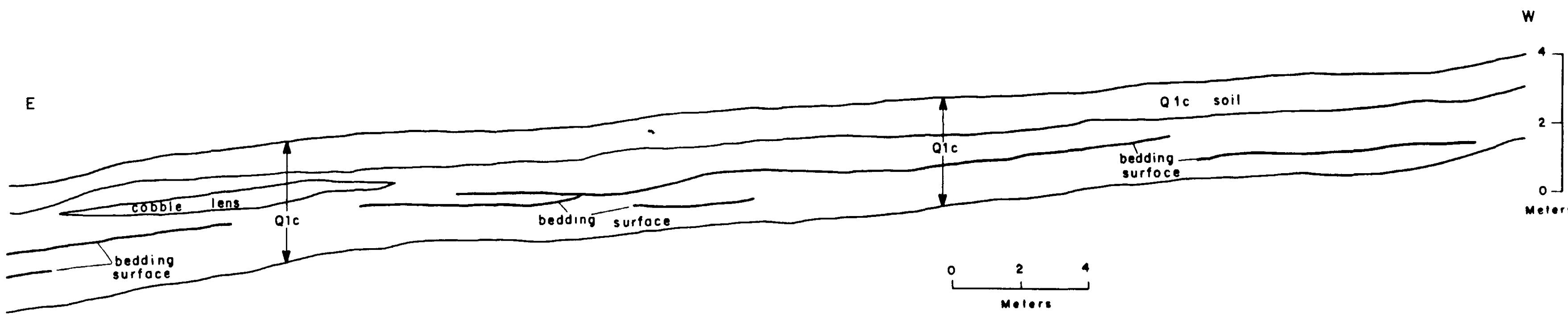

Figure A2.--Diagram of south wall of trench 4. Trench trends N. 85^{o} W. across the projection of fault F. Mapped in June 1982 by Swadley.

Unit	Description
Q1c	Gravel, angular, poorly sorted, poorly bedded; sandy matrix and scattered sand lenses; mapped bedding surfaces are poorly defined and discontinuous, may be scour surfaces. Weak soil development in unit, lower contact of soil mapped at base of Cca horizon (stage I carbonate development)

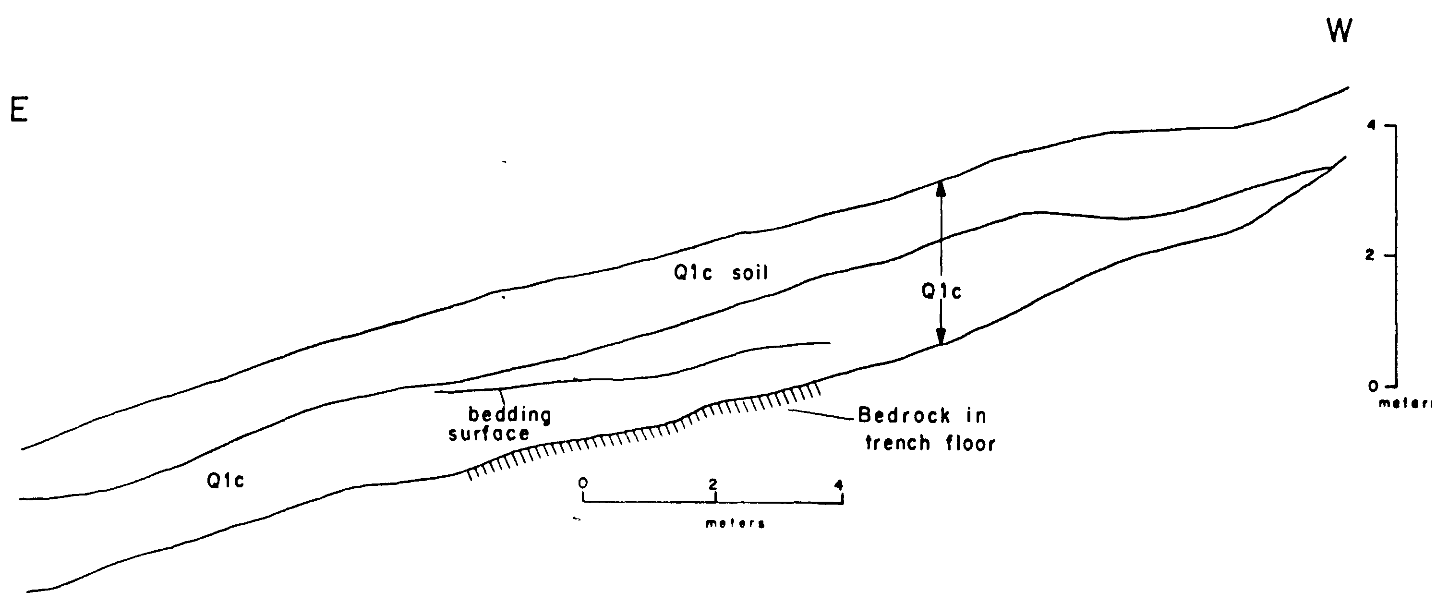

Figure A3.--Diagram of south wall of trench 6. Trench trends N. 70° W. across the projection of fault F. Mapped in June 1982 by Swadley and H. E. Huckins.

Unit	Description
Q1c	Gravel, sandy, angular, poorly sorted, poorly bedded; mostly pebbles and cobbles with scattered boulders. Weakly developed soil; lower contact mapped at base of Cca horizon (stage I carbonate development)

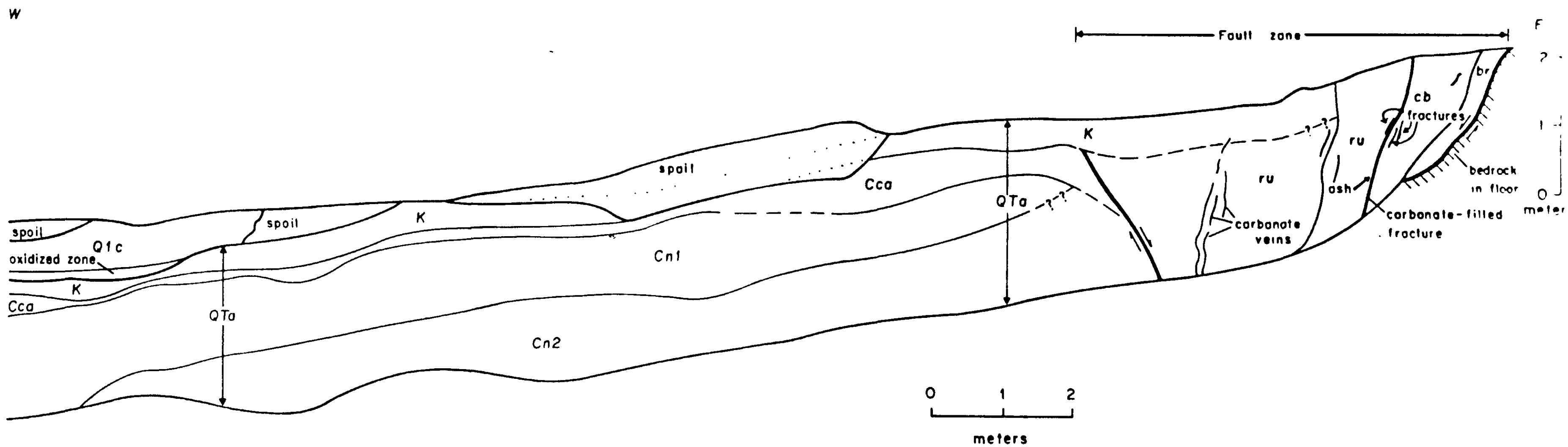

Figure A4.--Diagram of north wall of trench 8. Trench trends N. 80° E. across the Solitario Canyon fault zone. Mapped in November 1982 by Swadley and H. E. Huckins. QTa is displaced against Tertiary volcanic rocks by main fault at east end of trench. Minor fault at west edge of fault zone cuts QTa but not the K horizon developed in QTa. Later fracturing extends into and through the K horizon.

Unit	Description
Q1c	Gravel, sandy, unconsolidated, angular, poorly sorted
QTa	Gravel, coarse, angular, poorly sorted, soil developed in QTa consists of K, Cca, Cn1 and Cn2 horizons
K	K horizon--poorly sorted angular gravel with stage IV carbonate development; thin laminated zone at top. Oxidized zone at west end of trench consists of weathered fragments of K horizon in a matrix of reddish-brown sand
Cca	Cca horizon--angular poorly sorted gravel with stage III to II carbonate development
Cn1	Gravel, angular, moderately well sorted, mostly pebbles and small cobbles
Cn2	Gravel, coarse, angular, poorly sorted
br	Breccia, with abundant laminated opaline carbonate along main fault.
cb	Carbonate, porous and some fault breccia with scattered plates of laminated carbonate and brown opal
ru	Rubble and unsorted gravel, cemented with porous, secondary carbonate. Carbonate increases to the east across fault zone, locally it obscures the K horizon in this unit
Ash	Location of loose 1.2 m.y.-old basaltic ash along fracture in opposite wall of trench

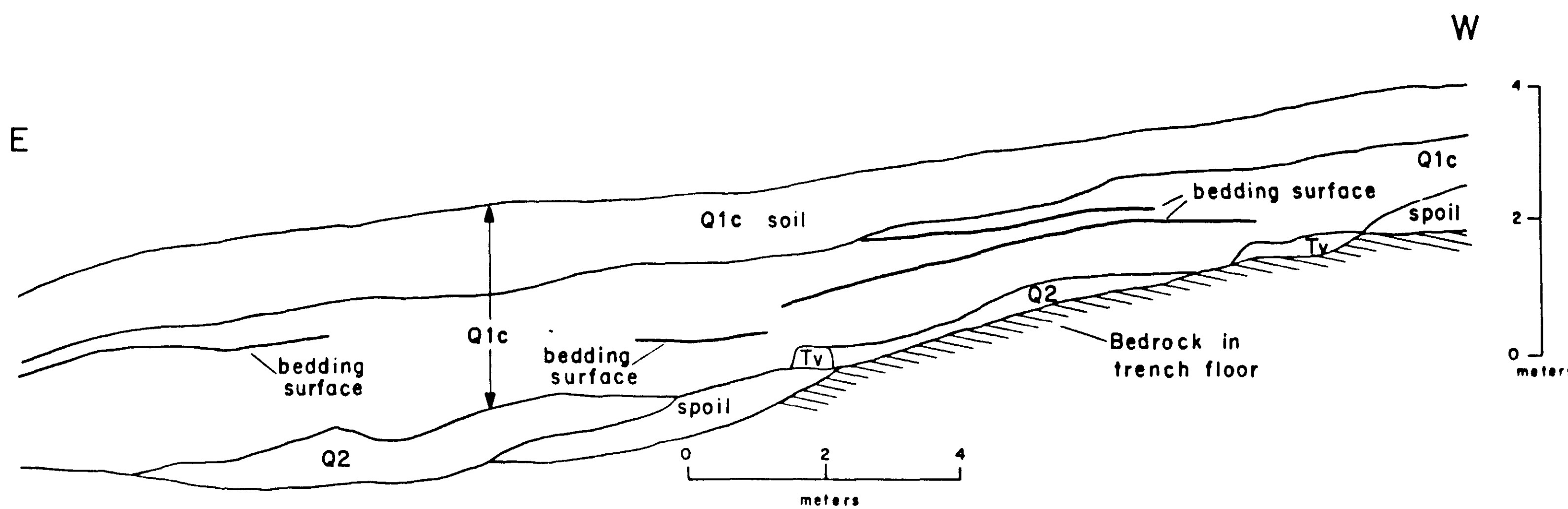

Figure A5.--Diagram of south wall of trench 9. Trench trends N. 65^{0} W. across projection of fault F. Mapped in June 1982 by Swadley and H. E. Huckins.

Unit	Description
Q1c Soil	Soil--weakly developed in sandy poor sorted gravel. Lower contact marked by base of stage I carbonate development
Q1c	Gravel, angular, poorly sorted, poorly bedded; pebble-cobble gravel with scattered boulders; sandy, silty matrix. Bedding surfaces shown are poorly defined and discontinuous, may be scour surfaces
Q2c	Gravel, angular, poorly sorted, nonbedded
Tv	Tertiary volcanic rocks--welded tuff, also exposed in trench floor

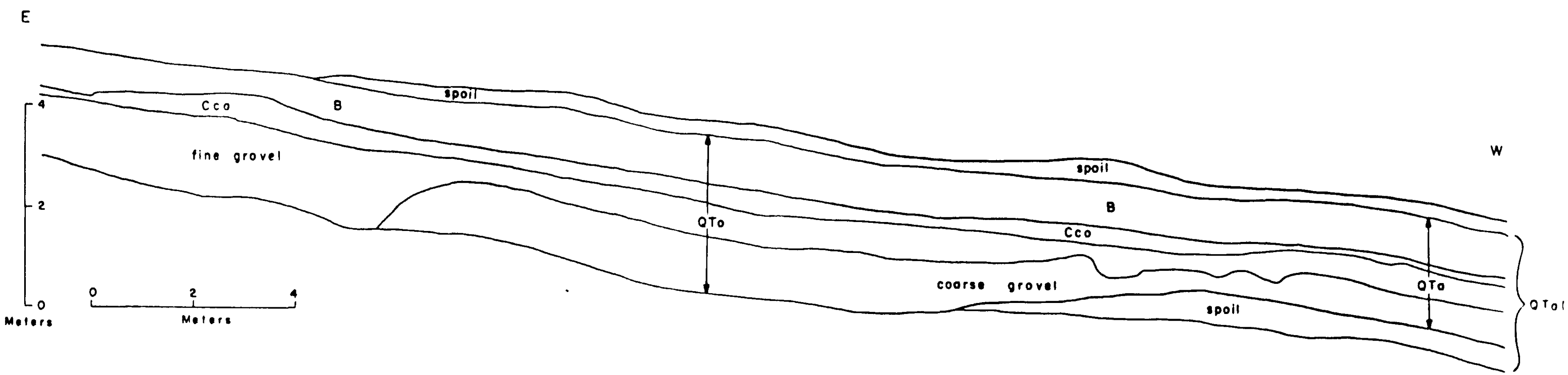

Figure A6.--Diagram of south wall of trench 10A. Trench trends N. 80^{0} E. across a projection of the Solitario Canyon fault zone. Mapped in April 1983 by Swadley and H. E. Huckins.

Unit	Description
QTa(?)	Gravel--consists of a coarse cobble to boulder unit that is unsorted and nonbedded overlain by a sandy, angular pebble to cobble gravel that is poorly sorted and poorly to moderately well bedded. Soil developed in unit consits of B and Cca horizons
B	B horizon--cambic, light-brown; 0.2-0.3 m thick; may include younger slope wash unit at top
Cca	Cca horizon--developed in poorly sorted sandy gravel, stage II to III carbonate development

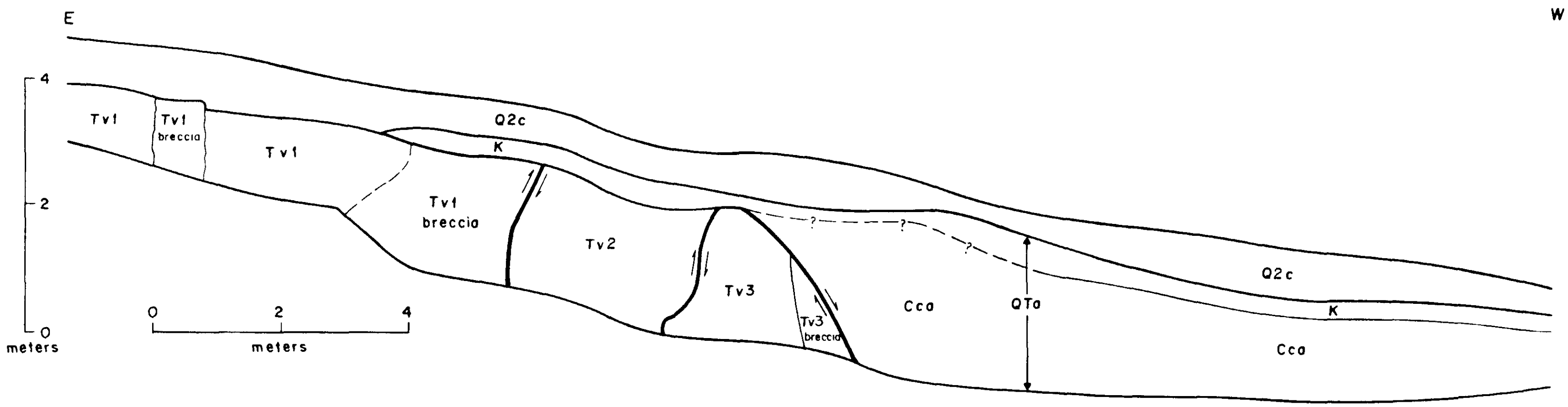

Figure A7.--Diagram of south wall of trench 10B, Solitario Canyon fault zone. Trench trends N. 80° W. Mapped in April 1983 by Swadley and H. E. Huckins. Fault at west edge of fault zone offsets QTa against Tertiary volcanic rocks. K horizon, developed in faulted QTa, and the overlying Q2c extend across the fault without offset.

Unit	Description
Q2c	Gravel, angular, poorly sorted, sandy matrix. Soil (not mapped separately) consists of light-brown cambic B horizon and a stage II Cca horizon
QTa	Gravel, coarse, poorly sorted, sandy matrix; cemented with stage III to IV carbonate development.
K	K horizon--gravel, angular, sandy matrix; cemented with stage III to IV carbonate development
Cca	CCa horizon--gravel, angular, poorly sorted; sandy, tuffaceous matrix; stage II carbonate development
Tv1	Tuff, welded, purplish-brown
Tv2	Vitrophyre, black
Tv3	Tuff, slightly welded, light-brown

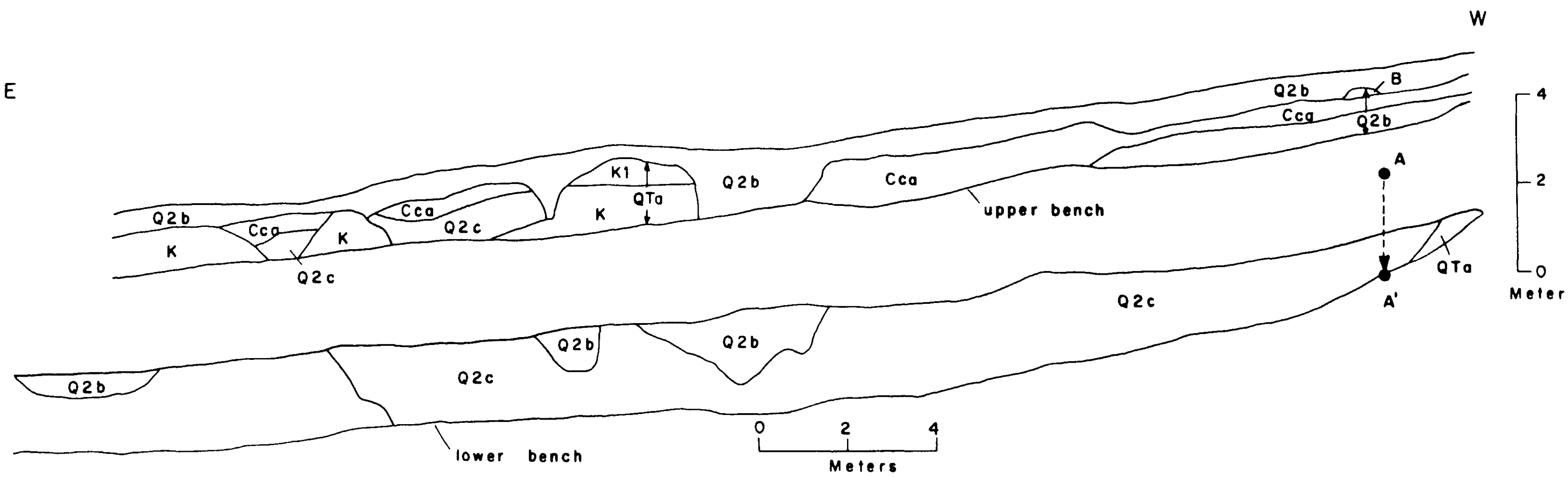

Figure A8.--Diagram of south wall of trench 11. Trench trends N. 75° E. across projection of fault D. Mapped in June 1982 by Swadley and H. E. Huckins. Trench cut on two levels, upper bench is 2-3 m wide. For clairty, lower level of cut has been displaced from A to A' in this figure.

Unit	Description
Q2b	Gravelly sand, gravel is mostly angular pebbles with scattered cobbles. Soil horizons (not mapped) consist of yellowish-brown cambic B horizon and thin stage I Cca horizon
Q2c	Gravel, angular, poorly sorted, non-bedded, sandy matrix; includes pebble- to boulder-size clasts. Soil horizons developed in Q2c consist of B and Cca horizons
B	B horizon--yellowish-brown, cambic; developed in sandy, poorly sorted gravel
Cca	Cca Cca horizon--stage I to II carbonate development in poorly sorted gravel
QTa	Gravel, angular, unsorted, nonbedded Soil developed in unit consists of K and Cca horizons
K	K horizon--stage III to IV carbonate development in unsorted gravel
K1	Laminated part of K horizon
Cca	CCa horizon--stage II carbonate development in unsorted gravel

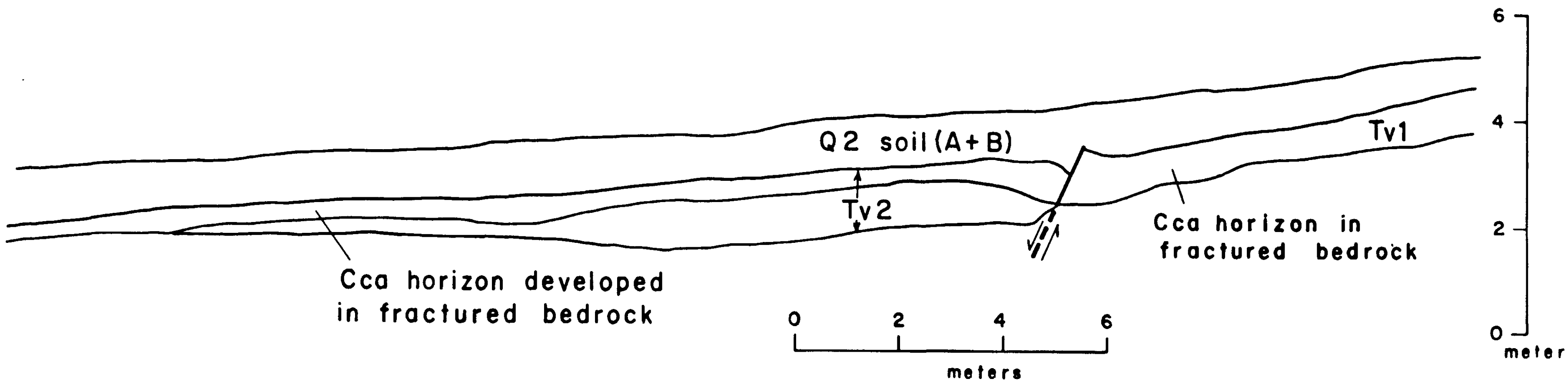

Figure A9.--Diagram of northwest wall of trench 12. Trench trends N. 45° E. across trace of fault E. Mapped in June 1982 by Swadley and H. E. Huckins.

Unit	Description
Q2 Soil	Soil developed across existing fault in bedrock, probably in eolian and slope wash deposits. No offset is apparent in soil. Soil development consists of thin A horizon and light-brown cambic B horizon (not mapped)
Tv1	Grayish-red welded tuff. Where exposed above trench floor includes common to abundant carbonate as coatings and fracture fillings.
Tv2	Dark-gray, platy-weathering welded tuff. Upper part of exposure in trench wall includes common to abundant carbonate as coatings and fracture fillings

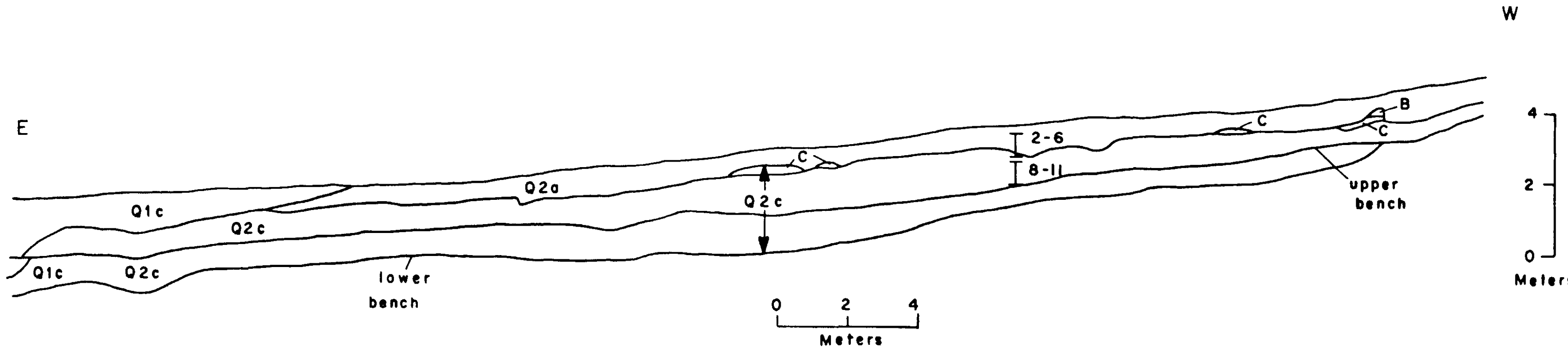

Figure A10.--Diagram of south wall of trench 13. Trench trends N. 50° E. across projection of fault H. Cut on two levels, upper bench is 1-1.5 m wide. Mapped in June 1982 by Swadley and H. E. Huckins. Sample locations for uranium-trend age determinations shown by bar

Unit	Description
Q1c	Gravel and sand, unconsolidated, poorly sorted non bedded
Q2b	Gravelly sand, poorly sorted; gravel chiefly pebbles with few cobbles. Soil development consists of yellowish-brown cambic B horizon and thin stage I Cca horizon (not mapped)
Q2c	Gravel, angular, poorly sorted, poorly bedded; sandy matrix; well consolidated. Exposed soil development in unit consists of B and Cca horizons
B	B horizon--light-brown, cambic. Single small remnant exposed
Cca	Cca horizon--poorly sorted sandy gravel with stage II carbonate development

Radiometric Ages

Sample No.	Unit	Age (in 10^3 yr)
YM13-2 thru 6	Q2a	41 ± 10
YM13-8 thru 11	Q2c	240 ± 50

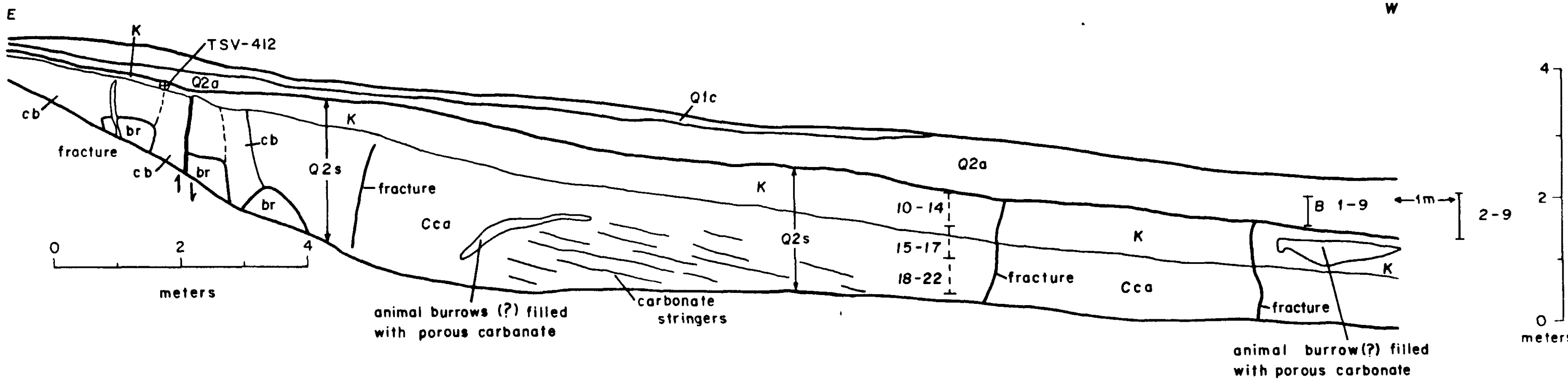

Figure A11.--Diagram of south wall of trench 14. Trench trends east-west across the trace at fault C. Mapped in May 1982 by Swadley, L. D. Parrish, and H. E. Huckins. Fault offsets blocks of Tertiary volcanic rocks. Fractures cut Q2s and its soil but not the overlying Q2a. The K horizon that developed in Q2s extends across the fault without offset but is fractured (fractures too small to show on this figure) and fracture surfaces are coated with secondary carbonate immediately above fault. Animal burrow 5 m west of the main fault may have been dug along a fracture in Q2s. Sample locations for uranium-trend age determinations shown by bar; bar is dashed where location is projected from north wall. Sample location for uranium-series age determinations (sample TSV-412) shown by cross.

Unit	Description
Q1c	Sand, gravelly, unconsolidated
Q2a	Sand, gravelly, slightly indurated with clay
Q2s	Sand, gravelly. Exposed soil horizons developed in unit consist of K and Cca horizons
K	K horizon--sand, gravelly, stage III to IV carbonate development
Cca	Cca horizon--sand, gravelly, stage I to II carbonate development; carbonate stringers along bedding(?) surfaces
cb	Colluvium and breccia with abundant laminar opaline carbonate Laminae parallel fractures, soil horizons, and surfaces of large blocks in underlying breccia
br	Breccia and blocks of Tertiary volcanic rocks

Radiometric Ages

Sample No.	Unit	Age (in 10^3 yr)
YM 14-2 thru 9	Q2a	90 ± 50
YM 14-10 thru 14	Q2s	270 ± 90
YM 14-15 thru 17	Q2s	420 ± 50
YM 14-18 thru 22	Q2s	480 ± 90
YM 14 B-1 thru 9	Q2a	38 ± 10
TSV-412-1	Q2s K horizon	>400 and >350
TSV-412-3	Q2s K horizon	>550
TSV-412-7	Q2s K horizon	>400

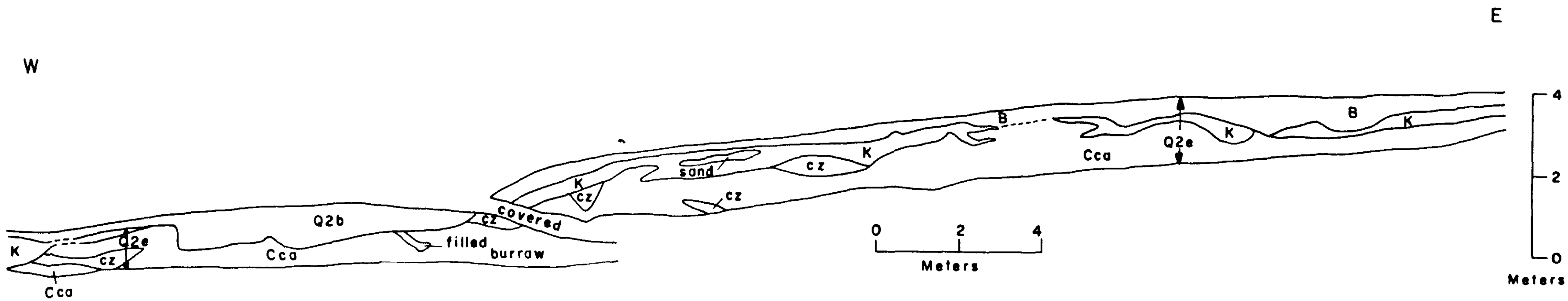

Figure A12.--Diagram of north wall of trench 16. Trench trends N. 75° W. across a projection of the Paintbrush Canyon fault. Mapped in June 1982 by Swadley and H. E. Huckins.

Unit	Description
Q2b	Sand, poorly bedded, moderately well sorted; locally cemented with carbonate at base. Unit channels into underlying Q2e
Q2e	Eolian sand, fine, well sorted, nonbedded. Soil development consists of B, K, and Cca horizons
B	B horizon--light-brown, cambic, developed in well sorted fine sand
K	K horizon--stage III carbonate development in well sorted sand. Horizon is discontinuous, probably disrupted by burrows
Cca	Cca horizon--well sorted sand with stage I to II carbonate development. Root casts common to abundant. Includes local zones of carbonate enrichment (cz) that may be nonpedogenic

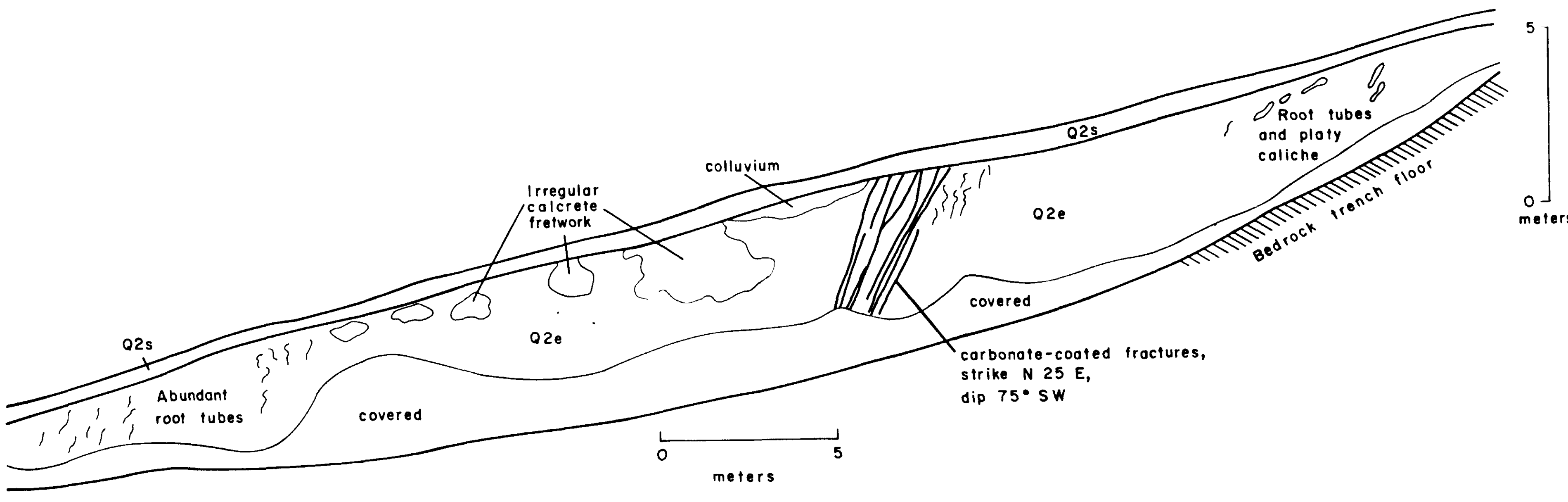

Figure A13.--Diagram of north wall of trench 16B, located near the southern end of the Paintbrush Canyon fault. Mapped in February 1983 by W. J. Carr (USGS). Fractures cut unit Q2e but not overlying Q2s.

Unit	Description
Q2s	Sand, light-grayish-brown, and angular gravel. Probably a mixture of slope wash and colluvium
Q2e	Sand, eolian, well sorted, nonbedded; includes scattered clasts and lenses of colluvial gravel; root tubes and secondary carbonate deposits common. Q2e soil not preserved

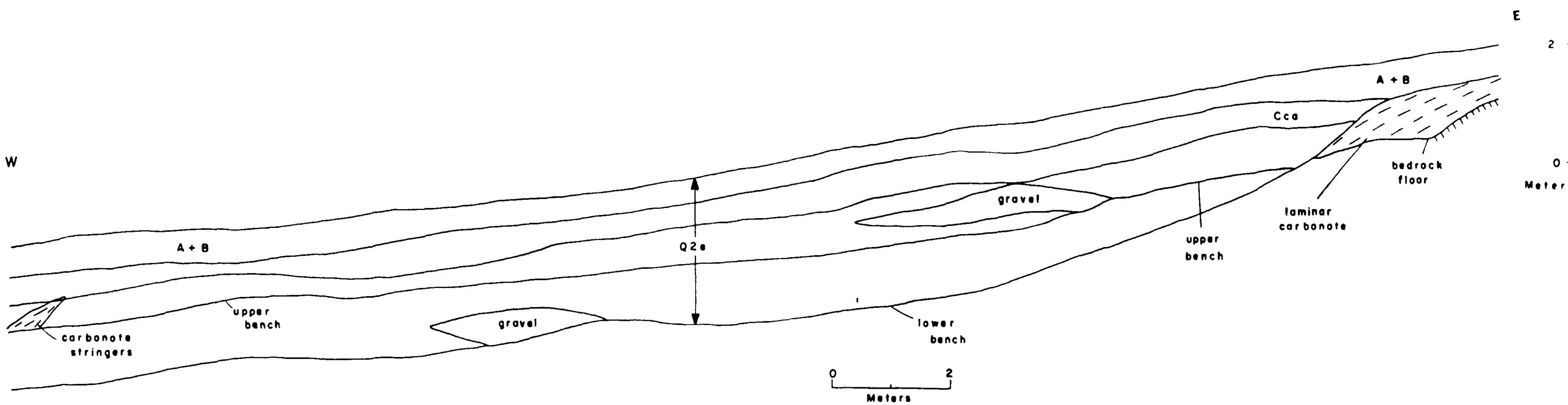

Figure A14.--Diagram of north wall of trench 17. Trench trends N. 55° W. across a projection of a branch of Paintbrush Canyon fault. Cut on two levels, upper bench is 1-2 m wide. Mapped in July 1983 by Swadley and L. D. Parrish.

Unit	Description
Q2e	Eolian sand, moderately well to well sorted, poorly consolidated, nonbedded; includes scattered clasts and lenses of colluvial gravel. Root casts locally common. Soil developed in unit consists of A, B, and Cca horizons
A+B	A and B horizons, undivided. A horizon is light-gray silt and clay; vesicular, preserved locally. B horizon is light brown, cambic
Cca	Cca horizon--stage II carbonate development in fine well-sorted sand

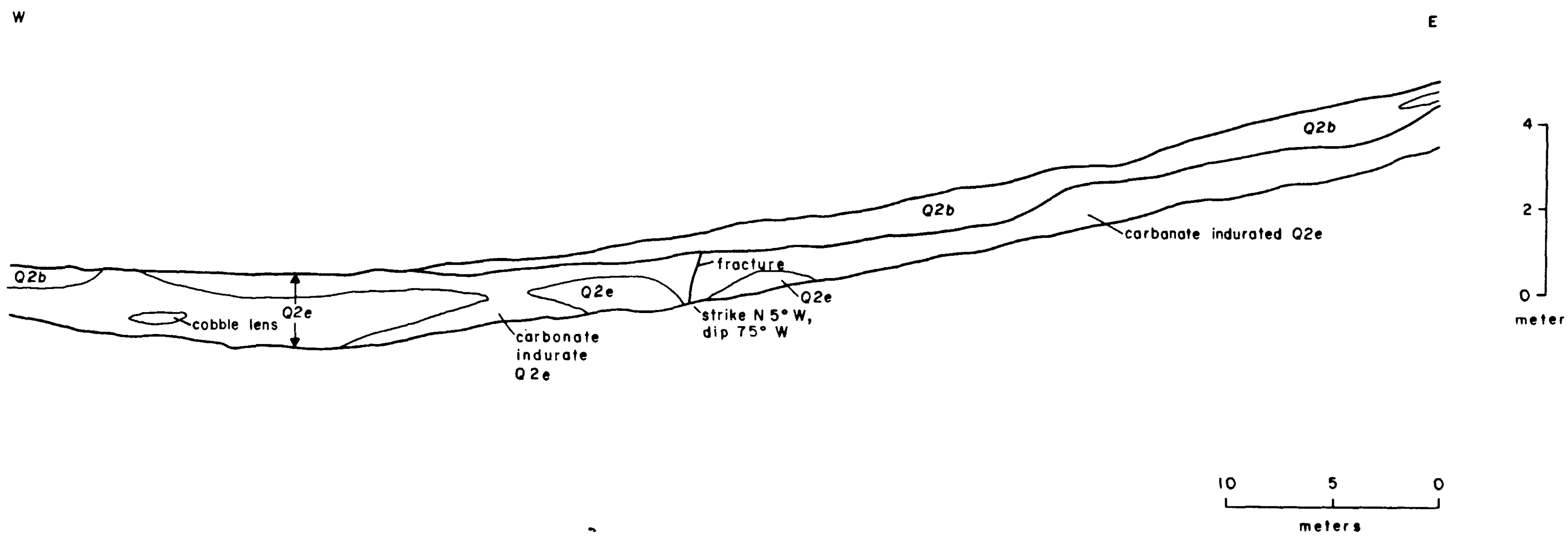

Figure A15.--Diagram of north wall of trench A1, Paintbrush fault. Trench trends east-west. Mapped in 1979 by A. J. Gordon (F&S) and L. D. Parrish (F&S). Fractures cut unit Q2e and its soil but not the overlying Q2b.

Unit	Description
Q2b	Gravelly sand, probably a mixture of colluvium and slope wash. Soil horizons (not mapped) consist of light-brown cambic B horizon and stage II Cca horizon
Q2e	Eolian sand, well sorted locally includes pebbles and cobbles (colluvium). Root casts common. Sand is commonly moderately indurated with patchy areas of nonpedogenic carbonate (shown by stipple pattern). Soil development consists of thin stage III K horizon (not mapped)

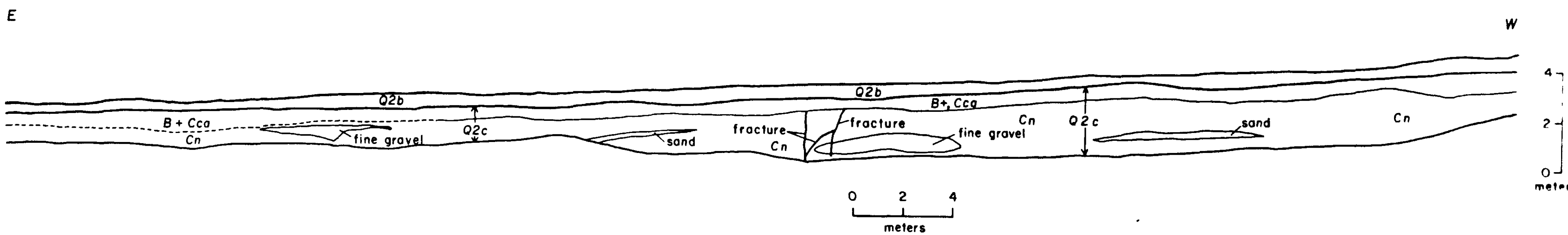

Figure A16.--Diagram of south wall of trench A2, Paintbrush Canyon fault. Trench trends N. 85^{0} E. Mapped in July 1983 by Swadley and L. D. Parrish. Fractures cut unit Q2c but not its soil or the overlying Q2b.

Unit	Description
Q2b	Sandy gravel, probably a mixture of slope wash and colluvium
	Soil (not mapped) consists of a weak cambic B horizon and a stage I Cca horizon
Q2c	Gravel, sandy, poorly sorted, poorly bedded
B+Cca	B and Cca soil horizons undivided: B horizon is light brown, cambic; developed in sandy gravel; Cca horizon, stage II carbonate development in sandy gravel
Cn	Gravel, very sandy, poorly sorted, poorly bedded; coarse, with scattered boulders; well indurated; includes lenses of sand and fine gravel

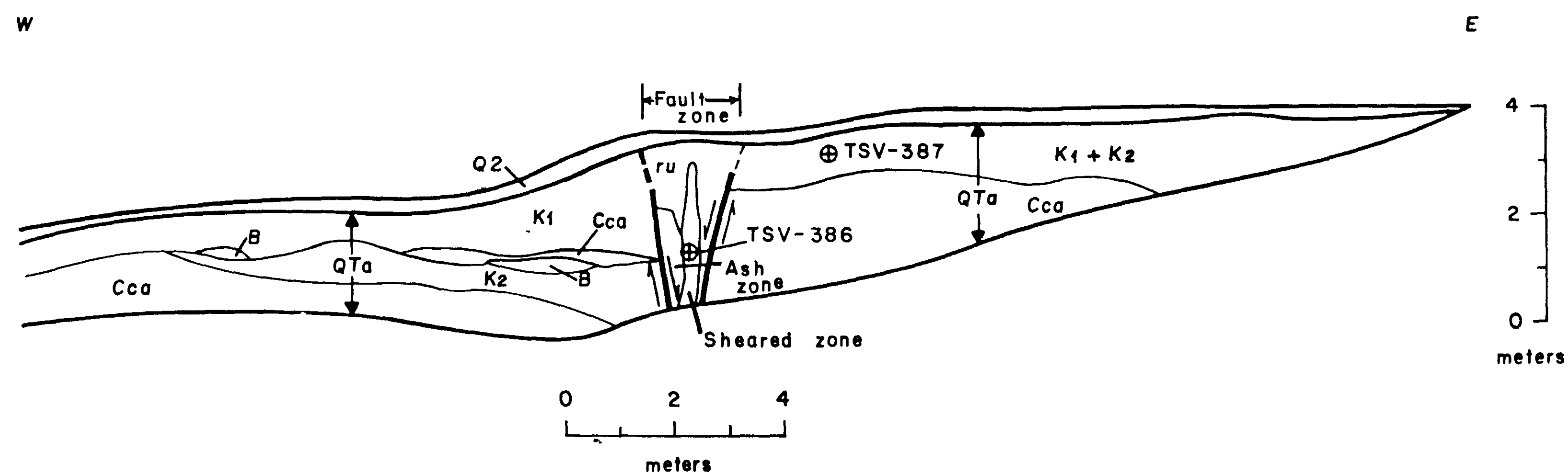

Figure A17.--Diagram of north wall of trench CF1, excavated across fault M. Trench trends east-west. Diagram modified from Swadley and Hoover (1983). Faults cut QTa and offset a pre-fault soil horizon (K2) down to the west. A post-fault soil horizon (K1) appears to overlie the fault without offset; however, the abundance of post-fault carbonate deposits in the fault zone partly obscures this horizon. Sample localities for TSV-386 and TSV-387 (table 2) are projected from the south wall of trench.

Unit	Description
Q2	Gravel, sandy, unsorted. Soil development consists of a clayey silt vesicular A horizon and a light-brown cambic B horizon (not mapped)
QTa	Gravel, coarse, angular, unsorted. Soil development in QTa includes four soil horizons described below
K1	K horizon--unsorted gravel, cemented with stage III to IV carbonate development; represents post-fault soil development. Anomalously thick K1 horizon shown west of fault zone is probably caused by nonpedogenic carbonate deposited in permeable material adjacent to the fault
CCa	Gravel, unsorted stage I carbonate development
B	B horizon--argillic, reddish-brown sand and gravel; remnant of pre-fault soil
K2	K horizon--gravel, unsorted; cemented with stage III to IV carbonate development. Represents pre-fault K horizon preserved in downthrown block; in upthrown block it merges upward with post-fault K1
Ash zone	Gravel containing stringers and pods of 1.2 m.y.-old basaltic ash
ru	Rubble and disturbed QTa gravel cemented with nonpedogenic(?) carbonate. Soil zones not recognized in fault zone because of abundant carbonate cement

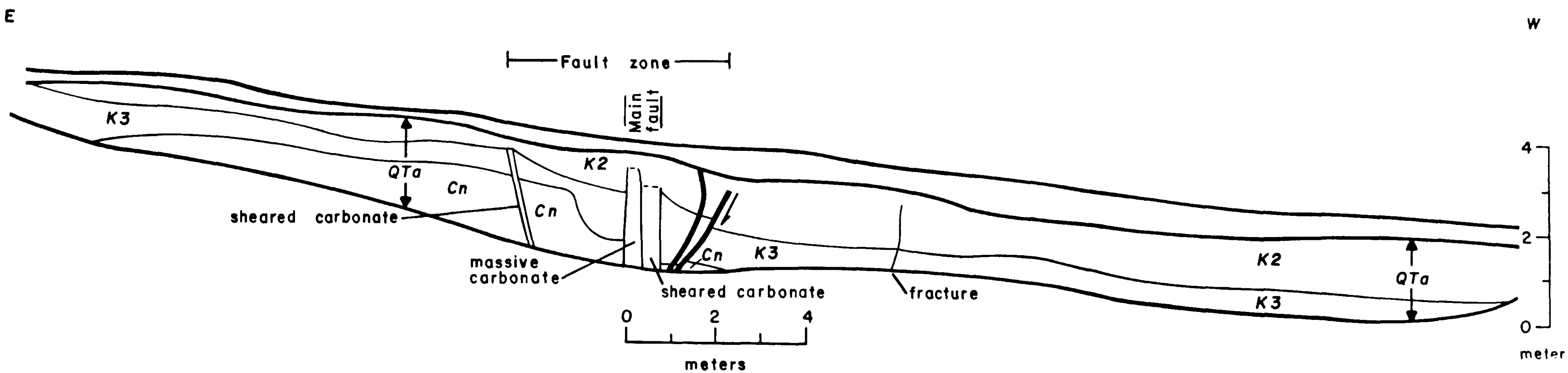

Figure A18.--Diagram of south wall of trench CF2, located across fault Q. Trench trends N. 88° W. Diagram modified from Swadley and Hoover (1983). Four faults cut QTa but not the overlying Q2. The main fault and two minor faults do not extend through the K2 horizon indicating some soil development after faulting. One fault does cut the K2 horizon which suggests a later epidsode of faulting. The apparent displacement of the lower contact of the K horizons may be due to post-fault deposition of carbonate in permeable zones near the faults.

Unit	Description
Q2	Sandy gravel; soil development consists of light-gray vesicular silt and clay A horizon 5-20 cm thick; and a pale-yellowish-brown to pale-brown cambic B horizon developed in sandy gravel; 5-70 cm thick (not mapped)
QTa	Gravel, coarse, nonbedded, poorly sorted. Soil horizons mapped separately
K2	Gravel, well cemented with massive to laminated stage IV carbonate; 0-1.5 m thick
K3	Gravel, moderatley cemented with stage III carbonate; 0.5-1.5 m thick
Cn	Gravel, coarse, poorly sorted, nonbedded

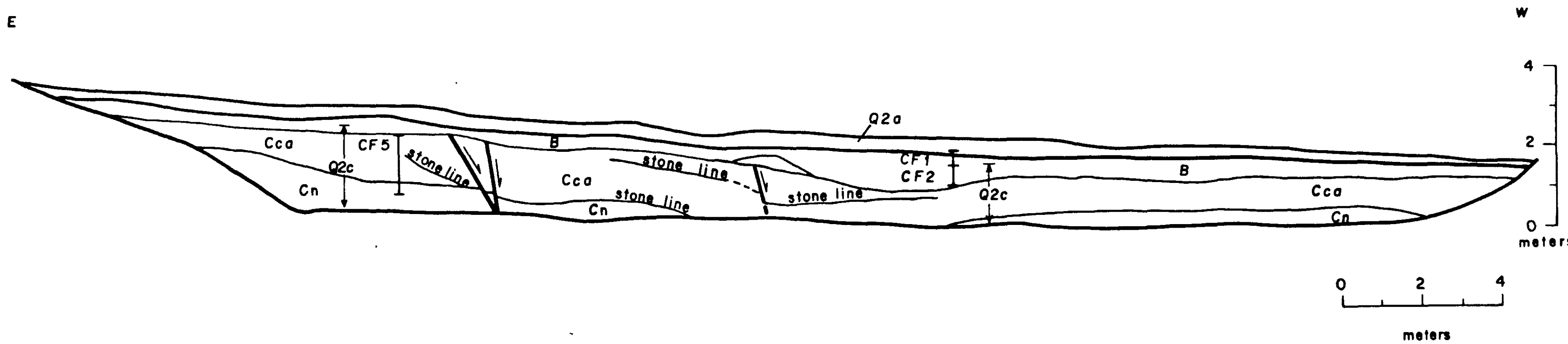

Figure A19.--Diagram of south wall of trench CF3. Trench trends N. 83° W. across fault Q. Diagram modified from Swadley and Hoover (1983). Three faults cut unit Q2c and its soil but not the overlying Q2a. Sample locations for uranium-trend age determinations shown by vertical bar.

Unit	Description
Q2a	Sand, silty, some gravel. Probably largely slope wash deposits
Q2c	Gravel, sandy, poorly sorted. Soil development consists of B, Cca, and Cn horizons
B	B horizon--cambic, light-brown, developed in sandy gravel. As mapped, upper part of unit includes the B horizon of the overlying Q2a (20-45 cm thick). Where B is thick, west of main fault, it probably includes some colluvial sand
Cca	Cca horizon--gravel, sandy, stage II carbonate development
Cn	Gravel, sandy, poorly sorted, fairly well bedded

Uranium-trend Age Determination

Sample No.	Unit	Age (in 10^3 yr)
CF1	Q2a	40±10
CF2	Q2c	270±20
CF5	Q2c	260±140