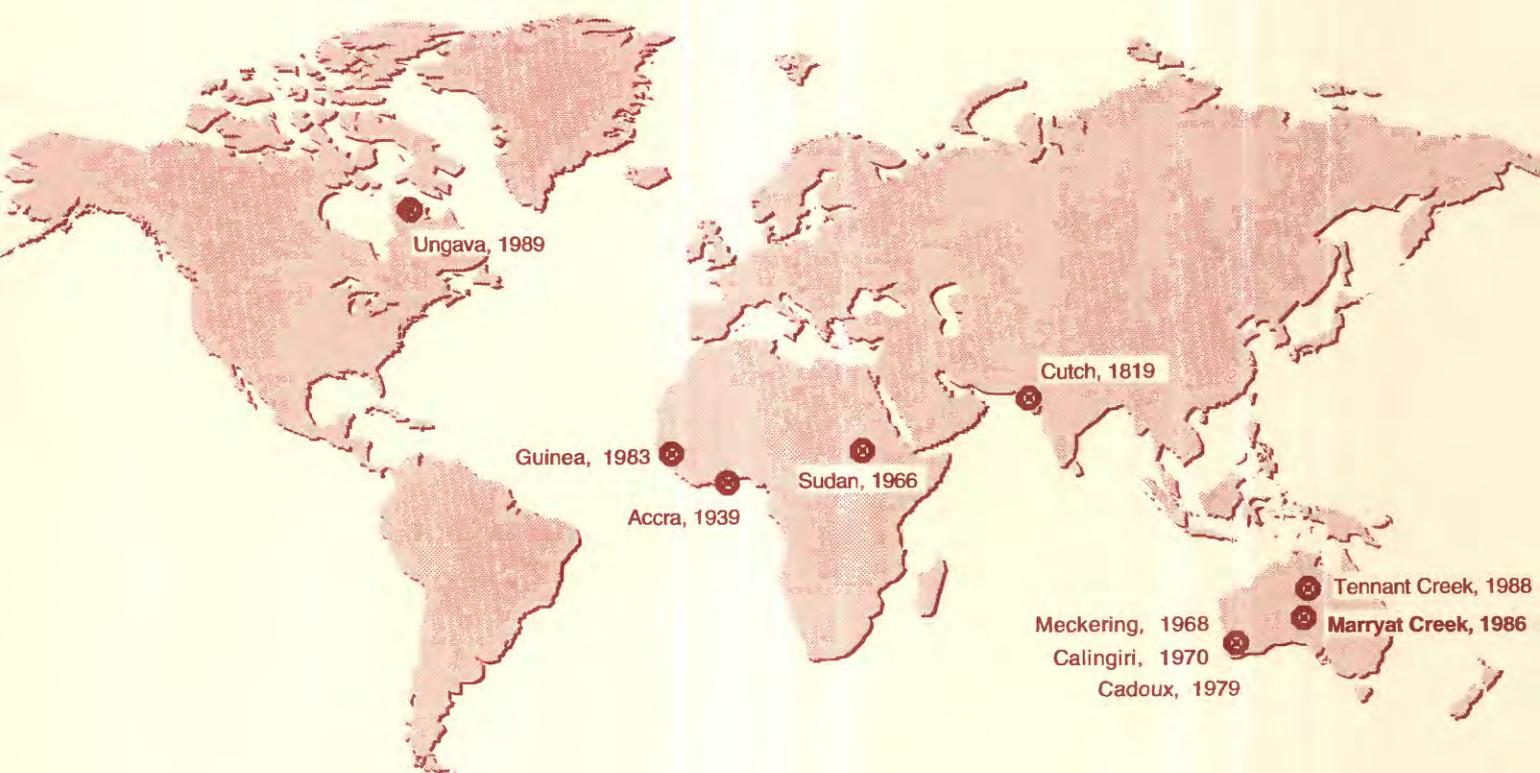


Geologic Investigations of the 1986 Marryat Creek, Australia, Earthquake— Implications for Paleoseismicity in Stable Continental Regions

U.S. GEOLOGICAL SURVEY BULLETIN 2032-B



Cover Global map showing the location of the 10 historical earthquakes that have caused surface faulting in the stable interior of continents.

Geologic Investigations of the 1986 Marryat Creek, Australia, Earthquake— Implications for Paleoseismicity in Stable Continental Regions

By Michael N. Machette, Anthony J. Crone, *and* J. Roger Bowman

PALEOSEISMOLOGICAL STUDIES IN AUSTRALIA

U.S. GEOLOGICAL SURVEY BULLETIN 2032-B

Investigations of the paleoseismology, deformation, and Quaternary stratigraphy associated with reverse faulting caused by a major earthquake in the interior of the Australian craton



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GLOSSARY OF EARTHQUAKE MAGNITUDE TERMS

M	Richter magnitude, typically equal to local magnitude (M_L) as originally defined
M_o	Seismic moment in dyne-centimeters
M_s	Surface-wave magnitude
m_b	Body-wave magnitude
M_D	Duration magnitude
M_L	Local magnitude

GEOLOGIC INVESTIGATIONS OF THE 1986 MARRYAT CREEK, AUSTRALIA, EARTHQUAKE— IMPLICATIONS FOR PALEOSEISMICITY IN STABLE CONTINENTAL REGIONS

By Michael N. Machette, Anthony J. Crone, and J. Roger Bowman¹

ABSTRACT

On March 30, 1986, an earthquake of surface-wave magnitude (M_s) 5.8 generated about 13 km of surface ruptures in the remote northern part of South Australia. This earthquake is significant because it occurred in the interior of the tectonically stable Precambrian shield (craton) of the Australian plate, about 2,000 km from the nearest plate margin. It joins only nine other historic earthquakes in the world that have produced documented surface ruptures in the stable interior of continents such as Australia. The earthquake epicenter (lat 26.22° S., long 132.82° E.) is near new fault scarps that were found along the upper reaches of Marryat Creek. The surface ruptures have a boomerang (open-chevron) shape in map view and were formed by compression, as were most other historic surface ruptures in Australia. Ruptures along the 5.5-km-long west trace trend 078° and record reverse-sinistral slip having a south-over-north sense of throw. Ruptures along the 7.5-km-long south trace trend 005° and record reverse-dextral slip having a west-over-east sense of throw.

P-wave, first-motion directions of the Marryat Creek main shock show a combination of reverse and strike-slip movement and indicate near-horizontal, northeast-southwest-directed compression. In contrast, analysis of the teleseismic body waves indicates almost pure thrust faulting on a fault plane that strikes $148^\circ \pm 20^\circ$ and dips about $35^\circ \pm 20^\circ$ SW. The body-wave data indicate an almost horizontal east-northeast-oriented compression direction (*P*-axis). The main shock focal depth is estimated to be 0–3 km, and the computed seismic moment of 5.8×10^{24} dyne-cm is consistent with an average slip of 0.3 m on a 13-km-long, 3-km-deep fault in Precambrian cratonic rock.

During our reconnaissance study of the Marryat Creek surface ruptures in the austral winter of 1990, we measured a maximum surface offset of 0.6 m near the apex of the ruptures. This offset diminishes to 0.1 m or less at the farthest points where the scarp is still recognizable. Within a few months of the earthquake, 84 topographic profiles were surveyed across the scarp to document the amount of vertical offset caused by the faulting. Based on these data, the average vertical offset along the entire length of the scarp is 28.5 cm, compared to a maximum vertical offset of 90 cm that was measured at one point. Widespread evidence of the reverse component of faulting was still visible, although sparse evidence remained of the subequal amounts of lateral movement. Where evidence of lateral slip was present, the slip directions and amounts indicated northeast-directed horizontal compression, which agrees with the direction indicated by the seismological data.

We excavated one trench across each trace of the 1986 surface ruptures to investigate the prehistoric activity and recurrence of surface-rupturing earthquakes on this fault and to characterize the near-surface deformation caused by the 1986 event. The trenches show that the 1986 surface ruptures are associated with faults that dip $45^\circ \pm 10^\circ$ to the south or west in the shallow subsurface and cut Proterozoic bedrock (granite and greenstone), an overlying layer of upper Quaternary(?) fluvial and colluvial deposits, and a thin mantle of Holocene(?) eolian sand that forms the modern ground surface.

Movement during the 1986 earthquake was mostly confined to the most prominent slip plane within a wider zone of older faults. Intensely fractured and altered bedrock adjacent to the 1986 failure planes indicates that the 1986 earthquake reactivated preexisting ancient faults that are part of a major fault zone or zones. Many fractures

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Table 1. Historic earthquakes in Australia that have produced surface ruptures.

[M_s , surface-wave magnitude of the earthquake. WA, Western Australia; SA, South Australia; NT, Northern Territory. There were three major earthquakes in the Tennant Creek sequence]

Date of earthquake	Location of earthquake	M_s	Surface rupture length (kilometers)	Maximum scarp height (meters)	Main reference
October 14, 1968	Meckering, WA	6.8	37	3.5	Gordon and Lewis (1980).
March 11, 1970	Calingiri, WA	5.7	3	<0.4	Gordon and Lewis (1980).
June 6, 1979	Cadoux, WA	6.4	28	<1.4	Lewis and others (1981).
March 30, 1986	Marryat Creek, SA	5.8	13	<0.9	McCue and others (1987).
January 22, 1988	Tennant Creek, NT	6.3–6.7	32	<2.0	Bowman and others (1990).

show no evidence of 1986 movement but instead are filled with sheared rock or clayey gougelike material that presumably formed during prehistoric slip events.

We found no stratigraphic or structural evidence of Quaternary movement on the faults that were exposed in the trenches. Thus, any earlier surface-rupturing earthquakes must predate the oldest Quaternary deposits in the trenches. On the basis of soil development, we believe that the oldest Quaternary deposits in the trenches are probably early late Pleistocene in age (less than about 140 ka (thousand years) old), although an experimental uranium-trend analysis suggests a geologically unreasonable age of only 8 ± 6 ka. The absence of any physiographic expression of ancient fault scarps or topographically aligned hills in this low-relief landscape in an arid climate suggests that the recurrence for surface-rupturing earthquakes is long—on the order of 100,000 years or more. However, because very old (middle Pleistocene or older) surficial deposits were not present in the trenches and because some suspicious geomorphic relations exist along the south trace of the fault, we cannot preclude the possibility of early Quaternary movement on the fault zone. If early or middle Quaternary movement did occur, then this ancient surface faulting is consistent with our conclusion that the recurrence of surface rupturing is measured in time intervals of at least hundreds of thousands of years or more.

Our investigations of the historical faulting at Marryat Creek, Tennant Creek, and Meckering in Australia and paleoseismologic data from the Meers fault in the United States all suggest that intraplate faults may have long repeat times for surface rupturing. Based on these observations, we suggest that the concept of recurrence intervals may not be appropriate for faults in stable continental interiors. Perhaps earthquake-hazard assessments for intraplate settings should be based on infrequent random earthquakes that occur on suitably oriented faults rather than only on faults having demonstrable Quaternary movement.

INTRODUCTION

Only ten historic earthquakes are known to have produced surface ruptures in the tectonically stable interior of

continents (table 1). Half of these earthquakes have occurred in Australia since 1968. On March 30, 1986, an earthquake having a surface-wave magnitude (M_s) of 5.8 produced about 13 km of surface rupturing near the upper reaches of Marryat Creek in the remote northern part of South Australia. The Marryat Creek earthquake nucleated at shallow depth in Proterozoic rocks of the Musgrave-Mann Block, almost 2,000 km from the nearest continental plate margin (fig. 1). The surface rupture is near Gosses Bore (well) on Anangu Pitjantjatjara freehold land about 45 km east-northeast of Kenmore Park, where ground shaking caused only minor damage. Owing to its remote location and recent occurrence, the Marryat Creek earthquake offers a valuable opportunity to collect geologic data on the long-term activity and characteristics of seismogenic faults in the interior of stable continental plates. In this report we use the term "seismogenic" to describe faults that are capable of generating large (M 6+) earthquakes and which are typically associated with surface rupturing and damage from ground motion.

Earthquakes are commonly divided in two major categories on the basis of their general tectonic setting: interplate earthquakes, which occur along or near the margins of lithospheric plates, and intraplate earthquakes, which occur in the interior of the plates. The concept of plate tectonics provides the broad geologic framework for understanding the fundamental causes and driving forces that produce interplate earthquakes—most interplate earthquakes result directly from the differential movement at the boundaries between adjacent lithospheric plates. In contrast, the tectonic framework and causes of intraplate earthquakes are very poorly understood (Sykes, 1978; Johnston, 1987).

Intraplate earthquakes can be further subdivided by whether their tectonic setting is related to plate-margin interactions (for example, backarc basins) or is distant from plate margins (Scholz and others, 1986) and mostly isolated from plate-margin interactions. Earthquakes in the latter group are usually considered to occur in the stable interior of continental plates (Johnston, 1989).

Historical records clearly show that earthquakes occur much less frequently in stable continental interiors than at plate boundaries; however, intraplate earthquakes

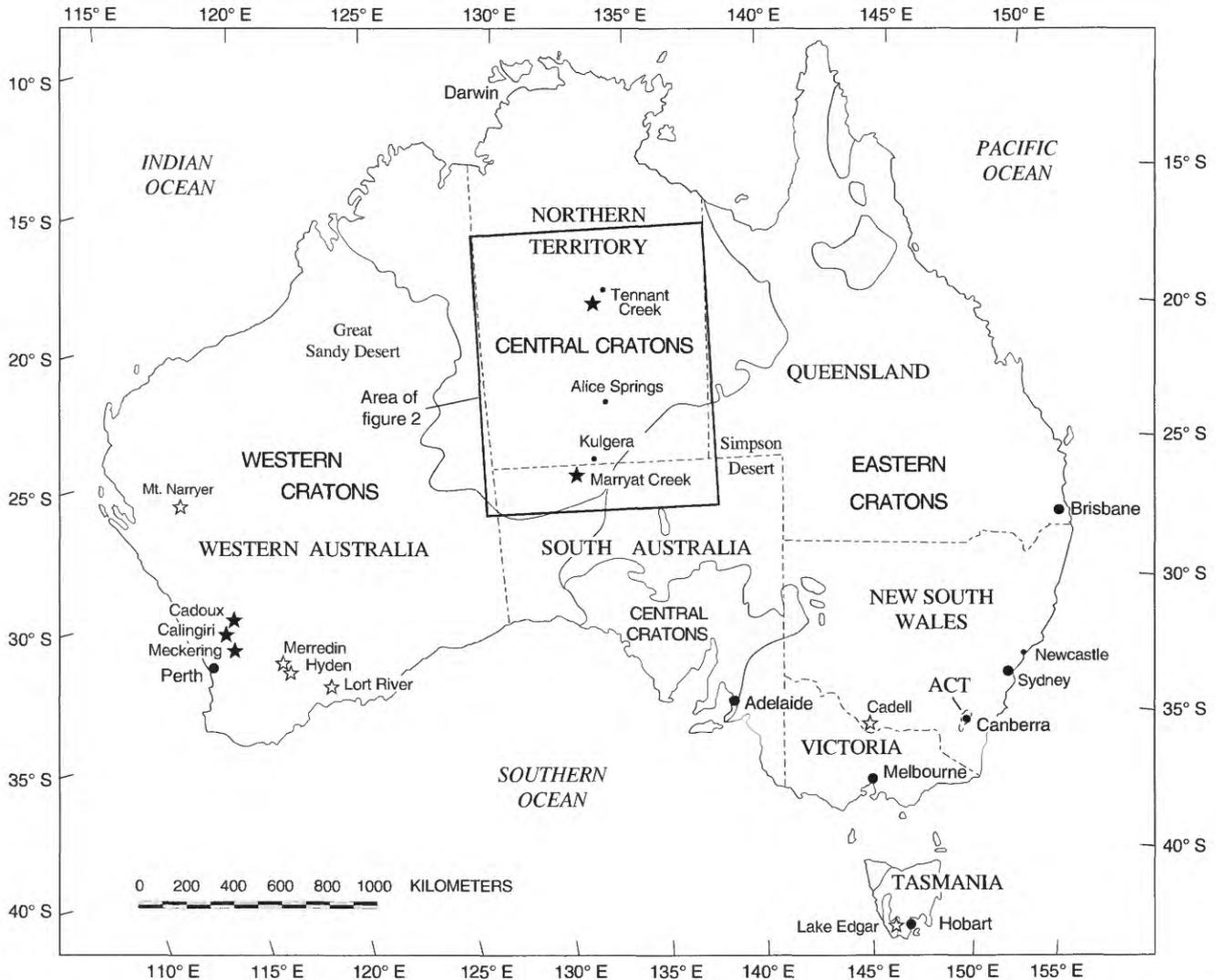


Figure 1. Index map of Australia showing features mentioned in the text and the locations of historic earthquakes that produced surface ruptures (solid stars) and locations of prehistoric fault scarps (open stars). Shaded areas show extent of the Central Cratons province (modified from Palfreyman, 1984). The map uses the Bonne projection.

pose a significant threat to lives and property worldwide (Johnston and Kanter, 1990) and can be extremely damaging for several reasons. First, because these earthquakes occur infrequently, both the general population and man-made structures are poorly prepared to cope with the severe ground motion. As a result, even earthquakes of modest size can be very damaging. For example, the Newcastle, Australia, earthquake of December 29, 1989, caused 13 deaths and about A\$1.5 billion in damage even though it only had a moderate moment magnitude (M 5.6). Second, the strong ground motion generated by major earthquakes ($M \geq 7.5$) may affect significantly larger areas than plate-margin earthquakes of comparable size (Nuttli, 1973a, b; Nuttli and Zollweg, 1974; McKeown, 1982; Hanks and Johnston, 1992). Based on intensity data from historical reports, a recurrence of the great earthquakes that struck the New Madrid, Missouri, area in the winter

of 1811–12 could cause serious damage and injury in an area about 20 times larger than that of the 1906 San Francisco, California, earthquake (about 600,000 km² in the New Madrid area versus about 30,000 km² in the San Francisco area) (Hamilton and Johnson, 1990).

The historical record of earthquakes in stable intraplate settings, especially in the central and eastern United States, is far too short and incomplete to accurately reflect the long-term activity of these faults. Efforts to understand the earthquake hazards in intraplate areas have been severely hampered by an almost complete lack of geologic data on the characteristics of the causative seismogenic faults. A key reason for the lack of earthquake-recurrence information is the rarity with which large intraplate earthquakes generate surface faulting. Geological investigations of prehistoric surface-rupturing earthquakes can provide valuable information on the location and magnitude of

ancient earthquakes and offer insight into the long-term activity of seismogenic faults over geologically meaningful periods of time (many thousands of years). These kinds of investigations, which are part of a discipline known as paleoseismology, are rapidly becoming a key component of earthquake investigations.

In contrast to the five historic surface-faulting earthquakes in Australia, only one such earthquake has occurred in a similar setting in North America. In December 1989, the Ungava earthquake produced a surface rupture in the Canadian Shield in a remote part of northern Quebec (Johnston and Bullard, 1990; Adams and others, 1991). Our interest in the Australian earthquakes was heightened by their extraordinary geographic and temporal concentration, the likelihood that the ruptures would be preserved because they are in remote but generally accessible areas, and the opportunity to find geologic evidence for prehistoric faulting and, thus, to investigate the long-term history of recently active seismogenic faults in a stable intraplate setting.

Even though data regarding the recurrence of large intraplate earthquakes is limited, the available studies suggest that the recurrence of surface faulting is measured in at least several tens of thousands of years and more likely in hundreds of thousands of years or possibly millions of years (Crone and Luza, 1990; Adams and others, 1992; Crone and others, 1992). Improving the quantity and quality of information about the activity of intraplate faults is vital for assessing earthquake hazards in continental interiors. Likewise, paleoseismic investigations can contribute to understanding the mechanics of intraplate faults, which provides insight into the way that strain energy accumulates and is released in stable continental crust during large earthquakes.

The Marryat Creek earthquake occurred on Anangu Pitjantjatjara freehold land in the outback of central Australia. The topography in the study area is gently undulating plains and low hills of bedrock that are traversed by eastward-flowing ephemeral streams. The two major drainages in the region are Marryat Creek on the south and Alcurra Creek to the north. West of the Stuart Highway, these creeks join the Alberga River, which flows southeastward to Lake Eyre North (elevation -16 m) in the Simpson Desert. Only about 1–2 m of local relief is present across the fault scarps in much of the study area; however, 5 m or more of relief is locally present near major drainages such as Marryat Creek and an unnamed large tributary drainage (fig. 3) where the channels are incised below the general elevation of the adjacent landscape. Within the study area, surveying data (Bowman and Barlow, 1991) indicate about 17 m of total relief along the west trace of the new scarps and about 27 m of relief along the south trace relative the lowest elevation, which is in a channel thalweg near the central part (apex) of the scarp.

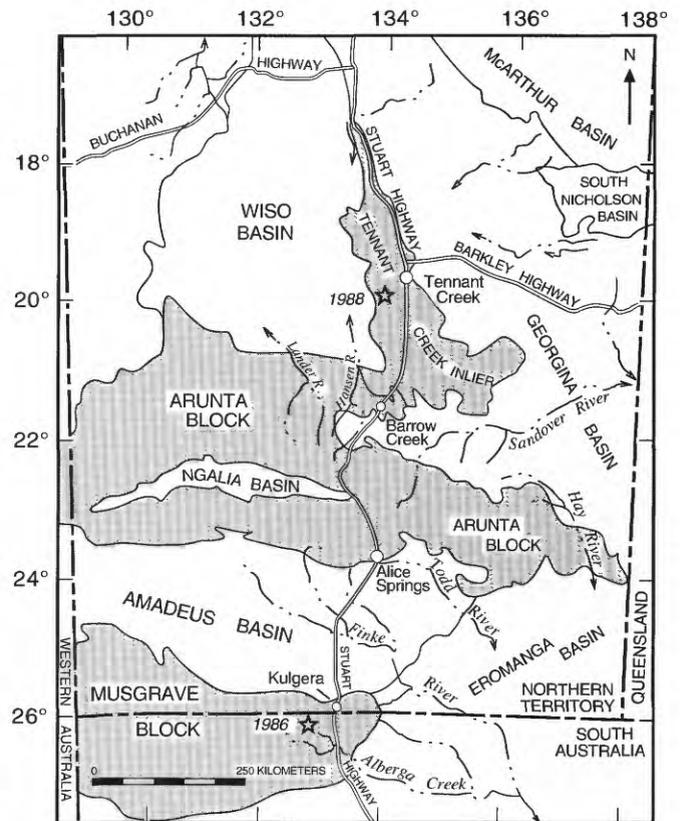


Figure 2. Index map of the Marryat Creek region showing major Phanerozoic basins and basement provinces (blocks) in the southern part of the Northern Territory and adjacent South Australia (modified from Kennewell and Huleatt, 1980). Epicentral locations of Marryat Creek (1986) and Tennant Creek (1988) earthquakes are shown by stars.

The Marryat Creek area is at an elevation of about 500 m, and its climate is generally arid and hot but is semiarid and continental at higher elevations (typically above 550 m). About 300 km to the north-northeast in Alice Springs (fig. 2) (elevation 550 m), where accurate climatic records are maintained, the average annual rainfall is 274 mm (table 2) (Bureau of Meteorology, 1988). Likewise, Ayers Rock (elevation 550 m and about 220 km to the northwest of the Marryat Creek area) receives about 330 mm of precipitation per year and has median annual maximum and minimum temperatures of 29.2°C and 12.7°C, respectively. Other recording stations that are close to the Marryat Creek area typically receive annual precipitation of 220–250 mm (table 2). With the exception of Coober Pedy, all of these recording stations are north of Marryat Creek and thus receive more moisture from the northerly monsoons that affect the central part of Australia in the warm austral summer months. Coats (1963) suspected that the precipitation in the area around Marryat Creek area ranges from 125–150 mm in the plains to about 275 mm in the low mountain ranges. These regional precipitation and temperature values suggest that Marryat

Table 2. Climatic data for recording stations near the Marryat Creek study area.

[Data from Bureau of Meteorology, 1988. Number of years of record, if known, is shown in brackets; n.d., not determined. NT, Northern Territory; SA, South Australia]

Recording station	Distance and direction from Marryat Creek	Elevation (meters)	Mean annual precipitation (millimeters)	Mean daily temperature (°C)	
				Maximum	Minimum
Alice Springs, NT	300 km to north-northeast	550	274	n.d.	n.d.
Ayers Rock, NT	220 km to west-northwest	526	331 [19]	29.2 [16]	12.7 [16]
Curtin Springs, NT	150 km to northwest	488	221 [32]	29.1 [21]	12.8 [21]
Kulgera, NT	60 km to northeast	526	251 [14]	28.2 [5]	13.0 [5]
Cooper Pedy, SA	360 km to south-southeast	215	153 [56]	27.7 [21]	13.5 [21]

Creek sites probably receive from 175 to 225 mm of precipitation, most of which falls in the warm months, although the historical records indicate that rainfall is quite variable from year to year (Coats, 1963). Vegetation in the Marryat Creek area consists mainly of hardy, low-growing, native grasses, scattered clumps of mulga (*Acacia spp.*) bushes, and small trees. The major drainages are lined with large eucalyptus and native fig (*Ficus platypoda*) trees (Coats, 1963). We estimate that vegetation covers about 10–25 percent of the faulted surfaces. Because of the arid climate, Marryat Creek is generally dry and flows infrequently, only about once every 5 years after very heavy rainfall (R. Lodge, Mildara Earthmovers, Kenmore Park, South Australia, oral commun., 1990).

During our week-long field study, we obtained most of our geological data from two exploratory trenches that were excavated across the 1986 scarps. These trench exposures allowed us to document the style of the near-surface deformation caused by the 1986 earthquake. We also deployed a temporary network of eight portable seismographs during our field studies with the hope of recording a sufficient number of late aftershocks to define the orientation of the fault plane that was responsible for the 1986 earthquake. In populated areas, cultural modification quickly destroys critical details of surface ruptures and important geological evidence about near-surface faulting. These modifications interfere with one's ability to comprehensively document the amount of offset and the geometry and characteristics of the surface ruptures. Fortunately, the 1986 ruptures are in a virtually unpopulated area, and surface effects should be preserved longer than if they were close to populated areas.

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complete our field studies as scheduled. We greatly appreciate their enthusiastic assistance. We also thank Donald Frazer of Kenmore Park, South Australia, and the Pitjantjatjara Council for granting us access to the Anangu freehold lands and for permission to excavate our trenches. In addition, we appreciate the willingness of Richard Lodge of Mildara Earthmovers (Kenmore Park) to transport his heavy equipment to the study area, to excavate the trenches, and to share his knowledge of local flora, fauna, and folklore over the campfire. Daniel R. Muhs (U.S. Geological Survey, Denver) prepared and analyzed the uranium-trend samples and interpreted the data for the soil in the Marryat Creek South trench. We also thank Steven G. Wesnousky and R. Ernest Anderson for their perceptive comments and reviews, which streamlined this report and improved its clarity.

GEOLOGIC SETTING OF THE MARRYAT CREEK EARTHQUAKE

The Marryat Creek earthquake occurred at the eastern end of the Musgrave Block (fig. 2), which is comprised mainly of Proterozoic-age Musgrave-Mann gneiss and Kulgeran granitoid rocks (Conor, 1978a, b, c, d). The Proterozoic history of the Musgrave Block was dominated by the Musgravian orogenic cycle. The oldest isotopically dated event in this cycle is an episode of probable high-grade metamorphism about 1,650–1,600 Ma (Plumb, 1979). About 1,390–1,350 Ma, volcanic and marine sedimentary rocks in the block were metamorphosed. The final phase of the Musgravian orogenic cycle consisted of granulite-phase metamorphism about 1,250 Ma, emplacement of the Kulgeran granites about 1,150–1,100 Ma, and, finally, an episode of brittle fracturing and emplacement of mafic and ultramafic intrusions along west-trending thrust faults (Plumb, 1979) about 1,100–900 Ma (Conor, 1978a, b, c, d).

²We use U.S. Geological Survey approved time terms in this report. These terms are abbreviated as follows: Ma, mega-annum (years) ago; m.y., millions of years; ka, kilo-annum (years) ago; and k.y., thousands of years. In addition, for the purpose of this report we use the following informal time terms: Holocene, past 10 ka; late Pleistocene, 10–130 ka; Pleistocene, 10 ka–1.6 Ma; and Quaternary, past 1.6 Ma.

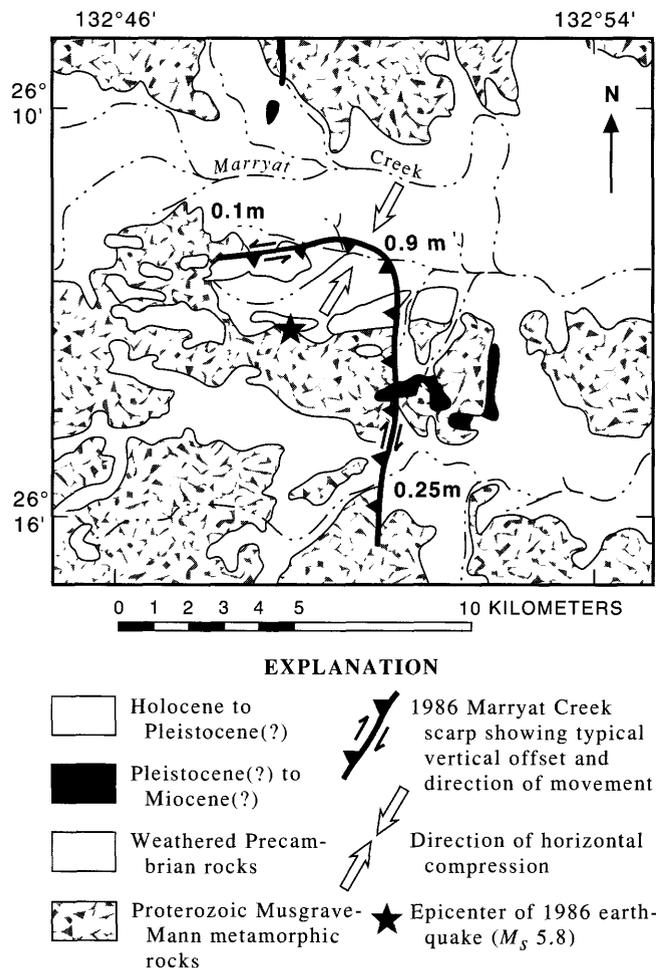


Figure 3. Simplified geologic map of the Marryat Creek surface ruptures. Geology generalized from Connor (1978a); trace of surface ruptures from Bowman and Barlow (1991). Large arrows indicate approximate direction of horizontal compression. Epicenter of main shock from McCue and others (1987).

The various Proterozoic rocks form crystalline basement that, in the study area, is locally covered by scattered patches of Tertiary rocks and Quaternary deposits (pl. 2I).

The locations of the 1986 surface ruptures coincide in part with the Marryat fault zone, a roughly east- to west-northwest-trending zone of Proterozoic faults (pl. 2I). As mapped by Connor (1978a), the fault zone is defined by a system of aligned 1,100–900-Ma noritic plutons and doleritic dikes and by a 5-km-wide zone of mylonite and pseudotachylite. The overall trend of the dikes is generally subparallel to the trend of the fault zone, but individual dikes have a variety of orientations. The mylonite and pseudotachylite, which are interpreted as evidence for ancient faulting, are characterized by almost ubiquitous brecciation of the country rock (Connor, 1978a, d).

The Precambrian to Quaternary geologic history of the Marryat Creek area is sketchy owing to extensive erosion and a paucity of rock outcrops. In general, the

oldest preserved rocks that lie on Proterozoic basement are late Tertiary in age (fig. 3, pl. 2I). These rocks consist of residual deposits (silcrete and ferricrete) and transported deposits that contain rounded pebbles of quartz, silcrete, calcrete, or petrified wood. The present-day distribution of the Tertiary deposits generally conforms to paleolandscapes, particularly higher level stream channels. Near the new surface ruptures, the Proterozoic rocks are overlain by late(?) Tertiary residuum, Quaternary clastic deposits (alluvium, colluvium, and eolian sand), and soils. The only Tertiary deposits mapped near the ruptures are small areas of deeply weathered, kaolinized Proterozoic rock and isolated remnants of deposits that mantled former (Tertiary) land surfaces, such as calcrete or ferricrete (fig. 3) (Connor, 1978a). The Quaternary deposits consist of alluvium in the modern drainage channels and colluvial and fluvial gravels in the interfluve areas that are capped by a thin veneer of eolian sand. The colluvial and fluvial gravels commonly have moderately developed soil profiles that consist of a thin A and a clay-enriched calcareous B horizon and (or) a siliceous horizon (Soil Survey Staff, 1975).

SEISMOLOGY OF THE 1986 MARRYAT CREEK EARTHQUAKE

The Marryat Creek earthquake occurred in central Australia near lat 26.22° S., long 132.82° E. (McCue and others, 1987). It caused no significant damage in the mostly unpopulated region, although several small communities and settlements are within about 50 km of the earthquake's epicenter (fig. 2, pl. 2I). Prior to 1986, the Marryat Creek region was virtually aseismic and no historical earthquakes had been felt in the area. Our discussions with Pitjantjatjara people indicate that they do not have an aboriginal word or expression for earthquake. The only earthquake recorded within 100 km of the 1986 event is a poorly located M_L 3.0 event on August 13, 1983 (McCue and others, 1987). The closest source of regular, moderate earthquake activity is in the Simpson Desert, 250–350 km to the southeast of Marryat Creek, where several $M > 6$ earthquakes have occurred since 1939.

The main shock of the Marryat Creek earthquake had a surface-wave magnitude (M_s) of 5.8, a body-wave magnitude (m_b) of 5.7 (McCue and others, 1987), and a seismic moment (M_0) of $5.0\text{--}5.8 \times 10^{24}$ dyne-cm (Fredrich and others, 1988; Boatwright and Choy, 1992). A focal mechanism determined from P-wave first-motion directions shows a combination of reverse and strike-slip movement and indicates near-horizontal, northeast-southwest-directed compression (McCue and others, 1987). In contrast, the analysis of teleseismic body waveforms indicates almost pure thrust faulting on a shallow-dipping ($35^\circ \pm 20^\circ$ SW.) fault plane that strikes $148^\circ \pm 20^\circ$ (Fredrich and others,

1988). The body-wave data indicate a near-horizontal compression direction (P-axis) that is directed to the east-northeast (066°). The main shock focal depth is estimated to be between 0 and 3 km (Fredrich and others, 1988).

The Marryat Creek earthquake was followed by few aftershocks. McCue and others (1987) reported that, during the 12 days after the main shock, only 17 aftershocks were large enough to be recorded at the permanent seismograph station in Alice Springs, about 300 km to the northeast. The detection threshold of this station is about magnitude 2.0 for earthquakes in the Marryat Creek area (McCue, 1990). The Australian Seismological Centre only reported and located 13 aftershocks of the Marryat Creek earthquake. In the few weeks following the main shock, only seven earthquakes occurred that had local (M_L) or duration (M_D) magnitudes of 2.8 or greater; the largest of these was M_L 4.2 (from 1986 catalog of the Australian Seismological Centre). The largest aftershock was an M_L 5.6 (m_b 5.6) earthquake that occurred on July 11, 1986, more than 3 months after the main shock. This aftershock was located about 10 km northwest of the main shock and probably occurred on a fault other than the one that ruptured during the main shock (Bowman and others, in press). The few microearthquakes that followed the July 11 event marked the end of the Marryat Creek aftershock sequence as recorded by regional stations.

LOCAL EARTHQUAKE MONITORING AT MARRYAT CREEK

We deployed a temporary network of eight portable seismographs around the 1986 fault scarp with the hope of recording enough aftershocks to better define the location and attitude of the 1986 fault plane at hypocentral depths. Although 4 years had elapsed since the main earthquake, lengthy aftershock sequences from two other major Australian earthquakes suggested that a sufficient number of microearthquakes might be occurring at Marryat Creek to warrant the study. For example, 4 years after the 1988 Tennant Creek earthquakes in the Northern Territory of Australia (Crone and others, 1992), 3–10 aftershocks per day were still being recorded at the nearby Warramunga array (Bowman and others, in press), and aftershocks recorded in 1983 defined a fault plane having a dip and orientation consistent with the surface rupture from the 1979 Cadoux earthquake in Western Australia (Dent, 1988).

The temporary network consisted of four seismographs recording digital data on nine-track magnetic tapes and four instruments recording analog data on magnetic tapes. The instruments operated for 12 days from August 31 to September 11, 1990, at locations that were geographically located using a Global Positioning System (GPS) receiver (Bowman and others, in press). Unfortunately, the

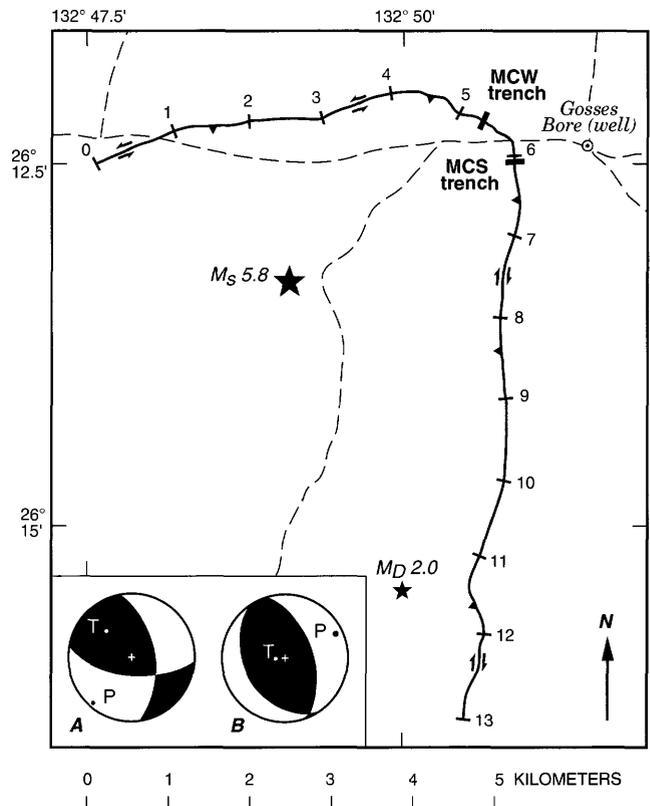


Figure 4. Index map of Marryat Creek surface ruptures. Distance from west end of scarps (in kilometers) is shown by ticks, trench locations are shown by black boxes, and dirt roads are shown by dashed lines. The epicenter reported by McCue and others (1987) is shown by large star (lat 26.22° S., long 132.82° E., about 3 km west-southwest of the two trench sites, Marryat Creek South and Marryat Creek West (MCS and MCW)). The earthquake with a duration magnitude (M_D) of 2 that was recorded by the 1990 temporary network is shown by a small star. **A** (inset), Focal mechanism and P- (compressional) and T- (tensional) axes for the Marryat Creek main shock as determined by P-wave first motions by McCue and others (1987). The preferred fault plane of this mechanism has a strike of 094° , dip of 67° S., and a large sinistral slip component. **B** (inset), Fault plane solutions for the Marryat Creek main shock as determined from teleseismic body waveform analysis by Fredrich and others (1988). The solution indicates almost pure thrust-fault motion. The preferred fault plane strikes 148° and dips about 35° SW.

seismometer cables for two of the stations, which had been buried during installation, were exhumed and destroyed by cockatoos and dingoes, thus reducing the amount of data obtained from these stations.

Two local seismic events were recorded by the temporary network, in addition to numerous regional and teleseismic events. Seismograms for these two events are shown in Bowman and others (in press). These events were located using HYPOELLIPSE (Lahr, 1980) and assuming the same velocity model that was used to locate the Tennant Creek aftershocks (Bowman, Gibson, and

Jones, 1990). The two local shocks had estimated duration magnitudes (M_D) of 1 and 2. The M_D 2 event occurred near the south trace of the 1986 fault scarp (fig. 4) at a depth of 1.1 ± 1.4 km. The M_D 1 event was outside the network, but, assuming a focal depth of 5 km, its epicenter would have been about 14 km northwest of the fault scarp (lat $26^\circ 5' 20''$ S., long $132^\circ 43' 26''$ E.).

It is unwise to draw any conclusions on the basis of only two local earthquakes; however, the location of the M_D 2 event close to and on the downdip side of the surface rupture suggests that it was an aftershock of the 1986 earthquake. The location of the M_D 1 event with respect to the 1986 scarp indicates that it probably has no direct relation to the 1986 event, although it might be related to a localized increase in stress in the area near the main shock rupture (for example, Das and Scholz, 1981).

A comparison of the seismic activity at Marryat Creek with other recent central Australian earthquakes reveals a wide range of aftershock activity that follows major intraplate earthquakes. The 1989 Ayers Rock, Northern Territory, earthquake (m_b 5.8) represents one extreme case of aftershock activity. This earthquake, which had a magnitude comparable to the Marryat Creek earthquake, completely lacked aftershocks (Bowman, Collins, and others, 1990). In contrast, the 1988 Tennant Creek, Northern Territory, earthquake sequence represents the other extreme case. At Tennant Creek, about 100 aftershocks per month were occurring 4 years after the main shocks (Bowman and others, in press). At Marryat Creek, the main shock was immediately followed by a modest number of aftershocks, and a few very small aftershocks occurred 4 years after the main shock.

GEOLOGICAL EFFECTS OF SURFACE RUPTURING

The Marryat Creek earthquake generated a boomerang-shaped surface rupture approximately 13 km long (fig. 3). The east-west-trending section (hereafter referred to as the west trace) is 5.5 km long and has an average trend of 078° . The north-south-trending section (hereafter referred to as the south trace) is 7.5 km long and has an average trend of 005° (fig. 4) (Bowman and Barlow, 1991). The apex of the boomerang-shaped trace is formed by a kilometer-long, west-northwest-trending section of scarps that cross the channel of an unnamed major tributary of Marryat Creek (pl. 2I). In August 1990, more than 4 years after the earthquake, scarps, small ground ruptures, and other surficial features were still evident along about 5.3 km of the west trace and about 6.8 km of the south trace, but many intricate details of the deformation had been destroyed by erosion and by grazing cattle.

The character of the surface ruptures varies along the trace of the scarp. In some places, the rupture is marked

by a discrete fault scarp that is composed of a gentle to flat slope on the uplifted (hanging wall) block, an asymmetric bulge and steep slope or free face at the point where the ground has ruptured, and a generally planar surface on the footwall. In other places, the surface deformation is expressed as a sinuous bulge and warping of the ground surface to form a pressure ridge. Topographic profiles across the ruptures (Bowman and Barlow, 1991; this study) show that the deformation is primarily in the hanging wall and is minimal in the footwall. En echelon offsets in the scarps are common along strike, and individual echelon sections of scarps are typically separated by ramps or monoclines.

SURFACE OFFSET

The maximum surface offset that we measured in 1990 was 0.6 m near the apex of the surface ruptures. This offset diminishes to 0.1 m or less at the most distant points where we could clearly identify 1986 deformation (fig. 3). When the surface ruptures were mapped in 1986, surveyors from the Australian Surveying and Land Information Group (AUSLIG) measured 84 topographic profiles across the trace of the surface ruptures and calculated the vertical offset caused by the faulting (table 3). We computed the average amount of vertical offset along the scarps (table 4) by selecting 50 representative offset values at approximately equally spaced sites along the fault (typically 3 or 4 values per kilometer). The plot of these values (fig. 5) shows the large variability in offset along the fault, the result, in part, of the en echelon pattern of the surface ruptures. The average vertical offset along the ruptures is 28.5 cm, which agrees with the estimated amount of fault slip based on the seismological data. The computed seismic moment for the main shock indicates an average of 0.3 m of slip on a 13-km-long, 3-km-deep fault (Fredrich and others, 1988). The maximum offset is 0.9 m and was measured on the west trace near the apex of the fault (at distance 5.2 km, fig. 5), about 195 m west of our Marryat Creek West trenching site.

LATERAL SLIP

McCue and others (1987) reported as much as 0.8 m of left-lateral slip on the west trace. Unfortunately, the only permanent cultural feature that crosses the scarp is a one-lane dirt track (the east-west road to Gosses Bore, pl. 2I). During the 4 years between the earthquake and our fieldwork, most evidence of lateral slip was obliterated. Animal trails and small ephemeral stream channels and rills were the only features that offered the potential to estimate the amount and direction of lateral slip. The area is actively grazed by cattle, so virtually all of the trails had been used and modified between the time of the

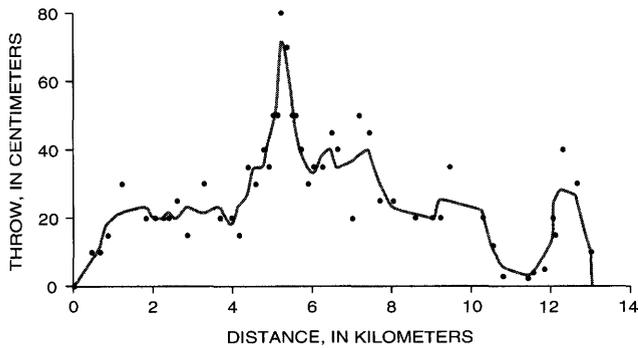


Figure 5. Plot of vertical surface displacement associated with the 1986 Marryat Creek earthquake. Data are from table 4; solid circles represent raw data, line represents smoothed data.

earthquake and our fieldwork. Nevertheless, some cattle trails retained equivocal evidence of lateral movement, and we found two well-established trails that we believe yielded valid estimates of lateral slip: (1) a maximum of 0.5 m dextral slip on the south trace near the apex, about 100 m north of the Gosses Bore road, and (2) 0.6 m of sinistral slip on the west trace, about 45 m west of the Marryat Creek West trench (fig. 4).

The morphology of the scarps and apparent directions of lateral slip are consistent with thrust faulting on a south-dipping plane on the west trace and on a west-dipping plane on the south trace. Assuming that both of these planes ruptured during the main shock and that the main shock nucleated at the intersection of these planes, the hypocenter of the main shock would be south and west of the apex of the scarp. Our measurements and those of McCue and others (1987) suggest that the reverse slip on the fault, which remains as the most visible component of faulting, was accompanied by comparable amounts of lateral slip along some parts of the ruptures. On the basis of an east-northeast (066°) maximum compression direction (Fredrich and others, 1988) and the orientation of the scarps, we would expect the largest amount of lateral motion to be along the eastern part of the west trace (near the apex), where the vertical component is relatively large and where the scarps are oblique to the primary compression direction. The 0.6 m of sinistral slip that we measured west of the Marryat Creek West trench is consistent with this expectation.

EVIDENCE OF PREEXISTING FAULT SCARPS

The only evidence of preexisting (Quaternary) fault scarps along the trace of the 1986 surface ruptures is along the southern end of the south trace where the upthrown block of the fault coincides with a subdued ridge that has about 2–5 m of local relief. Although this ridge could be interpreted as evidence for prior surface rupturing, it is not persistent along the higher and presumably older parts of

the landscape that were offset in 1986. At most places along the trace (Bowman and Barlow, 1991) and at both trenching sites, detailed scarp profiles (pl. 2B–D, F–H) show almost planar surfaces on either side of the 1986 ruptures. Most likely, this ridge simply delineates areas where the bedrock is slightly more resistant to erosion than elsewhere along the fault and is not the vestige of an ancient fault scarp.

Along much of the west trace, bedrock is exposed in the hanging wall (south side of the fault trace), which would be expected for a south-dipping reverse fault. Repeated uplift of the hanging wall would tend to expose bedrock on the south, whereas downdropping of the footwall would trap sediment and bury bedrock on the north (fig. 3). Although the presence of the subdued ridge and this pattern of bedrock outcrops are suggestive of pre-1986 faulting, we consider them to be, at best, circumstantial evidence of prior Quaternary or late Tertiary surface rupturing on these faults.

TRENCHING INVESTIGATIONS

Geological investigations of prehistoric surface-rupturing earthquakes offer valuable information about the location and magnitude of ancient earthquakes and provide insight into the long-term activity of seismogenic faults over geologically meaningful periods of time (many thousands of years), in contrast to the limited record from instrumental or historical seismicity (tens to hundreds of years). Thus, the primary objective of our study was to use geological data to determine the prehistoric rupture history of the faults that were activated in 1986. Geological investigations of ancient earthquakes are part of a relatively new discipline known as paleoseismology, which is an important element of earthquake-hazard assessment (Wesson and others, 1984; Crone and Omdahl, 1987). Exploratory trenching is commonly a key component of paleoseismic investigations because trenches can reveal critical stratigraphic relations between faulted and unfaulted deposits and can expose materials that will help establish the time of prehistoric surface-rupturing events.

METHOD OF STUDY

Our objective in trenching the Marryat Creek scarps was to expose old colluvial deposits that had accumulated adjacent to ancient fault scarps. These deposits would provide evidence of, and information about, prehistoric rupturing on these faults. For example, the thickness and dimensions of scarp-derived colluvium can be used to estimate the height of a prehistoric scarp, which provides a general indication of the magnitude of the associated prehistoric earthquake. In addition, the dating of Quaternary

deposits that can be stratigraphically related to prehistoric faulting provides limits on the timing of a paleo-earthquake.

SELECTION OF TRENCHING SITES

To locate suitable trenching sites, we conducted a basic geologic reconnaissance of the 1986 surface ruptures. We applied three main criteria to select the trench sites. First, we chose sites where the 1986 scarps were relatively large because other paleoseismic investigations have shown that, in many cases, large prehistoric scarps existed at the same site where large historical scarps have formed. This observation, and the fact that the degradation of a large scarp is more likely to leave an easily interpreted stratigraphic record than is a small scarp, indicated that we should trench large 1986 ruptures. Our second criteria was to choose sites where the deformation was both simple and confined to a relatively narrow zone, with the hope that all of the elements of past deformation would be exposed in the trenches. Our third criteria was to select sites where the surficial deposits were not visibly affected by modern, localized erosion and (or) deposition that could complicate stratigraphic relations in the trench.

We selected two trench sites. The first site, along the northern part of the south trace of the fault, is designated the Marryat Creek South trench (MCS, fig. 4). It is 293 m south of the dirt track (road) to Gosses Bore and 58.6 m north of [Australian] Bureau of Mineral Resources (BMR) survey station 113 (Bowman and Barlow, 1991). The second site is designated the Marryat Creek West trench (MCW, fig. 4). It is 68 m northeast of BMR station 116 (on a bearing of 335°), which is marked by a steel stake in the channel of an unnamed major tributary of Marryat Creek that crosses the scarps (pl. 2I). The Marryat Creek West trench is near the northeast apex of the surface ruptures, where the trend of the scarps changes from generally north on the south trace to generally east on the west trace. The surface ruptures trend about 295° at the Marryat Creek West trench, but locally their trend varies between 280° and 330° (pl. 2E).

At each trench site, we made detailed topographic maps using a high-precision, self-adjusting level and a cloth tape measure. We surveyed the elevation of points (usually at 5-m intervals) along a series of lines parallel to the 1986 surface ruptures, using the nearest BMR station as a local reference elevation (zero datum). These maps (pl. 2A, E, scale 1:500) show the local aspect and slope of the faulted geomorphic surfaces and document the geometry of the surface ruptures in detail. We also measured three topographic profiles across the surface ruptures at each trench site. The middle of the three profiles was the eventual location of our trenches.

The trenches were oriented perpendicular to the local trend of the ruptures and were centered on the modern ruptures. Each trench extended 10–20 m into the footwall and hanging wall of the fault. The trenches were excavated using a bulldozer having a blade slightly more than 2 m wide (fig. 6). Although the trenches were 2–2.5 m deep, bedrock was encountered at less than 0.3 m depth in the Marryat Creek West trench and at about 1.25 m depth in the Marryat Creek South trench. The deep and wide trenches provided excellent exposures of the Quaternary deposits, the faults, and the shallow Proterozoic bedrock.

After the trenches were excavated, the walls were thoroughly scraped with mason's trowels to expose fresh material, and the stratigraphic contacts and structural features were identified and marked on the trench walls using multicolored flagging and common nails. A grid of string lines at 1-m intervals was constructed to provide vertical and horizontal control for the mapping. The positions of stratigraphic contacts and structural features were transferred to metric-gridded mylar sheets at a scale of 1:25. After the mapping was completed, we described the geologic units and soils and collected samples (table 5) to determine the physical properties and the age of selected Quaternary deposits.

THE MARRYAT CREEK SOUTH TRENCH SITE

DESCRIPTION OF SURFACE RUPTURES NEAR THE SITE

At the Marryat Creek South trench site (MCS, pl. 2A), the surface rupturing is typically confined to a single well-defined scarp with no significant subsidiary splays (fig. 7). At distances greater than several meters away from the scarp, the adjacent land surface is essentially undeformed (pl. 2B–D). The maximum vertical surface offset near the trench is 61 cm. The free face of the scarp accounts for about two-thirds of this offset, and the remaining one-third of the offset is the result of a gentle monocline in the hanging wall, adjacent to the free face.

In detail, the rupture trace at the Marryat Creek South site is composed of 15–30-m-long sections of fault scarps that form a left-stepping en echelon pattern (fig. 7). The scarps of two adjacent en echelon sections are commonly 10–15 m apart. The height of an individual scarp gradually decreases toward the end of a section, whereas the height of the scarp on the adjacent section progressively increases. The ground surface in the overlapping area between two sections is commonly warped into a gentle ramp or monocline. Individual sections of scarps trend northwesterly (310°–315°), whereas the general trend of



Figure 6. Photograph showing bulldozer excavating the Marryat Creek West trench. View to the southwest.

Table 5. Data for samples collected from the Marryat Creek South trench.

[Geologic units are described on plate 1 (symbols in parentheses are soil horizon designations). Horizontal and vertical locations are from center of sampling hole or channel]

Reference symbol	Field number	Geologic unit	Horizontal axis (meters)	Vertical axis (meters)	Type of analysis
A	MCS-2a	es (Bt)	12.25-12.35	2.90-3.10	Grain size, uranium trend.
B	MCS-2b	cfg (Btk)	12.25-12.35	2.75-2.88	Grain size, uranium trend.
C	MCS-2c	cfg (Btk)	12.25-12.35	2.60-2.72	Grain size, uranium trend.
D	MCS-2d	cfg (Bkq)	12.25-12.35	2.46-2.58	Grain size, uranium trend.
E	MCS-2e	cfg (Bkq)	12.25-12.35	2.32-2.46	Grain size, uranium trend.
F	MCS-2f	fg (Bkm)	12.25-12.35	2.18-2.30	Grain size, uranium trend.
G	MCS-3a	es (soil)	10.30-10.40	2.98-3.03	Thermoluminescence dating.
H	MCS-3b	cfg (soil)	10.30-10.40	2.70-2.80	Thermoluminescence dating.

the ruptures is almost north (353°) along the 300-m-long section between the trench site and the Gosses Bore road (pl. 2A). We measured strikes of 334° and 341° on individual faults in the trench (pl. 1A). South of the Marryat Creek South trench, the scarps are mainly simple and not en echelon; however, they form a fine-crenulate pattern on aerial photographs (fig. 8), typical of surface ruptures along shallow-dipping thrust faults.

STRATIGRAPHY IN THE TRENCH

The stratigraphic units in the Marryat Creek South trench consist of 0.7–1.2 m of unconsolidated Quaternary deposits that overlie relatively intact to extensively altered and sheared Proterozoic greenstone (fig. 9, pl. 1A). A small wedge of colluvium has accumulated at the base of the scarp since it formed in 1986.

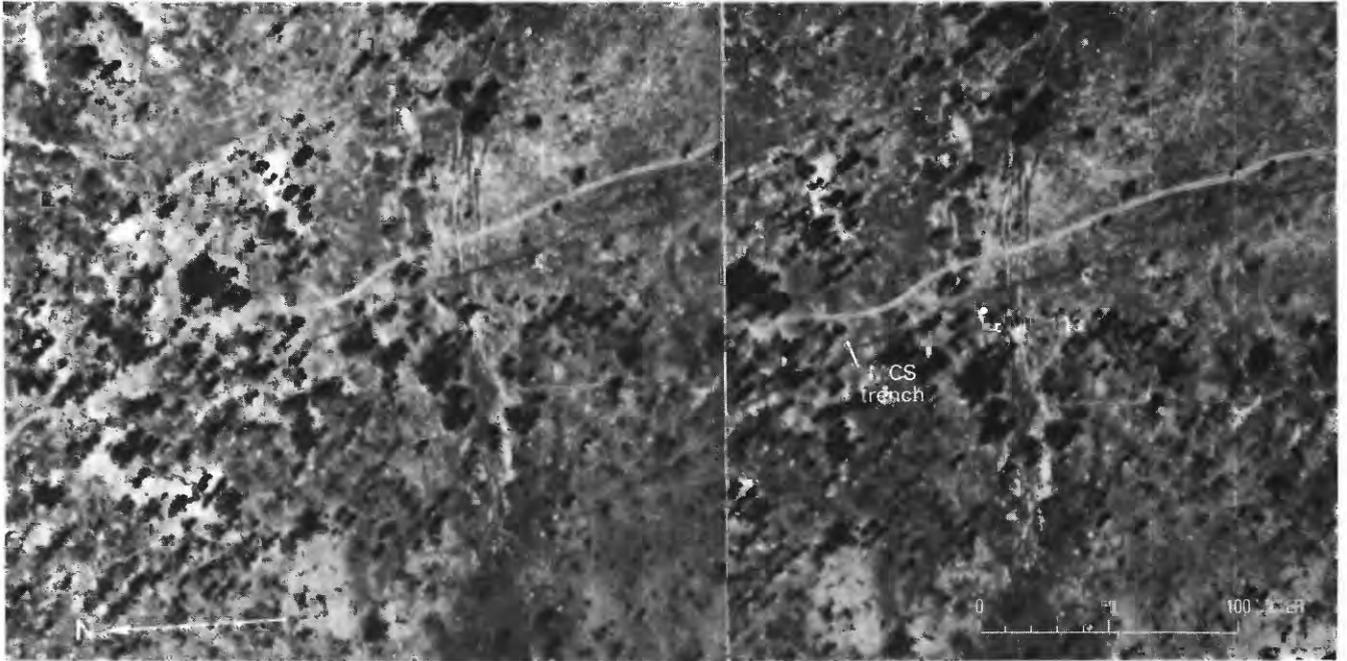


Figure 7. Stereographic aerial photographs showing fault scarps near the Marryat Creek South trench site (pl. 2A). BMR station 113 is about 57 m south of the Marryat Creek South trench. The fault scarps in this area are primarily singular and simple. The scarps directly south (right in photograph) show a typical left-stepping en echelon pattern. Aerial photographs available from Australian Geological Survey Organisation, Canberra, ACT.

The Quaternary deposits are divided into three units based on their textural characteristics and their content of calcrete and lithic fragments (fig. 10, pl. 1A). The uppermost unit is a 10–20-cm-thick layer of red eolian sand (unit *es*) that blankets much of the surrounding landscape. The sand is typically well sorted and nonstratified and has a very thin (about 2 cm thick) accumulation of organic material (A horizon) at the top. Because vegetation is sparse and organic matter collects slowly in soils in arid climates, the presence of a weak (incipient) A horizon indicates that the sand has been stable for at least several decades to centuries. In contrast, active sand deposits north of the Gosses Bore road and along Marryat Creek (to the north) are mostly unvegetated and contain no visible darkening at the surface that would indicate an accumulation of organic matter.

Beneath the red eolian sand, a thin layer of nonstratified, poorly sorted sandy gravel (colluvial/fluvial gravel on fig. 10; unit *cfg*, pl. 1A) is present in both walls of the trench. The thickness of this gravel varies greatly from as little as 5 cm to as much as 75 cm. We interpret this deposit as a mixture of colluvium and fluvial sediment that mantled the land surface before being buried by the eolian sand. A moderately developed calcareous B horizon, about 60 cm thick, has formed in the gravel. The upper 30 cm of the B horizon contains abundant clay (Btk horizon; Soil Survey Staff, 1975) and the lower 30 cm contains abundant silica (Bkq horizon; Soil Survey Staff,

1975) (table 6, fig. 11). The soil carbonate has stage I–II morphology (Gile and others, 1966) in the Btk horizon and stage II morphology in the Bkq horizon.

The oldest Quaternary deposit in the trench is a discontinuous, poorly sorted, clast-supported, sandy gravel that we interpret as a fluvial gravel (fig. 10; unit *fg*, pl. 1A). The gravel is as much as 75 cm thick in the south wall of the trench and 75–125 cm thick in the north wall; the gravel rests unconformably on bedrock and probably fills an east- or northeast-trending channel. Clasts in the fluvial gravel are composed of deeply weathered diabase(?), gneissified granite, and fragments of carbonate-rich rock (calcrete?) that average 10–15 cm in diameter. Because the general landscape slopes gently eastward, the gravel clasts were probably derived from bedrock and Tertiary deposits to the west. A weakly cemented calcareous B horizon (Bkm) has formed in the gravel and has, in places, stage II calcium carbonate morphology (see section on “Description of Units Exposed in the Trenches”).

The relative age of the alluvial surface that is faulted at the Marryat Creek South trench is indicated by the soil at the modern surface (eolian sand) and the soil on the former land surface (colluvial/fluvial gravel) (units *es* and *cfg*, pl. 1A). The soil in the eolian sand is probably quite young (certainly Holocene), whereas the underlying soil probably represents a soil that formed during the late Pleistocene, before it was buried by the veneer of eolian sand. We base the age assignments of these soils on

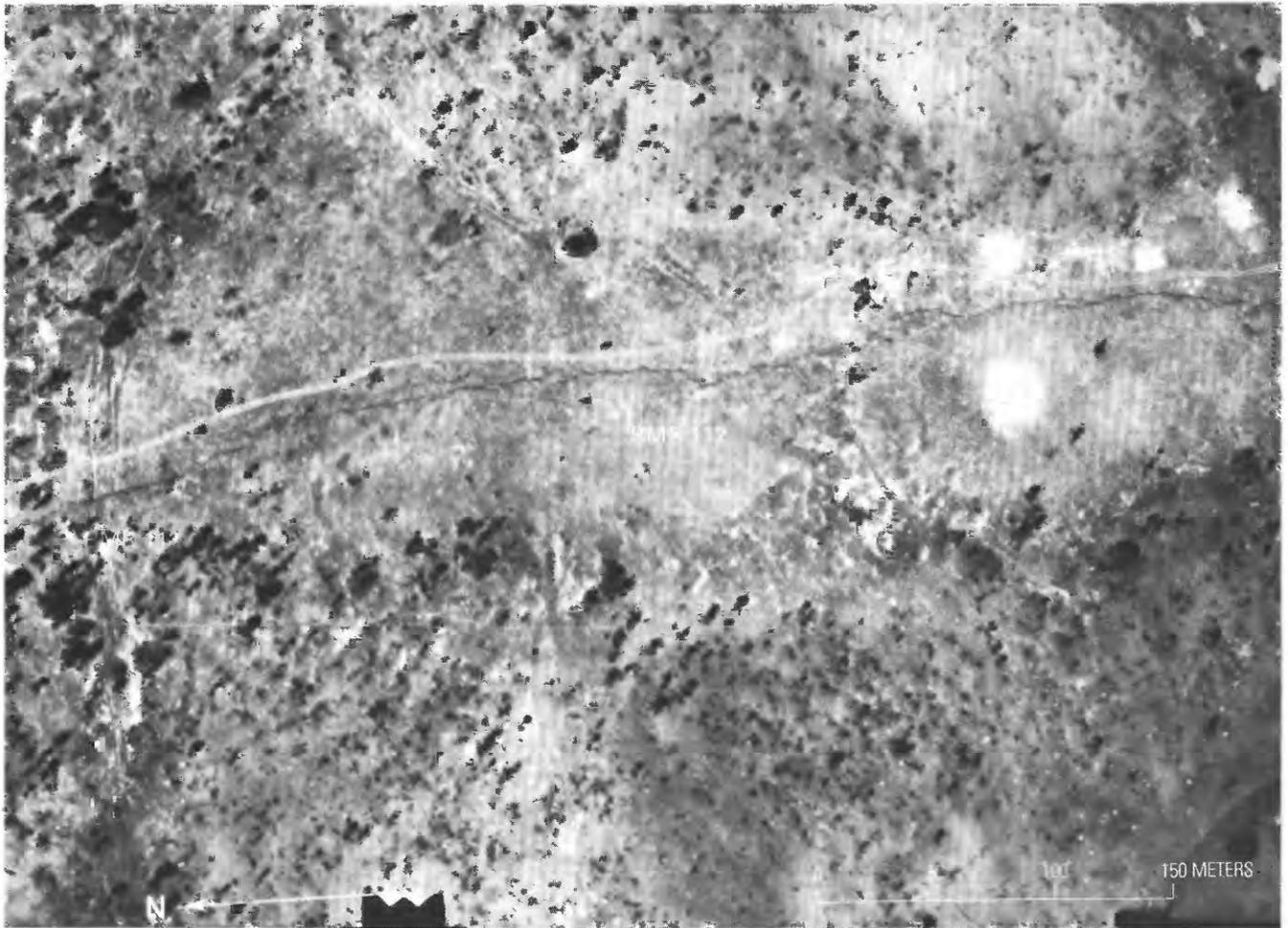


Figure 8. Aerial photograph showing fault scarps south of the Marryat Creek South trench site. The north (left) edge of this photograph overlaps with figure 7. The fault scarps in this area are primarily singular but have a crenulate pattern that is typical of thrust-fault ruptures. Aerial photographs available from Australian Geological Survey Organisation, Canberra, ACT.

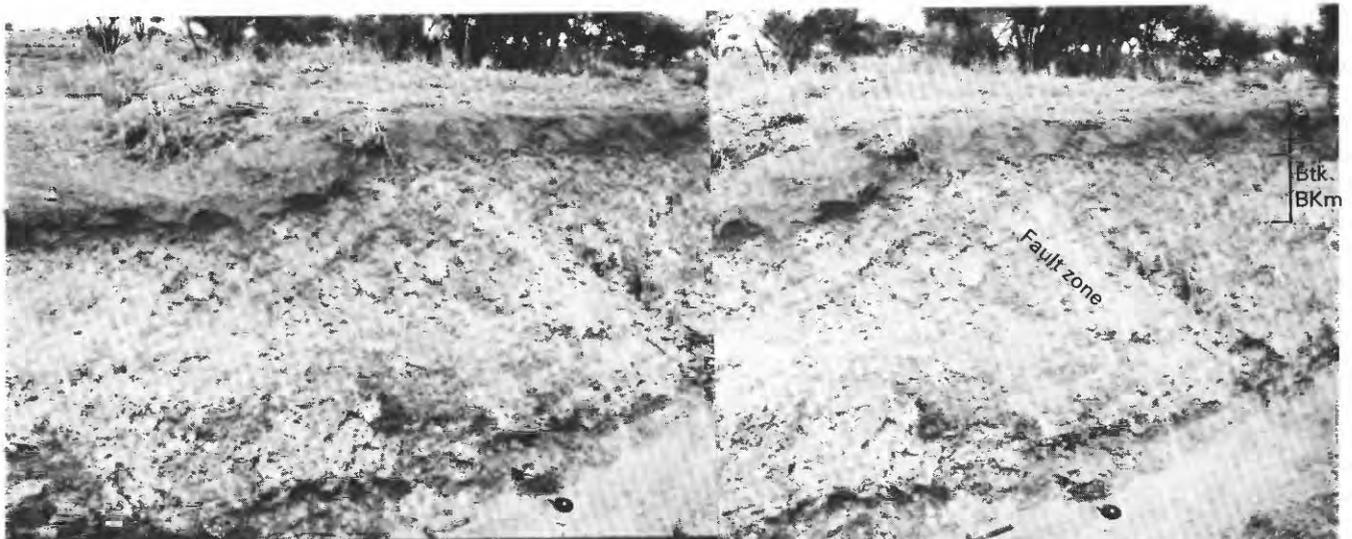


Figure 9. Stereographic photographs of the south wall of the Marryat Creek South trench (pl. 1A). The 1986 fault plane intersects the land surface at the base of the 50-cm-high fault scarp (fig. 11, pl. 2C). The soil in the trench is moderately well developed and consists of A and Bt (dark-colored) horizons over Btk and Bkm (light-colored) horizons. The lower two-thirds of the trench is in fractured, altered, and sheared Proterozoic greenstone. Pieces of flagging along string line are 1 m apart.

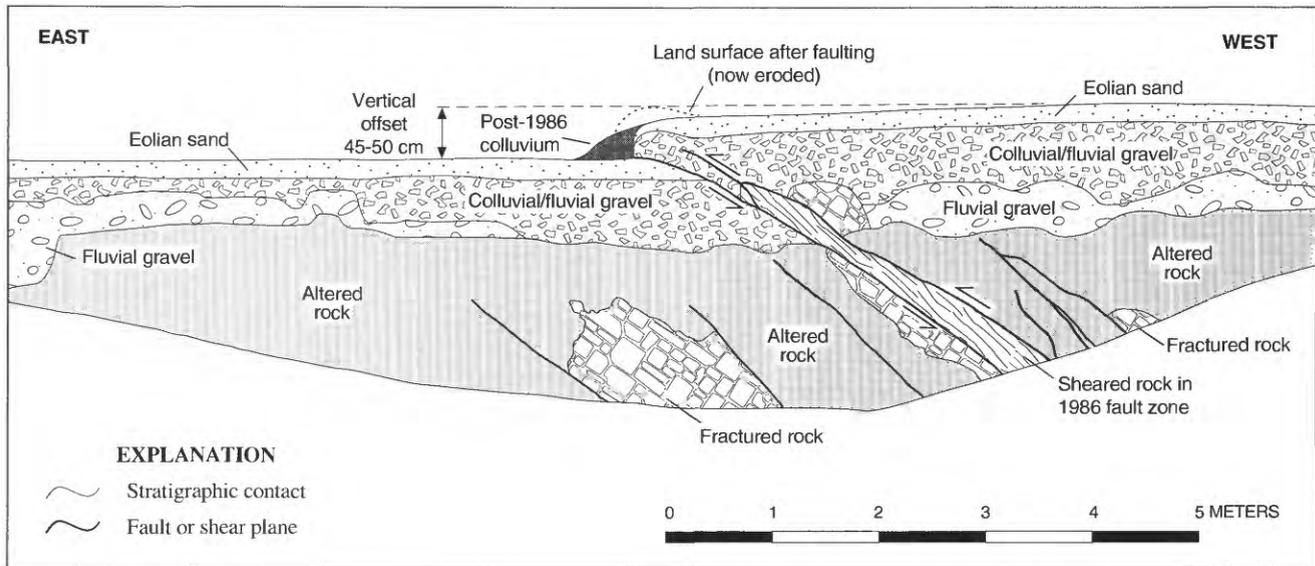


Figure 10. Simplified map of south wall of Marryat Creek South trench. Detailed descriptions of units are in the section on “Description of Units Exposed in the Trenches.” Horizontal and vertical scales are equal.

(1) the strong horization of the soil (A/Bt/Btk and Bkq/Bkm); (2) the presence of a 75-cm-thick, moderately well developed, clayey (Bt) horizon (fig. 12); and (3) the presence of a 60-cm-thick calcic (Bkq) horizon having stage III morphology and layers of silcrete. We discuss our soil-age estimates, the preliminary results of uranium-trend dating, and the implications for these age estimates in the “Discussion and Conclusions” section.

Bedrock in the Marryat Creek South trench consists of extensively fractured, altered, and sheared greenstone that we infer to be Proterozoic in age on the basis of regional geologic mapping (Conor, 1978a, b, c, d). The least altered greenstone (fig. 10; unit rf, pl. 1A) is fractured into roughly equidimensional blocks 10–15 cm in size. The original gross fabric of the greenstone is still visible, but most of the feldspar grains are weathered to a chalky white color. The greenstone contains wispy lenses and seams of quartz that are oriented subparallel to faults that moved in 1986. These lenses, seams, and fractures are evidence that these rocks have undergone a long history of deformation.

Most of the greenstone is pervasively altered to a massive claystone (fig. 10; unit ra, pl. 1A) that contains no visible relict fabric. Most of this altered greenstone is strongly oxidized and contains abundant veins of quartz and calcium carbonate. The upper part of this unit is calcareous and contains irregular masses of calcium carbonate and near-vertical veins that probably are infilled ancient fractures. Some carbonate is also present deeper in the altered greenstone, but it is restricted to near-vertical joints and vein fillings along old shear planes that are parallel to the 1986 fault plane. The latter carbonate, which

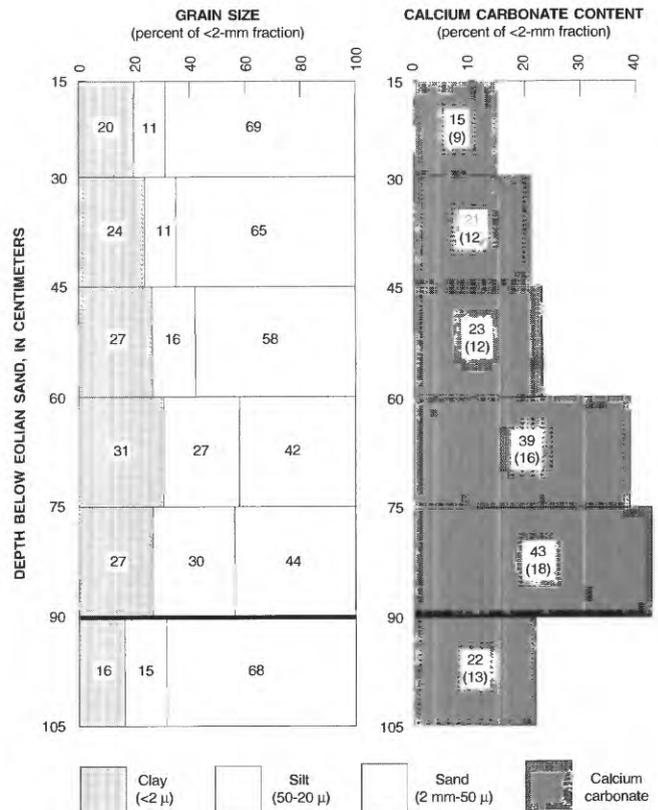


Figure 11. Analyses of grain size and calcium carbonate content from the soil (samples MCS-2, table 8) in the Marryat Creek South trench. Number within graph indicates content of component. Numbers in parentheses indicate content on whole-soil basis, rather than <2-mm basis. Heavy line at 90 cm indicates boundary between different parent materials (unit cfg above, unit fg below).

Table 6. Grain-size distribution and calcium carbonate content for the relict soil in the Marrayat Creek South trench. [Values (in percent) estimated for soil parent material units (values for units *cfg* and *fg*) are shown in bold]

Sample number	Soil horizon	Sampling depth (centimeters)	>2-mm fraction of soil	<2-mm fraction of soil (A)	Grain-size distribution in <2-mm fraction of soil			CaCO ₃ content
					Sand	Silt	Clay	
MCS-2a.....	2Bt1.....	17-30	37	63	69	11	20	15
MCS-2b.....	2Bt2.....	30-45	41	59	65	11	24	21
MCS-2c.....	2Btk1.....	45-60	50	50	58	16	27	23
MCS-2d.....	2Btk2.....	60-75	38	62	42	27	31	39
MCS-2e.....	2Bkqm.....	75-90	59	41	44	30	27	43
Unit <i>cfg</i>	2Cu.....	17-90	50	50	65	25	10	10
MCS-2f.....	3Bkm.....	90-105	40	60	68	15	16	22
Unit <i>fg</i>	3Cu.....	90-105	50	50	74	20	6	6

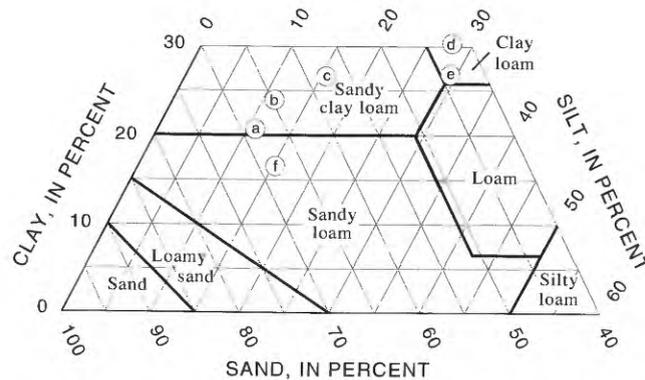


Figure 12. Grain-size data for the soil in the Marrayat Creek South trench. Letters within circles refer to the samples labeled MCS-2 in table 8 and show sand, silt, and clay content of <2-mm fraction of the soil. Sand is defined as particles between 2.0 mm and 0.05 mm in diameter, silt between 0.05 mm and 2 μ , and clay less than 2 μ (Soil Survey Staff, 1975). See figure 11 for additional data about this soil.

is very fine grained, is probably translocated soil carbonate. The quartz veins also are generally aligned with the 1986 shear zone and are probably mineralized shear zones. The greatest oxidation and weathering in the greenstone is confined to the upper 20–25 cm of the unit; below this depth, significant oxidation is present only along old shears that were subsequently occupied by roots.

STRUCTURAL FEATURES IN THE TRENCH

The Proterozoic greenstone in the trench contains numerous shear zones, but the near-surface slip during the 1986 earthquake was confined to a single, 25–30-cm-wide, reverse-slip fault zone. The fault zone has a strike of

334°–341° in the trench and an average dip of 55° W. At least 75 cm of dip-slip displacement (measured at the top of unit *cfg*, pl. 1A) occurred on the main fault zone as a result of the 1986 earthquake. This amount is a minimum value because it does not include the effects of minor folding in the upthrown block. The amount of dip slip measured in the trench is almost twice the 45–50 cm of vertical surface offset that was determined from profiles across the surface ruptures adjacent to the trench, as one would expect for a gently dipping thrust fault.

The main fault zone (that was reactivated in 1986) and other shear zones in the altered greenstone are filled with dark-red material that has a sandy loam to sandy clay loam texture (fig. 13). The material commonly contains a few percent of greenstone fragments that were probably derived



Figure 13. Closeup view of gougelike zones and fractured greenstone in the Marryat Creek South trench. Center of photograph is at 12.20 m on the horizontal axis (pl. 1A) and 1.15 m on the vertical axis. The scale shows inches over centimeters and is about 18 cm long.

from the adjacent bedrock. On the basis of texture and association with the active fault planes, the obvious interpretation is that this material is fault gouge; however, the material is not clay rich and instead is texturally similar to, although distinctly redder than, the adjacent soil material (B horizons). Although the presence of greenstone fragments in the fault-zone material suggests that some differential movement has occurred on these planes, the similarity in the color and texture between the fault-zone material and the overlying soil suggests that some of the material may be oxidized soil that has filled channels left by decaying roots of trees and shrubs, which preferentially grow along preexisting shear zones. Alternatively, the fault-zone material may be polygenetic—partly the result of ancient faulting and partly the result of downward translocation of soil material along preexisting fault planes.

Reverse slip on the fault zone has transported the colluvial/fluvial gravel (unit *cfg*, pl. 1A) in the hanging wall over the eolian sand (unit *es*, pl. 1A) in the footwall and created a compressional bulge in the Quaternary units at the scarp. It is likely that the surficial expression of the bulge was quickly removed by erosion (fig. 11) because the poorly consolidated Quaternary deposits were oversteepened and

broken into erodable blocks. A wedge of post-1986 colluvium (fig. 10; unit *csw*, pl. 1A), which contains blocks of the overthrust Quaternary deposits (unit *csb*, pl. 1A), has accumulated at the base of the scarp.

OBSERVATIONS PERTINENT TO THE TIMING OF PREHISTORIC SURFACE RUPTURING

The presence of intensely fractured and altered greenstone at and adjacent to the fault zone that slipped in 1986 is strong evidence that the 1986 earthquake reactivated a preexisting ancient fault. Many of the fractures in this fault zone show no evidence of movement in 1986, but some are filled with gougelike material that may have formed during prehistoric faulting events. Movement during the 1986 earthquake was mostly confined to the widest and most prominent (that is, a fundamental) slip plane within a wider ancient fault zone.

Quaternary deposits in the trench are deformed only by the 1986 earthquake. Any prehistoric ruptures at this site occurred prior to the deposition of Quaternary units, and, therefore, prehistoric earthquakes cannot be dated directly. Determining the age of the Quaternary units in



Figure 14. Photograph showing typical surface ruptures along the west trace of the Marryat Creek fault scarp. The scarp here is about 50 cm high. View is to the southeast in the area a few hundred meters west of the Marryat Creek West trench site. Large trees in the distance are growing along the channel of the unnamed tributary of Marryat Creek that is shown on plate 2I.

the trench, however, will establish the minimum time since the penultimate faulting event. Efforts to date these deposits using the uranium-trend technique of Szabo and Rosholt (1991) have been unsuccessful, and no conventional-dating materials (such as charcoal or organic matter) were found. We use an independent (but less direct and less limiting) approach to establish the age of earlier surface faulting at this site by estimating the time required to deposit the Quaternary units and form the soils that were exposed in the trenches. We discuss our age estimate for the Quaternary deposits and soil in the "Discussion and Conclusions" section of this report.

THE MARRYAT CREEK WEST TRENCH SITE

DESCRIPTION OF SURFACE RUPTURES NEAR THE SITE

The surface ruptures near the Marryat Creek West trench (MCW, pl. 2E) are composed of singular fault scarps

as much as 0.5 m high (fig. 14, pl. 2F-H) and, less commonly, closely spaced multiple fault scarps that have an irregular crenulate pattern in map view. The scarps are echelon (pl. 2E) and have a pattern and spacing similar to scarps near the Marryat Creek South trench. The scarp adjacent to the Marryat Creek West trench is 46 cm high, but the actual surface offset is greater because of monoclinial warping in the upthrown fault block. We estimated 60 cm of left-lateral slip from an offset cattle track about 100 m west of the trench. Only a few bedrock outcrops are present near the scarps in the apex area and for a distance of several kilometers to the west (pl. 2I). Two of the most prominent outcrops are adjacent to the Marryat Creek West trench (pl. 2E), and the southern end of the trench extended across the end of one of these outcrops. These outcrops, which are in the hanging wall about 10–20 m south of the scarp, are composed of fractured, sheared granite. Although we found no compelling evidence of a preexisting scarp in the modern topography, the presence of narrow, elongate outcrops of bedrock adjacent to the trench site is curious and, as we discussed, may be circumstantial evidence of prior Quaternary(?) surface rupturing on this fault.



Figure 15. Photograph showing the Marryat Creek West trench. Note the gently dipping alluvial surface at this site and the low outcrop of granite near the back of the trench. View is to the southwest. Large trees in background are growing along the creek bed shown on plate 2E.

The landscape at the Marryat Creek West trench site (fig. 15) is a smooth, gently southward sloping alluvial surface that has a subdued, slightly incised drainage pattern (pl. 2E). About 10 percent of the land surface along the trace of the surface ruptures is covered by small shrubs, tufts of grass, and sparse trees. Because the alluvial surface is not significantly dissected and projects to near the modern stream level, we suspect that is latest Pleistocene or Holocene in age. In contrast, the alluvial plain directly west and north of the Marryat Creek South trench site is about 5–7 m above stream level and thus must be older than the surface at the Marryat Creek West trench site.

STRATIGRAPHY IN THE TRENCH

The stratigraphic units in the Marryat Creek West trench consist of a 15–35-cm-thick veneer of unconsolidated (surficial) Quaternary deposits that lies on relatively solid, but sheared, altered, and fractured Proterozoic granite (figs. 16, 17). The surficial deposits at the base of the scarp are buried by a thin wedge of colluvium that has

accumulated since 1986. With time, this wedge will thicken at the expense of the unconsolidated deposits in the uplifted block.

The Quaternary deposits are divided into two units on the basis of their textural characteristics and their content of sand and lithic fragments (pl. 1B). The uppermost deposit is red eolian sand (fig. 17; unit *es*, pl. 1B) (see section on “Description of Units Exposed in the Trenches” in this report) that forms a 10–20-cm-thick blanket across the gently sloping alluvial surface at the trench site. The sand, which is well sorted (sand texture in soil nomenclature; Soil Survey Staff, 1975) and nonstratified, was probably derived from deflation of the Marryat Creek floodplain and other ephemeral streams in the area. The upper part of the sand has a very thin (about 2 cm thick) accumulation of organic matter that defines a weak A horizon (Soil Survey Staff, 1975). The presence of an A horizon (although weak) indicates that the upper part of the eolian sand has been stable for at least many decades or centuries; this age estimate is based on the sparse vegetation and the slow rate at which organic matter accumulates in arid environments.

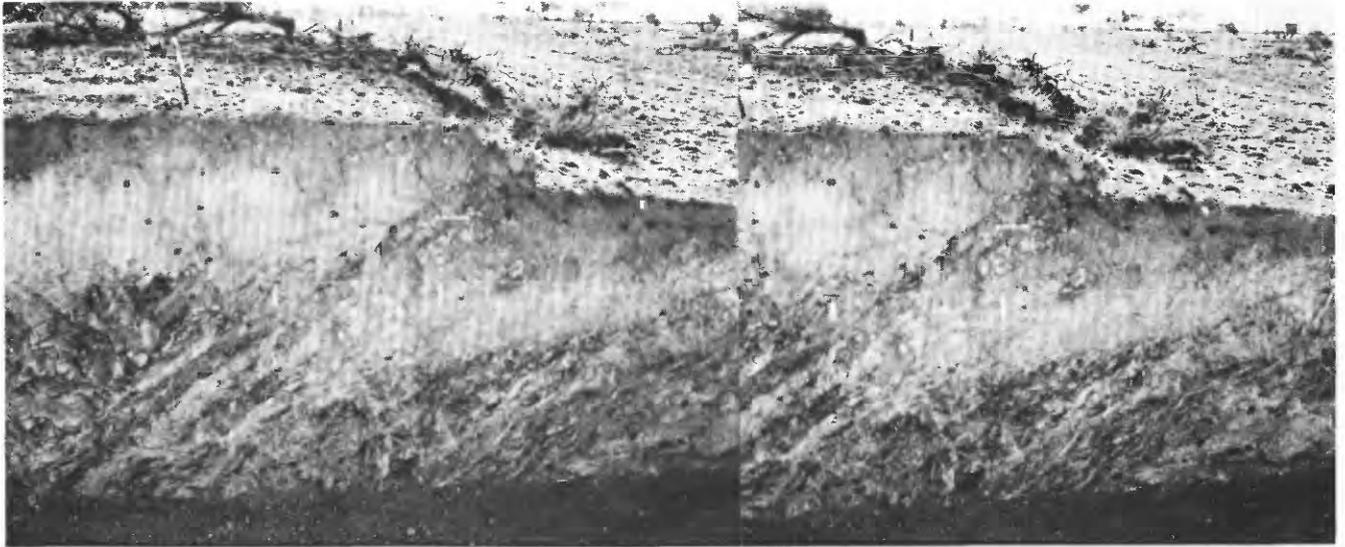


Figure 16. Stereographic photographs showing the west wall of the Marryat Creek West trench (pl. 1B). The 1986 fault intersects the land surface at the base of the fault scarp, which is 43 cm high (fig. 17, pl. 2G). The soil in the trench is not as well developed as the soil in the Marryat Creek South trench but consists of A and Bt (dark-colored) horizons over a Bsk (light-colored) horizon. The lower three-fourths of the trench is in fractured, altered, and sheared Proterozoic granite. Scale below scarp is about 18 cm long and is divided into inches above and centimeters below. Pieces of flagging along string line are 1 m apart.

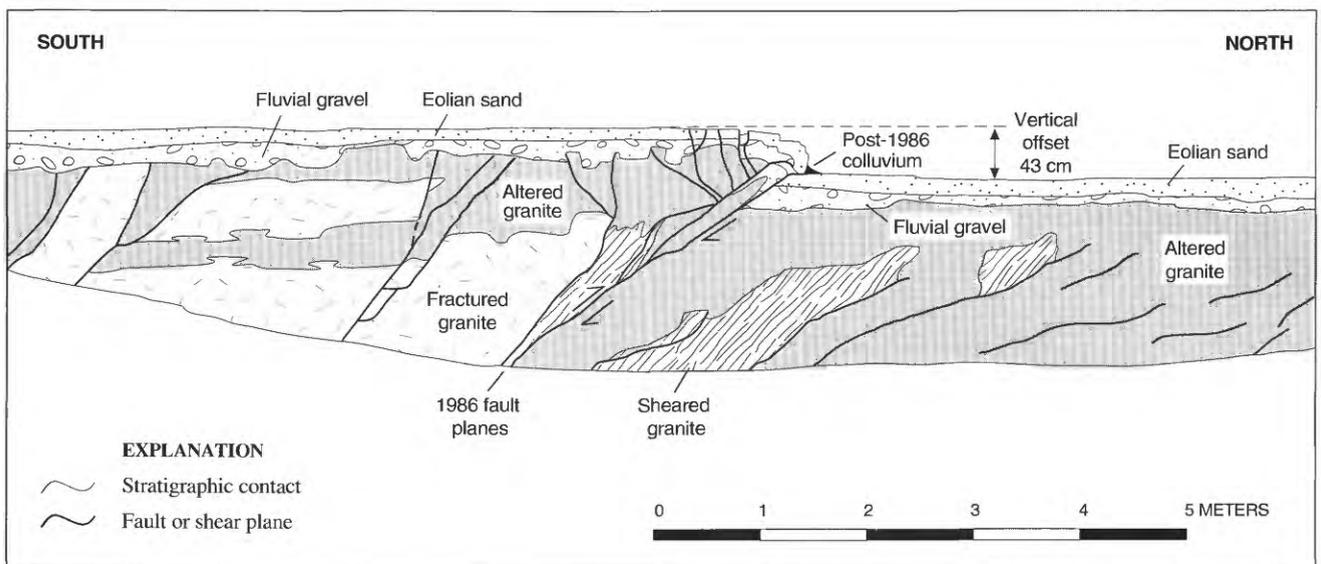


Figure 17. Simplified map of west wall of Marryat Creek West trench. Detailed description of units are in the section on "Description of Units Exposed in the Trenches." Horizontal and vertical scales are equivalent.

The lower part of the eolian sand has a clay-enriched B horizon (Bt), which is about 12 cm thick in the southern end of the trench where it was described (see section on "Description of Units Exposed in the Trenches" in this report). The Bt horizon was formed from sand that initially had little or no clay but that now has a sandy loam (+) texture (as estimated in the field). (We use the plus (+) symbol to informally indicate that the sample would plot at the high-clay end of textural field for sandy

loam.) This change in texture reflects the addition of a considerable amount of clay that was supplied either by eolian processes or by in-place weathering and clay translocation. The Bt horizon has a coarse subangular blocky structure that breaks into weak, fine subangular blocky peds. The ped structure also indicates that a significant amount of clay is present in the sand. Sand containing less than about 5 percent clay (sand texture) has massive or single-grain structure (Birkeland, 1984).

A poorly sorted and weakly stratified, sandy fluvial gravel (fig. 17; unit fgy, pl. 1B) is beneath the eolian sand. The gravel contains 60–70 percent gravel-size clasts that are typically 2–3 cm in diameter and subangular to subrounded; the clasts are composed of granite and calcrete, which suggests that they were derived from local sources. The gravel extends the length of the trench and lies unconformably on Proterozoic granite (fig. 17). The gravel is host to the basal part of the soil (Bsk horizon) that has formed in the overlying eolian sand. The Bsk horizon (14–33 cm depth where described) is a brown sandy loam (texture estimated in field). Although no clay films are apparent on sand grains or peds, the soil probably contains significant accumulations of postdepositional clay and calcium carbonate, and thus we designate it as a Bsk horizon. The carbonate has stage I (veinlets) to II (nodules) morphology (Gile and others, 1966) and forms coatings that are as much as 2 mm thick on weathered granitic clasts. The gravel (unit fgy, pl. 1B) varies in thickness from 5 to 75 cm and pinches out against granite at the south end of the trench. Although the origin of this deposit is uncertain, we suspect that it is a mixed fluvial and colluvial deposit that mantled the land surface before being buried by the eolian sand.

We suspect that the soil on the unconsolidated deposits formed during the latest Pleistocene and Holocene. This age estimate is based on the soil's moderate thickness (33 cm) and horizonation (A/Bt/Bsk), the translocation of clay and carbonate, the development of weak soil structure, and the weak morphology of the carbonate accumulations. In comparison to the soil described and analyzed in the Marryat Creek South trench, which we consider to have formed during most of the late Pleistocene (see sections on "Discussion and Conclusions" and "Description of Units Exposed in the Trenches" in this report), the soil on the faulted surface at the Marryat Creek West trench is significantly less developed.

A thin cover of unconsolidated deposits lies unconformably on Proterozoic granite in the Marryat Creek West trench (fig. 17). Because the characteristics and properties of the granite are so variable, we subdivide it into three categories (f, fresh; a, altered; s, sheared) on the basis of the degree of fracturing, shearing, and weathering (units rgf, rga, and rgs, pl. 1B) (see section on "Description of Units Exposed in the Trenches" in this report). The boundaries between some of the granitic units are defined by faults and shear zones, whereas other contacts are gradational. In some places, an unknown but significant amount of movement on these faults and shear zones has juxtaposed granites that have substantially different properties.

Near the outcrop at the south end of the trench, the fresh granite (unit rgf) retains a recognizable intrusive rock fabric. Quartz is preserved, but the feldspar and

ferromagnesian minerals are altered and oxidized. Although we describe this as fresh granite, it is soft and easily broken with a hammer. It is intensely fractured and jointed to form orthogonal joint-bounded blocks (10–20 cm dimensions). The fresh granite shown on the trench map (pl. 1B) is bounded by major shear zones, which in turn contain extensively altered granite (unit rga).

The altered granite (fig. 17; unit rga, pl. 1B) has either poorly recognizable or no recognizable intrusive-rock fabric. The feldspar and ferromagnesian minerals are completely altered to clay, but quartz grains are still preserved locally. The granite is oxidized to mottled orange and light gray brown as compared to the light-gray color of the fresh granite. The altered granite is very soft, and most fragments can be broken easily by hand. It is more densely jointed than the fresh granite, and joint-bounded blocks have maximum dimensions of about 10 cm. As a map unit, the altered granite contains numerous discrete fracture surfaces that give the rock the overall appearance of being pervasively sheared.

The most altered of the granitic units is best described as terminally altered and sheared material that resembles claystone (fig. 17; unit rgs, pl. 1B). It has no visible igneous rock fabric and little evidence of its original mineralogy; however, because of its close association with the fresh and altered granite, it is probably extremely altered granite. The areas of the trench mapped as sheared granite correspond to prominent ancient shear zones in which a combination of shearing and near-surface weathering have destroyed all of the primary rock fabric and minerals. Shear zones within and bounded by the sheared granite have a weak south-dipping fabric, much of which is highlighted by subtle color differences. This south-dipping fabric is typically subparallel to the general boundaries of the shear zones as shown on the trench map (fig. 17, pl. 1B).

STRUCTURAL FEATURES IN THE TRENCH

The fault zone that ruptured in 1986 has an apparent dip of 36° S. and a strike of 290°–295° in the Marryat Creek West trench as estimated from our mapping. The 1986 slip was confined to a narrow but conspicuous fault plane along the northern boundary of a 10–100-cm-wide ancient fault zone (fig. 18). The 1986 fault plane (pl. 1B) bifurcates upward in the trench and expands into a 15-cm-wide shear zone; differential movement occurred in 1986 along both planes that bound this zone. Near the surface, differential slip along the fault plane produced extensional fractures and cracks in the hanging wall that are present only within 1.25 m of the main scarp.

The 1986 rupture produced about 43 cm of vertical surface offset as measured from the trench map (fig. 17) and scarp profile (pl. 2G). To create a 43-cm-high scarp on a fault plane dipping 36° requires about 73 cm of



Figure 18. Closeup view of the 1986 fault planes and shear fabric in the Marryat Creek West trench. Center of photograph is at 6.05 m on the horizontal axis and 1.70 m on the vertical axis of plate 1B. The scale shows inches over centimeters and is about 18 cm long.

transport along the fault plane; however, we measured only 46–47 cm of displacement on the fault by restoring the base of the fluvial gravel (unit fg) to its formerly continuous configuration. Thus there is a 26-cm discrepancy in the dip-slip displacement from the stratigraphic restoration versus that estimated from the geometric reconstruction based on the scarp height and fault dip. Some of this discrepancy is the result of folding at the thrust front, minor compaction in the Quaternary deposits, and collapse of soil blocks, all of which would reduce the actual displacement of stratigraphic contacts. In addition, some of the discrepancy results from undulations and irregularities in the contact between the bedrock and unconsolidated deposits and contacts that dip into the walls of the trench. Finally, some of this discrepancy may be the result of an unknown amount of left-lateral slip that was clearly expressed by geomorphic relations immediately after the faulting in 1986 (McCue and other, 1987).

The initial slip in 1986 probably occurred on the basal strand of the fault zone, which transported the lowermost wedge of the modern soil on the hanging wall over the equivalent soil on the footwall. Additional movement was concentrated along the upper part of the shear zone

and thrust pieces of the Quaternary deposits over the wedge of the modern soil in the hanging wall. In the final stages of movement, gravity collapse near the nose of the overriding block produced the system of extensional fractures and fissures (pl. 1B).

OBSERVATIONS PERTINENT TO THE TIMING OF PREHISTORIC SURFACE RUPTURING

All morphologic evidence of prehistoric (Pleistocene) movement along this part of the 1986 Marryat Creek ruptures has been eroded owing to the major unconformity between the granitic rock units (units rgf, rga, and rgs) and the overlying, thin, unconsolidated surficial deposits. However, the trench exposed a 10–15-m-wide zone of pervasive shearing and alteration in the granite that is evidence of an ancient fault zone. The extreme alteration of the rocks in this fault zone is probably related to mechanical brecciation of the granite by earlier faulting. The width of the fault zone and the extent of the brecciation and alteration suggest that a significant amount of differential movement has occurred across this zone. Only selected

fault planes within this ancient fault zone were reactivated, even though the shear fabric within the entire fault zone was subparallel to the 1986 faults. Thus, the 1986 earthquake reactivated faults that probably have a long history of recurrent movement. Unfortunately, stratigraphic evidence of prehistoric movement on these faults was not preserved in the trench.

The subdued landscape along the 1986 surface ruptures indicates that the recurrence of movement on these faults during the late Cenozoic is long—probably 100,000 years or more in duration. We base this recurrence estimate on our studies in southern New Mexico where we have attempted to evaluate the preservation potential of fault scarps in arid and semiarid climates. In southern New Mexico, we estimate that 1–2-m-high fault scarps formed on unconsolidated alluvial deposits are still recognizable after about 100,000 years and that larger scarps would persist longer in the landscape before they are obscured by erosion. The climate and vegetation in southern New Mexico is similar to that of the Marryat Creek area, so we suspect that, if they existed, we could recognize meter-high scarps in the Marryat Creek area that were about 100,000 years old.

The presence of the granite outcrops in the hanging wall (upthrown) of the fault that rise almost 1 m above the surrounding low-relief terrain may be circumstantial evidence of Quaternary(?) uplift in the hanging wall. The presence of relatively fresh granite outcrops at the surface in the hanging wall suggests that this side of the fault has been elevated relative to the footwall and that deeply weathered rock has been erosionally stripped from the hanging wall. Conversely, only deeply weathered, extensively altered and sheared bedrock is preserved in the footwall block. These relations imply that the hanging wall has been periodically uplifted, whereas rock in the footwall has endured weathering for a long time. We speculate that this differential uplift would have to be Quaternary in age to keep relatively fresh granite at the surface.

DISCUSSION AND CONCLUSIONS

The Marryat Creek trenches provide ample evidence that the 1986 surface ruptures reactivated selected strands of ancient shear zones in Proterozoic crystalline rock (granite and greenstone). Offset contacts that were exposed in both trenches show that Quaternary deposits were affected only by the 1986 surface ruptures. Any prehistoric ruptures on these faults predate deposition of the Quaternary deposits, yet equivocal geomorphic relations provide circumstantial evidence of possible Quaternary(?) movement on these faults. Accordingly, the age of the oldest Quaternary deposits that were unfaulted before 1986 provides a minimum time since the penultimate surface-rupturing event on this fault.

LIMITS ON THE TIMING OF PREHISTORIC FAULTING AT MARRYAT CREEK

The stratigraphic evidence from both trenches indicates that any prior faulting along the 1986 Marryat Creek rupture zone must predate deposition of the unconsolidated Quaternary sediments. Unfortunately, this general statement offers little specific information about the minimum time of the event and thus is of limited value in characterizing the long-term activity on the Marryat Creek fault. In this section we use quantitative soils data (clay and carbonate contents) and uranium-trend data to estimate the minimum time that must have lapsed since a previous Marryat Creek-type faulting event.

In semiarid and arid regions of the world, studies of soils (pedology) and Quaternary geology have shown that calcium carbonate accumulates gradually in the soil and that this accumulation is mainly derived from airborne sources. The soil carbonate is a product of dissolution and downward translocation of Ca^{++} derived from silt- and clay-size calcium carbonate and from calcium that is dissolved in rainwater. Worldwide studies of soils in arid and semiarid areas indicate that the calcium carbonate in calcic soils is commonly supplied by calcareous airborne dust (see Machette, 1985). The amount of available calcium is dependent on, among other things, the proximity of local sources of calcium such as limestone outcrops or carbonate-rich lacustrine deposits. As a result, the rate of calcium carbonate accumulation in soils can vary greatly over a region. Near the Marryat Creek site, very little carbonate rock is exposed and the eolian sands that blanket the area are generally noncalcareous. Thus, most of the calcium that was supplied to the land surface and is now in the soils was probably brought in as airborne dust and dissolved in rainwater or it was derived from reworked calcic soil and calcrete that are part of older, nearby landscapes.

Using the laboratory data for the soil at the Marryat Creek South trench (table 6), we sum the total amounts of calcium carbonate and clay in the soil and calculate the total accumulation of these components (table 7). For carbonate at this site, we assume that it is a product of translocation of Ca^{++} derived from airborne sources (a major component) and from calcrete fragments in the gravel (a minor component). Then, we obtain the amount of secondary carbonate by subtracting the quantity of primary carbonate (minor component) from the total carbonate. Machette (1978) presented an example of this methodology. We use a similar strategy for the clay, although there are large uncertainties in estimating primary clay content because of variations in depositional environments. The amounts of secondary carbonate and clay, 13.1 g and 12.8 g, respectively (table 7), that have accumulated in the soil are a direct measure of the time since the host deposit became geomorphically stable (that is, the deposit was no longer accumulating or being significantly affected by erosion). Finally, by applying geologically determined rates

Table 7. Data and calculations for net gain of clay and calcium carbonate content in a 1-cm² column through the relict soil in the Marryat Creek South trench.

[Estimated values for the soil parent material units (cfg and fg) are shown in bold. Leader (-) indicates no value can be calculated. Values in parentheses are initial (modeled) amounts of clay and carbonate in soil parent material. These values are subtracted from weight gains reported in columns F and I to give net gain for soil. Formulas for individual columns are as follows:

$$E=(A\div 100)\times D \text{ (A is from table 6)}$$

$$H=(A\div 100)\times G$$

$$F=(B\times C\times E)\div 100$$

$$I=(B\times C\times H)\div 100$$

Sample number	Thickness of sampled layer (centimeters) (B)	Bulk density (g/cm ³) (C)	Clay content			CaCO ₃ content		
			<2 mm (percent) (D)	Total (percent) (E)	Weight (grams) (F)	<2 mm (percent) (G)	Total (percent) (H)	Weight (grams) (I)
MCS-2a.....	13	1.60 e	20	13	2.7	15	9	1.9
MCS-2b.....	15	1.65 e	24	14	3.5	21	12	3.0
MCS-2c.....	15	1.65 e	27	13	3.2	23	12	3.0
MCS-2d.....	15	1.7 e	31	19	4.8	39	16	4.1
MCS-2e.....	15	1.7 e	27	11	2.8	43	18	4.6
Unit cfg.....	73	1.65	(10)	(5)	(6.0)	(10)	(5)	(6.0)
MCS-2f.....	15	1.65 e	16	10	2.5	22	13	3.2
Unit fg.....	15	1.65	(3)	(3)	(0.7)	(6)	(3)	(0.7)
Net gain.....	-	-	-	-	12.8	-	-	13.1

of carbonate and clay accumulation in soils that have developed in similar climatic and environmental settings, we can estimate the amount of time that is required to form the soils at Marryat Creek. Although this method is fraught with uncertainties (Machette, 1978, 1985), it offers a first-order estimate of the age of the landscape at the Marryat Creek sites.

Unfortunately, there are no data on rates of soil formation in the Marryat Creek region, mainly because there have been no detailed stratigraphic studies or efforts to date the Quaternary deposits. As noted previously, the Marryat Creek region has a hot, arid to semiarid continental climate with annual rainfall of approximately 175–225 mm. Soils formed in similar climates and lithologic regimes in the southwestern part of the United States (Machette, 1985) typically have accumulated calcium carbonate at rates of 0.10–0.25 g of CaCO₃ per cm²/k.y. If this general range in accumulation rates applies to the soils at Marryat Creek, then the net gain in secondary soil carbonate (13.1 g, table 7) could be accomplished in as little as 52 k.y. (13.1 g at 0.25 g per k.y.) to as long as 131 k.y. (13.1 g at 0.10 g per k.y.). Inasmuch as the current rainfall at Marryat Creek falls in the low end of the range stated above and there is no known local source of abundant calcareous dust, the soil is probably closer to the 130-ka age estimate than the 52-ka age estimate. Furthermore, the overall degree of soil development at Marryat Creek is consistent with this age estimate. For comparison, soils with similar morphology in the Western United States commonly are pre-late Pleistocene in age (>130 ka; Birkeland, 1984; Machette, 1985). In addition, we emphasize that these estimates are probably minimum values because unconformities (such as between units fg and cfg in the Marryat Creek South trench) can represent significant gaps in time.

Attempts to date the surficial material in which this soil is formed were unsuccessful. A uranium-trend determination by D.R. Muhs (U.S. Geological Survey, Denver) yielded a geologically unrealistic age of 8±6 ka. We do not know why the soil yields such a young isotopic age, but the development of the soil in terms of horizonation, clay increase with depth, and calcium carbonate morphology all strongly favor a markedly longer residence time. No suitable material was found in either trench that could be dated by traditional dating techniques, such as radiocarbon.

Geomorphically, the general lack of topographic expression of a preexisting fault scarp in this low-relief landscape and this semiarid climate implies that recurrence of surface-rupturing earthquakes is long—probably a hundred thousand years or more. However, the arguments we present with respect to the history of faulting at the Marryat Creek West site allow some early Quaternary movement on this trace of the fault as indicated by the presence of a subdued escarpment along parts of the ruptures. Although these arguments are not compelling, the circumstantial evidence of an episode of early or middle Quaternary movement would also imply recurrence intervals that are at least a hundred thousand years or longer.

THE RECURRENCE OF SURFACE-FAULTING EARTHQUAKES IN STABLE INTRAPLATE SETTINGS

The stratigraphic and structural observations from our study provide only very broad limits on the recurrence of surface-rupturing earthquakes on the faults that ruptured during the 1986 Marryat Creek earthquake. We argue here that the recurrence of surface rupture on the faults that

slipped in 1986 is on the order of 100,000 years or more. This is consistent with the conclusion from similar studies of the 1988 Tennant Creek earthquakes in the Northern Territory of Australia (Crone and others, 1992). Based on these two studies, faults in the Australian craton that have ruptured historically have very long recurrence intervals. This observation agrees with the evidence of a long recurrence interval for surface-rupturing earthquakes on the Meers fault in southwestern Oklahoma, which is the only other fault we know of in a similar tectonic setting for which there are comparable paleoseismic data (Crone and Luza, 1990). If recurrence intervals of a hundred thousand years or more are typical of individual seismogenic faults in the stable interior of continents, then the hazard posed by damaging earthquakes on a single fault is very small compared to a human's life span. The implications of our findings with respect to seismic hazards in continental interiors are discussed in more detail by Crone and others (1992).

Geologic data on recurrent surface-faulting earthquakes in the stable interior of continental plates is very limited, in part because historic ruptures in these settings are rare. Therefore, the five surface-rupturing earthquakes in Australia during the past 25 years provide a valuable source of data. In addition to these historic ruptures, nine prehistoric fault scarps have been identified in the southern part of the Australian continent (fig. 1):

- The Lort River fault scarp near Hyden, the Mt. Narryer fault scarps, and scarps near Merredin (all in Western Australia) (Gordon and Lewis, 1980; Denham, 1988; McCue, 1990)
- The Campasp and Taurura scarps south of Cadell in Victoria (Tickell and Humphries, 1987; Don Cherry, oral commun., 1992)
- A piedmont scarp along the western base of the northern part of the Flinders Range in northeastern South Australia (Williams, 1973)
- The Roopena and Ash Reef scarps on the Eyre Peninsula, northwest of Adelaide, South Australia (Bowman and others, 1993)
- A scarp that crosses Lake Edgar in southwestern Tasmania (McCue, 1990)

Paleoseismic investigations of some of these sites could provide important additional data to refine our estimates of the frequency of occurrence of major earthquakes in the stable continental interior of Australia and other similar regions in the world. A greater understanding of the long-term activity of potentially seismogenic faults in the continental interiors will provide a more complete picture of the geological processes that cause continental crust to rupture catastrophically and ultimately will lead to improved earthquake-hazard assessments in both Australia and other so-called stable continental regions.

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DESCRIPTION OF UNITS EXPOSED IN THE TRENCHES

In the following discussion, the surficial units are classified according to the predominant grain size of the material in the deposit. For example, a deposit that contains 25 percent sand and 75 percent gravel is a sandy gravel on the basis of its overall grain size; however, the textural description of this deposit is based on the texture of the <2-mm fraction and is named and classified according to the soil terminology of the Soil Survey Staff (1975). For the preceding example of the sandy gravel, if the <2-mm fraction is composed of 25 percent clay, 25 percent silt, and 50 percent sand, then texturally this sandy gravel is classified as a sandy clay loam, and the deposit is classified as a very gravelly sandy clay loam (fig. 19). The (+) and (-) designations are informal and indicate clay-enriched and clay-depleted samples, respectively, within an individual textural class. Soil-color notations were determined by comparing soil peds to a Munsell Color Chart (Munsell Color Co., Inc., 1954) and are followed by "m" to show the color of a moist sample or by "d" to show the color of a dry sample.

MARRYAT CREEK SOUTH TRENCH

Eolian sand (unit es). Quaternary well-sorted, nonstratified, fine- to coarse-grained, subangular to subrounded sand that contains the generally noncalcareous upper part of a soil that extends to the top of Proterozoic bedrock (units ra and rf). Soil in unit es has a 2-cm-thick A horizon with weak, platy structure (table 8; not sampled) and a Bs or Bt horizon (2–17 cm depth). B horizon is red (2.5YR 4/7 m), has a loamy sand (+) to sandy loam texture (as estimated in the field), and contains less than 5 percent gravel (subangular fragments of calcrete derived from underlying deposit). The <2-mm fraction is slightly sticky and slightly plastic, has medium to fine, moderate, subangular blocky structure, and is loose to weakly friable. Sand grains have few thin clay films, none on peds; no secondary carbonate is visible, but sand is calcareous (about 15 percent CaCO₃, table 8). Lower contact is abrupt and smooth. Thickness is 17 cm, but locally as much as 20 cm. For comparison, eolian sand adjacent to the nearby stream has sand (+) texture and is red (2.5YR 4/8 d).

Colluvial and fluvial gravel (unit cfg). Quaternary poorly sorted, nonstratified, subangular to subrounded gravelly sand deposited by colluvial (slope wash and debris flow) and fluvial processes. Most of unit is matrix supported but contains minor lenses of clast-supported gravel. Most clasts are 1–2 cm in diameter

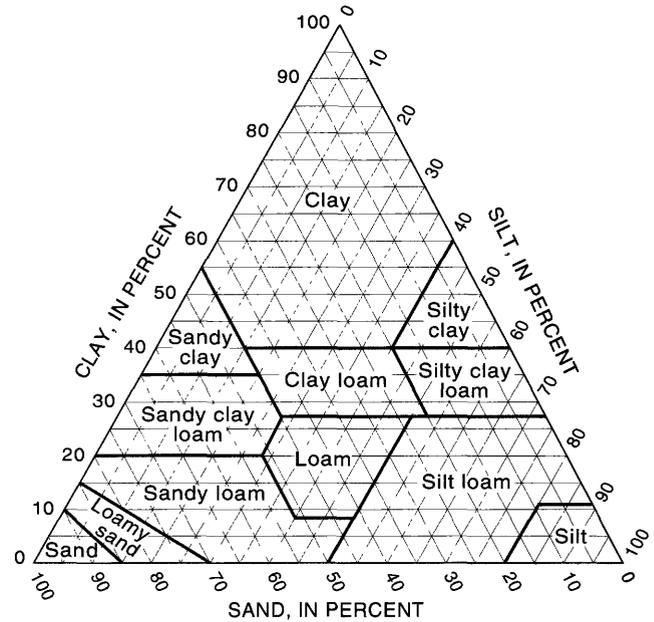


Figure 19. Grain-size distribution for textural classes (Soil Survey Staff, 1975). Sand is defined as particles between 2.0 mm and 0.05 mm in diameter, silt between 0.05 mm and 2 μ , and clay less than 2 μ .

but largest are about 20 cm. Clasts consist of carbonate-rich rock, weathered diabase(?), and grussified granite. Unit contains the medial, clayey and calcareous (Btk and Bkq horizons) part of a soil that extends from surface (in unit es) to the top of Proterozoic bedrock (units ra and rf). Thickness of gravel varies from about 5 cm to as much as 75 cm (as described here).

Btk is yellowish red (5YR 5.5/6 d), has a sandy clay loam texture (samples MCS-2b, MCS-2c, table 8), and is sticky and slightly plastic in upper 20 cm to slightly sticky and very slightly plastic in lower 20 cm. Gravel content increases from 10 percent near top (pebble size; 80 percent subangular fragments of calcrete and 20 percent angular lithic fragments) to about 50 percent (pebble size; 60 percent subangular fragments of calcrete and 40 percent angular lithic fragments). Soil structure grades downward from moderate, medium to fine, angular blocky to weak, coarse to fine, subangular blocky and single grain; soil is loose to weakly friable. Grains and peds have thin clay films and stage I carbonate (veinlets in matrix and coatings on base of clasts only) in upper part and few, very thin clay films and stage II calcium carbonate (coatings on tops and bottoms of clasts) in lower part. Lower contact is gradual and irregular. Btk horizon is about 30 cm thick.

Bkq is reddish yellow (5YR 6/6 d), has a clay loam texture (samples MCS-2d, MCS-2e, table 8), and is slightly sticky and slightly plastic. Gravel content is visually

Table 8. Particle-size data for samples from the Marryat Creek South trench.

[Sand content determined by wet sieving; silt and clay contents determined by pipette method. Iron oxides were removed with 5 percent oxalic acid heated to boiling for 2–3 hours. Calcium carbonate was removed with 10 percent HCl, and organic matter was removed with sodium hypochlorite adjusted to a pH of 9.5. Symbols: (+), high-clay end of textural field; (–), low-clay end of textural field; n.d., not determined]

Sample number	Sampling depth (centimeters)	Textural classification	Grain-size class (percent)			CaCO ₃ content (percent)
			Sand	Silt	Clay	
Not sampled (A, Bs)...	0–17	Sandy loam.....	n.d.	n.d.	n.d.	n.d.
MCS–2a (2Bt).....	17–30	Gravelly sandy clay loam (–).....	68.7	10.8	20.5	14.9
MCS–2b (2Btk1).....	30–45	Gravelly sandy clay loam.....	64.9	11.4	23.8	21.0
MCS–2c (2Btk2).....	45–60	Gravelly sandy clay loam.....	57.9	15.6	26.5	23.1
MCS–2d (2Bkq).....	60–75	Gravelly clay loam (–).....	42.1	27.3	30.6	38.9
MCS–2e (2Bkq).....	75–90	Gravelly clay loam.....	43.7	29.6	26.7	42.8
MCS–2f (3Bkm).....	90–105	Very gravelly sandy loam (+).....	68.4	15.2	16.4	21.9

estimated to be 60 percent of volume (pebble to small cobble size; 80 percent subangular fragments of calcrete and 20 percent angular lithic fragments). Soil structure is both massive (calcrete) and moderate, tabular (silcrete) to single grain in lower part. Clasts have stage II (coatings on tops and bottoms of clasts) to stage III (weakly cemented matrix) calcium carbonate morphology. Lower contact is sharp and irregular. Bkq horizon is about 30 cm thick.

Fluvial gravel (unit fg). Quaternary poorly sorted, weakly stratified, subangular to subrounded, clast-supported gravelly sand. Clasts consist of carbonate-rich rock, weathered diabase(?), and grussified granite. Gravel fills channel cut in Proterozoic bedrock (units ra and rf) that is about 50 cm deeper on north wall of trench. Fluvial gravel varies in thickness from 0 cm (outside of channel) to about 75 cm on south wall of trench and from 75 to 125 cm on north wall of trench. Where unit is thin (as at sampling locality), it contains white (5YR 8/1 d) to reddish-yellow (5YR 6/8 d) Bkm horizon (basal calcareous part of soil, samples MCS–2d, MCS–2e, table 8). Where the unit is thick, the soil extends deeper as a less concentrated and uncemented calcareous Bk horizon. Bkm horizon is about 30 cm thick, has single-grain structure and stage III calcium carbonate morphology, and is weakly cemented to moderately cemented.

Sheared rock (unit rs). Consists of altered Proterozoic greenstone (unit ra) that has been sheared by brittle deformation. Largest intact blocks of rock in the shear zone are 1–2 cm in diameter. Gross fabric of the sheared rock is parallel to the faults in the Marryat Creek South trench. Mapped as a separate unit between the two fault planes that were activated in the 1986 earthquake.

Altered rock (unit ra). Proterozoic greenstone, lacks original fabric, is extensively altered and sheared into a light-greenish-gray clay, and contains abundant quartz veins. Upper 20–25 cm of altered rock is oxidized. Also contains irregular-shaped masses and veins of microcrystalline calcium carbonate. Carbon-

ate veins are concentrated near the top of the unit and are aligned along near-vertical fractures, which indicate that carbonate was translocated from carbonate-rich clasts in overlying surficial deposits. Quartz veins are aligned with west-dipping shear fabric that parallels the modern fault zone (pl. 1A) and is clearly a pre-1986 feature. Below the upper 20–25 cm, the prominent oxidation is mainly confined to old shears that are occupied by roots. Thin zones of gougelike material are present along shears within unit ra or between units ra and rf. This material commonly consists of oxidized, red (2.5YR 4/8 d) to yellowish-red (5YR 5/8 d), fine-grained sand (sandy loam to sandy clay loam texture) that contains less than 5 percent lithic (greenstone) fragments. The similarity in color and texture of the gouge and the Bt horizon above suggest that the material in the shear zones may be soil that filled ancient channels and tubes that were formed by tree and shrub roots. If so, then the filling is substantially younger than the shear zone it occupies. Thickness of the altered greenstone is unknown, base is covered.

Rock (unit rf). Proterozoic greenstone, fractured and broken into roughly equidimensional blocks that are commonly 10–15 cm on a side, except adjacent to major faults or shear zones where they are typically 2–3 cm on a side. Freshest greenstone contains wispy lenses and seams of quartz (0.1 mm wide) that are common along northwest-striking (310°) planes that dip 25° S., subparallel to the modern fault zone.

MARRYAT CREEK WEST TRENCH

Eolian sand (unit es). Quaternary well-sorted, nonstratified, fine- to coarse-grained, subangular to subrounded sand that contains the generally noncalcareous upper part of a soil that extends down to the top of Proterozoic bedrock (units rga, rgf, and rgs). About 10 percent of the land surface is vegetated by small shrubs, tufts of grass, and sparse trees

(1 percent of the land surface). Where described, the soil in unit **es** has a 2-cm-thick A horizon and a 12-cm-thick Bt horizon. The A horizon is a reddish-brown (mottled 5YR 4/2 to 5YR 5/6 d) loamy sand that has weak platy structure and a sharp smooth lower boundary. The Bt horizon (2–14 cm depth) is a reddish-yellow (5YR 5.5/6 d; 5YR 4/6 m) sandy loam (+) (as estimated in the field) and contains less than 5 percent gravel (subangular 1–2-cm fragments of calcrete derived from underlying deposit). The <2-mm fraction is slightly sticky and very slightly plastic, has moderate, coarse subangular blocky structure that breaks to weak, fine subangular blocky structure, and is loose to weakly friable. Sand grains and root tubes commonly have thin clay films, but peds do not. Lower contact is diffuse and smooth. Unit is commonly 10–20 cm thick. For comparison, the young eolian sand that is derived from nearby stream beds has sand (+) texture and is red (2.5YR 4/8 d).

Young fluvial(?) gravel (unit **fgy**). Quaternary poorly sorted and weakly stratified, fine- to coarse-grained, subangular to subrounded very gravelly sand that contains a Bsk horizon. Bsk horizon (14–33 cm depth) is a brown (7.5YR 4.5/6 m) to strong brown (7.5YR 5/6 d) sandy loam (as estimated in the field) and contains 60–70 percent gravel (subangular 2–3-cm-diameter fragments of granite and calcrete). The <2-mm fraction is slightly sticky and very slightly plastic, has moderate, coarse subangular blocky structure that breaks to weak, fine subangular blocky structure, and is loose to weakly friable. No clay films are apparent on sand grains or peds. Carbonate has stage I–II morphology and forms <2-mm-thick coats on clasts of weathered granite. Lower contact is sharp, but irregular. Thickness is commonly 15 cm but ranges from 5 to 30 cm.

Sheared granitic rock (unit **rgs**). Proterozoic granite having partly recognizable granitic fabric and mineralogy. Quartz grains are generally recognizable, but

feldspar and ferromagnesian minerals are completely altered to light-greenish-gray clay. Most of rock displays shear fabric and patterns of alternating orange and gray brown. In most intensely sheared parts, recognizable blocks of unit **rgs** are angular to subrounded and commonly 2–5 cm in size (10 cm maximum). Unit is mainly along modern fault plane or along shear planes to the north in trench.

Pervasively altered granitic rock (unit **rga**). Proterozoic granite having no vestiges of original fabric or mineralogy; extensively altered and sheared into light-greenish-gray clay. Granitic protolith inferred from its gradation to fresher granite (unit **rgf**) and from inclusion of about 5 percent of sheared granitic rock (unit **rgs**). Masses of unit **rga** define ancient shear zones in which the combination of shearing and near-surface weathering have effectively destroyed the original fabric and mineralogy of the rock. Oxidation in the altered granitic rock produces a mottled orange and gray-brown appearance. Most of unit displays shear fabric and patterns of coloration that are roughly parallel to modern fault planes (shallow south dipping). Blocks of rock are very soft and can be broken by hand. Unit is mainly along major shear planes and within the footwall block of the fault.

Fractured granitic rock (unit **rgf**). Proterozoic granite having recognizable fabric and mineralogy. Quartz is fresh, but feldspar and ferromagnesian minerals are partially altered. Rock is soft and is easily broken with a hammer. Commonly contains small microfractures filled with clay. About 25 percent of rock has fractures and joints that are filled by 1–3-cm-thick veins of secondary silica. As a whole, the unit is intensely fractured and jointed to form orthogonal blocks having maximum dimensions of 10–20 cm, and blocks of this rock are commonly bounded by major shear or fault zones that contain altered or sheared rock (unit **rga** or **rgs**). Exposure of unit is restricted to footwall of fault in trench.

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