6

Archaeoseismology

Shaking Out the History of Humans and Earthquakes

JAY STRATTON NOLLER

1. Using Archaeology to Solve a Paleoseismic Problem

Intuitively, archaeology and geology should be used together to address one of the common and deadly natural hazards—earthquakes. Yet, until recently, the twain did not meet on even ground, and then not always as successful joint ventures (see commentaries of Karcz and Kafri, 1978, 1981; Stiros, 1988; Guidoboni, 1996). Avenues of investigation of earthquakes lie within a continuum between historical archaeology and seismology for 19th and 20th century earthquakes and between archaeology and geology/paleoseismology for earlier events (Pavlides, 1996). Any one of these disciplines may look at the same event with a different view and purpose. What the body of literature reveals is that multidisciplinary studies are rare until the 1990s.

Earthquakes, like related natural hazards, are phenomena that occasionally interrupt the flow of society by changing topography, altering resource availability, damaging structures, and taking lives. A number of these events have been described as significant points of departure for societal change (e.g., Soren, 1966; Armijo et al., 1991; Nur, 1998). Perhaps the best known of these is the 1755 Lisbon Earthquake that is widely credited as making a mark on European history

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and thought (e.g., Voltaire, 1759) by precipitating the end of the Age of Enlightenment.

Much of the early work involving the archaeological investigation of earthquakes and their damaging effects was that of explaining the direction of toppling of columns, collapse of structures, and deformation of architecture. Inherent strengths and weaknesses of this approach are easy to see (Rapp, 1986; Stiros, 1988). Unfortunately, early studies did not follow supportable interpretations and relied instead on drama or conjecture (Guidoboni, 1996). Yet despite recent advances in the field this tradition seems to continue.

New insights are being obtained through interdisciplinary study of the source of a damaging earthquake, the accompanying seismically disturbed structures and materials of human construction, and the effects on society. Here not only are answers about the cause of building destruction answered, but also the entire human picture of a natural disaster can be set within the context of a natural (geologic) event. The archaeological record, with its remnants of durable materials and anthropogenic strata, provides the human context for information that, when analyzed with the geologic record, ultimately is of direct relevance to modern society. Better models of earthquake activity and impacts are thus described.

Tectonically active regions provide unique niches for human occupation and food resources (King et al., 1994; Noller and Lightfoot, 1997). Active faults and folds impede and hence alter the flow of surface and ground water. Fault scarps locally dam rivers and form lakes providing long-lived lacustrine and related habitats for life (Sangawa, 1989). The accumulation of sedimentary deposits adjacent to faults and in tectonic depressions, along with development of soils thereon, leads to enhanced, and in some areas unique, floral and faunal communities (King et al., 1994). Thus, it is not surprising that we find occupation sites, especially for nonagrarian societies, along fault scarps and other tectonic landforms.

This chapter is not meant to be a thorough review of the field now commonly referred to as "archaeoseismology." Rather, it provides a view of studies that in one fashion or another have set out to purposefully study the parameters of historic and prehistoric earthquakes, the primary pursuit of the field of paleoseismology, through the use of archaeology. The study of destruction levels in archaeological excavations has been an important and significant starting point for most "mainstream" archaeoseismic studies, and the literature on this subject is voluminous. The reader interested in such works is encouraged to refer to the compilation of Stiros and Jones (1996), as much of that body of literature will not be covered here.

2. Approaches and Results of Archaeoseismology

There is no unique approach to applying archaeology and geology in an archaeoseismic study. The toolbox of approaches is large due to the wide range of potential archaeologic and geologic settings across the globe. Also, the spectrum of expertise that can be drawn into such a study adds further latitude in approach. As Guidoboni (1996) pointed out, a successful archaeoseismic study is one in which many disciplines, including archaeology, geology, seismology, and civil engineering participate throughout the investigation. The approach should be designed to answer, in the simplest sense, questions of earthquake dimension: "When?" "What happened?" "Where?" and "How big?" The goal should be to quantify the parameters that are part of a seismic hazard assessment, including the date of the most recent earthquake or time elapsed since the last event, timing of earlier earthquakes, sense (relative direction) of fault slip, maximum displacement, average displacement, surface rupture length, fault slip rate (creep, co-seismic), earthquake recurrence interval, location of past earthquakes (epicenter), and maximum credible earthquake (McCalpin, 1996).

The study of human history has richly increased our understanding of the magnitude and location of past earthquakes (Lee et al., 1988). Typically, workers develop paleointensity maps that show the distribution of known or interpreted seismic damage. The centroid of the mapped seismic zones is taken as the estimate of the earthquake epicenter. The maximum intensity and distribution of intensity are useful for estimating the magnitude and other parameters of earthquakes (Ambraseys, 1996). Much of the current literature in archaeoseismology addresses these two basic questions. These important foci of archaeoseismology require little in the way of earth science study, and hence, as stated earlier, this chapter does not cover these.

Since the early 1990s studies have shown that archaeology can be used to reveal the activity of a fault, including the chronology of earthquake events or tectonic activity, the amount and direction of surface deformation, and the recurrence of events (Table 6.1). In answering questions related to these three, ancillary information relevant to the location of epicentral areas and event magnitude may arise (Table 6.1). The following sections address three of the basic questions of archaeoseismology and focus on the importance, manner of approach, and history of each. Finally, a case study is detailed that provides data for the important western boundary fault of the San Andreas fault system, the San Gregorio fault. As presented by these examples, important seismic hazard assessment parameters can be quantified by a single archaeoseismic study.

2.1. When Did the Earthquake Occur?

2.1.1. Dating an Earthquake

Establishing the age of an earthquake is one very important contribution that archaeology can make. Natural catastrophes, such as earthquakes and floods, are commonly recorded as they have widespread impact on society. The documentation of these catastrophes as markers in human history has the unintended benefit of being a rich record of earthquake events that have been mined by seismologists (e.g., Ambraseys, 1996). But such records do not extend far back in time and the limit of what is "historical" is not everywhere the same. It is important then to make the distinction between a "historical" earthquake and a

Table 6.1. Use of Archaeology in Paleoseismic Settings around the World

Paleoseismic setting	Archaeological setting	Uses[a]	Event age(s)	References
Faults				
Strike-slip				
Dead Sea Transform, Israel	Offset Umayid house (?)	C		Reches and Hoexter, 1981
	Offset Crusader castle	CD	Dawn, May 20, 1202	Marco et al., 1997; Ellenblum et al., 1998
Dead Sea Transform, Jordan	Offset Islamic city walls	C	A.D. 1068	Whitcomb, 1994
	Offset Roman reservoir	C	A.D. 363	T. Niemi, pers. comm., 1999
San Andreas Fault, USA	Offset occupation site	CDR	5+ in last 2,000 years	Noller et al., 1992; Noller and Lightfoot, 1997
San Gregorio Fault, USA	Offset occupation site	CDM	A.D. 620–A.D. 1400	Noller et al., 1995; Simpson et al., 1997; this chapter
Normal				
Hongguozigou Faults, China	Offset Great Wall of China	CDLM	A.D. 1739	Zhang et al., 1986
Weihe Basin, China	Offset artifact-bearing deposits	CDR	2000 B.C.–A.D. 1556	Zhang et al., 1995
Arima-Takatsuki Fault, Japan	Sheared occupation site	CL	3 B.C.–A.D .3	Umeda et al.,1984
Amorgos Island, Greece	Submerged architecture	C	Post-Roman	Stiros et al., 1994
Korinth Fault, Greece	Submerged port	CDLM	A.D. 400 (1 of 3 since A.D. 100)	Scranton et al., 1978; Noller et al., 1997
Kyparissi, Greece	Deformed (faulted) stoa	CLD	520 B.C.	Stiros, 1988
Sparta Fault, Greece	Written accounts	DMR	464 B.C.	Armijo et al., 1991
Coastal faults, Israel	Offset and submerged Roman port moles	CL	Unknown number	Mart and Perecman, 1996
Egna, Italy	Offset Roman villa	CD	2500 B.C.–«A.D. 100; A.D.200	Galadini and Galli, 1999
Fucino, Italy	Artifact-bearing strata	C	>A.D. 6	Michetti et al., 1996
Hierapolis Fault, Turkey	Offset Roman and Byzantine structures	CDLM	Two post-Roman	Hancock and Altunel, 1997
Thrust				
Reelfoot Fault, USA	Artifact scatter	C	pre-800–1000 A.D.	Kelson et al., 1996
Folds				
Epirus, Greece	Occupation sites, rock shelters	D	Paleolithic (200–10 ka)	King et al., 1994

Coseismic Deformation				
Ground Motion				
Global	Damaged architecture, etc.	CLMR	Various	Mainstream archaeoseismology. For a review see Stiros and Jones, 1996
Liquefaction				
New Brunswick, Canada	Disrupted occupation sites	CL	A.D. 1500–1800	Broster et al., 1993
New Madrid Seismic Zone, USA	Disrupted occupation sites	CLMR	4 in last 6,000 years	Saucier, 1991; Tuttle and Schweig, 1995, 1996; Tuttle et al., 1996, 1999a,b
Wabash Valley, USA	Artifact-bearing strata	C		Munson et al., 1992
Tsunami				
Cascadia Subduction Zone, USA	Buried occupation sites, oral tradition	C	17th century A.D.	G. Carter, pers. comm., 1992; J. Stein, pers. comm., 1995
Landlevel Change				
Cascadia Subduction Zone, Canada	Occupation site	CD.	B.C. 1500; <A.D. 1100	Reinhardt et al., 1996
Korinthia, Greece	Harbors, marine facilities, quarries	CD	Various, Unknown	Vita Finzi and King, 1985; Flemming and Webb, 1996; Stiros, 1988; Stiros and Pirazzoli, 1995; Pirazolli et al., 1996; Noller et al., in prep.; Papageorgiou and Stiros, 1996; Stiros et al., 1996
Larrisa Plain, Greece	Settlement patterns, written accounts	D	Various, Unknown	Demitrack, 1986; Caputo et al., 1994
Lokris, Greece	Submerged occupation site	D	2 in last 4,000 years	Ganas and Buck, 1998
Aleutian Islands, USA	Occupation sites	CD	Holocene	Winslow and Johnson, 1989
Cascadia, Subduction Zone, USA	Occupation sites, fish weirs	CD	post 410–720 A.D.	Grant and Minor, 1991
Coastal Maine, USA	Occupation sites	D	Holocene	Anderson et al., 1984

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[a] The listed studies apply archaeology principally (C) to derive the chronology of earthquake events or tectonic activity; (D) as an indicator of pre- syn- and/or postseismic deformation; (L) to locate event; (M) to estimate intensity and/or magnitude of an earthquake; (R) to estimate recurrence of events.

"paleoearthquake." Historical earthquakes are those events observed and recorded in a written, carved, or crafted work or by oral history, tradition, or legend. Archaeologists, as well as historians, philologists, and ethnographers, use ancient sources, oral histories, and legends to determine the decade, year, month, day, or time of day of a cultural event (Stiros and Jones, 1996). Paleoearthquakes have no such (at least remaining) human testimonial, thus requiring study of the geological and/or archaeological record and a reliance on a less certain dating scheme.

An interesting study that integrated oral history with paleoseismology is that of G. Carter (Personal Communication., 1992). In this study they used radiocarbon-dated leaves in a tsunami deposit to date the ca. 1700 A.D. Cascadia subduction zone event. An oral tradition of a giant wave (tsunami) that arrived during an autumn's full moon allowed them to reach a subannual estimate of the age. Such a cultural tie would make this a historical earthquake. Although the exact calendar year was not obtained with their data, the study does illustrate how study of a natural hazard of great social importance can strengthen its human context.

Archaeological survey and excavation can reveal earthquake histories through the study of destruction levels and other architectural damage, sites* buried by co-seismic deposits, sites disturbed by faults (see case study that follows), sites disturbed by other types of surface deformation, or features constructed or inscribed to commemorate an earthquake. In these contexts, seismically disturbed archaeological structures, materials, and deposits constrain the maximum age for the event. Overlying postevent structures and strata provide a minimum age constraint. Features produced during the event are of natural construction, such as fault scarps and sand blows, but these have been difficult to date until recently (Noller and Forman, 1998; Zreda and Noller, 1998). Because an earthquake occurs so suddenly and lasts for only a matter of seconds, for anyone to create a record while it occurs would be extremely rare. Rather, the creation of a cultural feature marking the event occurs subsequently, such as the inscription of stiles in China (Lin and Wu, 1993).

Dating of archaeological materials and deposits is carried out by methods familiar to geologists (e.g., thermoluminescence; Noller et al., 2000) and those exclusively within the realm of archaeologists (e.g., seriation of sculpture, ceramics/pottery, and stone tools; Aitken, 1990) (Table 6.2). Geochronologic results can be expressed as sidereal (e.g. 324 B.C. May 20, 1270), numerical (e.g., cal. ^{14}C 1250 ± 40), calibrated (e.g., aminozone 2), and correlative (e.g., marine oxygen isotope stage 3) (Noller et al., 2000). The best dating methods for archaeoseismology are those providing sidereal results, followed by radiocarbon (the "workhorse" dating method for paleoseismology) and its numerical results, other methods providing numerical results, and methods with calibrated results (e.g., ceramic/pottery). Other methods will generally provide useful results, with specific circumstances making some equal in accuracy to those just listed. At present, sidereal results are useful to no less than one year, the smallest unit of time measure used for events in seismic hazard assessment (SHA). Any further

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**Site* is informally used here as a place of cultural reference, whether an occupation site, a place of special interest, or a concentration of human deposits

Table 6.2. Geochronological Methods for Use in Archaeoseismology

TYPE OF RESULTS

≡≡≡NUMERICAL-AGE≡≡≡≡≡≡≡≡≡≡≡≡[a]--

--------------------≡≡≡Calibrated-Age≡≡≡≡≡≡≡≡[a]--------------------

--------------------≡≡≡Relative-Age≡≡≡≡≡≡≡≡[a]--------------------

--≡Correlated-Age≡[a]

TYPE OF METHOD

Sidereal	Isotopic	Radiogenic	Chemical and biologic	Geomorphic	Correlation
Historical records *Dendrochronology* Sclerochronology and other annual growth in other organisms (e.g., mollusks)	*Radiocarbon* Cosmogenic isotopes ^{36}Cl, ^{10}Be, ^{26}Al, ^{14}C, ^{3}He, and others[b] Uranium-series ^{210}Pb	Thermoluminescence Optically stimulated luminescence Infrared stimulated luminescence Electron-spin resonance	*Obsidian hydration* and tephra hydration *Lichenometry* Amino-acid racemization Soil chemistry	*Soil-profile development* Rock and mineral weathering *Scarp morphology* and progressive landform modification Rock-varnish development Rate of deposition Rate of deformation Geomorphic position	*Archaeology* *Stratigraphy* Tephrochronology Paleomagnetism Climatic correlation

[a] Triple-dashed line indicates the type of result most commonly produced by the methods below it; single-dashed line indicates the type of result less commonly produced by the methods below it.

[b] Some cosmogenic methods, particularly exposure ages, have some similarities with methods in the "Radiogenic" column.

Note: Methods in italics are discussed in this chapter. This table is based on that in Noller et al. (2000).

refinement in age, such as season, month, or second, might find use in future SHAs.

An age estimate is only as good as the context from which it is derived (Noller et al., 2000). Context in archaeoseismology is provided through Quaternary geologic and archaeological stratigraphy. These branches of stratigraphy significantly differ from what most geologists practice because so much of the record is still active or present at the surface (Morrison, 1991) or acted on by cultural processes (Harris, 1989). Morphostratigraphy, allostratigraphy, pedostratigraphy, ethnostratigraphy, and other means of keeping account of the relationships of deposits, surfaces, intrusions, event horizons, and other stratigraphic units are integral to this field of study. The Harris Matrix (Harris, 1989) in use by archaeologists parallels that used by paleoseismologists in developing event stratigraphies, an important part in assigning ages to paleoearthquakes.

2.1.2. Case Studies

All archaeoseismic studies contribute age control in one form or another on earthquake or tectonic activity. Worldwide, finding a seismically disturbed archaeological site probably means it was a Holocene earthquake. Such a generality is based on the global rise of civilizations in the past ca. 7,000 years and the dramatic increase in human population of the past several centuries. In the latest Holocene we find more people living in seismically active regions, along with the development of complex societies came the development of more artifacts unique to a specific period of human history. Hence the utility of archaeology in establishing the date of an event, especially in the historic past and during periods of high social order and trade.

In most published accounts, archaeology has only provided *ante quem* or *post quem* constraints on an earthquake. I believe that this is not because of our inability to closely constrain age, but is rather an artifact of a discipline in its early stages of development. Prior to the advent of recent developments in paleoseismology, archaeoseismology was more an accidental type of study involving the geologist as consultant after excavation has removed some of the vital context to reveal a potentially seismogenic feature (Rapp, 1986). However, even purposefully setting out to study an archaeological site that lies across a fault does not necessarily guarantee the result of a well-constrained event age. For example, small (<100 m^2), discrete lithic scatters along the San Andreas fault at Fort Ross typically only provide a maximum age for a series of the last two to five earthquakes. In another example, activity on the Hierapolis fault, Turkey, is constrained only by faulted Roman-era structures (Hancock and Altunel, 1997). The lack of an historical record of an event on the Hierapolis fault leaves us with an uncertain minimum age on the youngest of these surface-rupturing events.

The most commonly sought-after use of archaeology for dating an event involves an earthquake feature in direct context with an artifact of well-defined age. Stained-glass windows, still propped against the walls of the basilica in which they were to be placed, were submerged by an earthquake on the Korinth fault in A.D. 400 (Noller et al., 1997). These impressive art pieces and other artifacts found at Kenchreai, Greece, provide the fix of a firm age on the earthquake.

Locally, archaeological materials may only provide an *ante quem* age estimate. In the epicentral zone of the 1940 Khait earthquake, pottery sherds provide information on the maximum age of gravitational collapse of a fault scarp (Nikonov, 1995). In this study a single collapse debris (colluvial wedge?) deposit is interpreted to represent one (scarp-producing) event. Sherds of the 6th to 8th centuries A.D. are present in a widespread debris layer at the base of the scarp. Locally overlying this is a soil with a 16th century A.D. radiocarbon age estimate. Lichenometry and dendrochronology provide additional lines of evidence for the timing of these three most recent events (Nikonov, 1995).

Ground cracks formed in a residential site during an earthquake on the Arima–Takatsuki fault, Japan, and were infilled with artifacts of Yayoi age (3 B.C.–3 A.D.) (Umeda et al., 1984). Such cracks are unlikely to stay open for more than a few weeks or months, hence the Yayoi age (3B.C.–3A.D.) artifacts establish the age of the event. This age estimate is further constrained by an overlying undisturbed occupation horizon of Yayoi Age. Age of this event may be reported as 2000 ± 300 yr BP, so long as the age of the archaeological period is well constrained and accepted. Otherwise, only the period name (in this case Yayoi Age) should be used as that conveys more of the information on age that is based on seriation of cultural materials.

Liquefaction features are one of the most prevalent and telling lines of evidence of paleoearthquakes. Archaeology has found an important place in the study of liquefaction features produced during earthquakes in relatively stable intraplate tectonic settings, where rate of landscape change typically outpaces that of tectonic deformation (Obermeier et al., 1990). Locating archaeological sites in Holocene water-lain deposits is a successful means of identifying liquefaction-producing earthquakes (Sangawa, 1989; Saucier, 1991). Not only do occupation horizons provide evidence for the age of an event (e.g., Broster et al., 1993), it is argued that they actually set up conditions favorable for the formation of liquefaction features (Saucier, 1991; Tuttle and Schweig, 1995, 1996; Tuttle et al., 1999a, b). The compactness of archaeological deposits and floors leads to greater overpressure in seismically accelerated saturated sand, causing it to liquefy and form dikes, sills, and blows. Areas surrounding an archaeological deposit are less likely to develop the overpressured conditions necessary for liquefaction to occur. It is not surprising then that some of the reported occurrences of paleoliquefaction in intraplate settings have an archaeological context. Examples of these include the Wabash Valley seismic zone of Indiana (Munson et al., 1992) and the maritime provinces of Canada (Broster et al., 1993).

Ages of liquefaction-producing earthquakes are constrained using intercalated blow sands and archaeological deposits revealed in archaeological excavations. The occupation horizon is assumed to be exposed at the surface when the earthquake occurs, leaving the site buried beneath erupted sand blow deposits. Artifacts and other datable material within the occupation horizons provide maximum age estimates for the liquefaction feature present above, and minimum age constraints for a feature present below. Four such events were revealed in excavations at three sites near Osaka and Lake Biwa, Japan (Sangawa, 1989, Fig. 6.1). In the epicentral area of the major destructive earthquakes of the

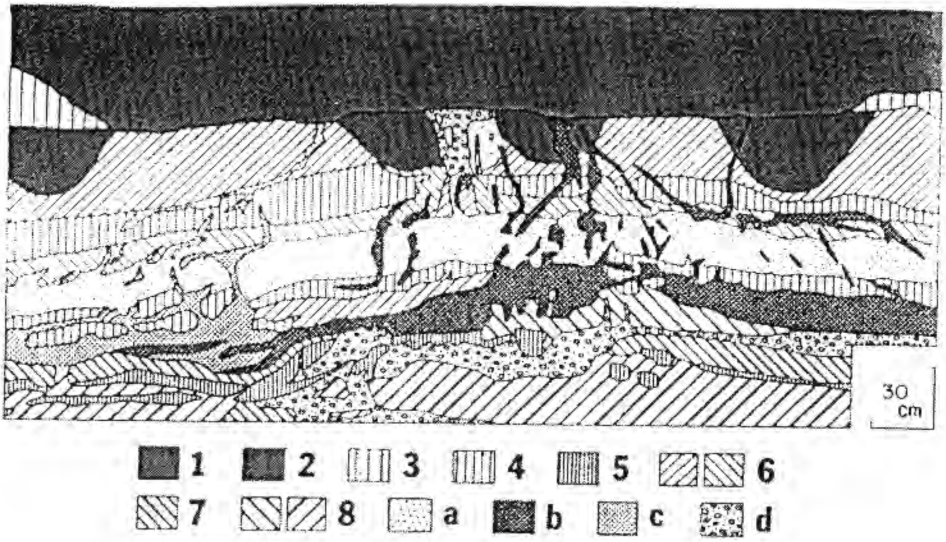


Figure 6.1. Log of excavation wall through archaeological deposits and liquefaction features of four paleoearthquakes. The exposed section is composed of archaeological or artifact-bearing deposits 1–6, and natural deposits 7–8. Events in chronological order are a, b, c, and d. From Sangawa (1989; used with permission of the Quaternary Association of Japan).

1811–1812 New Madrid earthquakes, four events are constrained by archaeological materials and occupation horizons (Tuttle and Schweig, 1995, 1996; Tuttle et al., 1999b).

2.2. What Did the Earthquake Do?

2.2.1. Quantifying Surface Effects

Deformation of the earth's surface occurs as a result of a moderate- to large-magnitude earthquake. Fault slip at depth in the Earth's crust is well represented, although not fully, by surface deformation (Yeats et al., 1996). Rupture on a fault during a >M5 earthquake may be directly or primarily expressed by a fault scarp. Surface deformation may also be indirectly or secondarily produced by processes (e.g., slope failure) accelerated by the earthquake. An important pursuit of paleoseismology is the measurement of the amount, distribution, and short-term and long-term rates of fault slip at the surface because earthquake magnitude and amount of surface deformation are strongly correlated (Wells and Coppersmith, 1994). Even though earthquakes occur at great depth (typically >10 km), the amount of slip at the earthquake focus is well represented (50% or more of it in many cases) by fault slip at the surface (Yeats et al., 1996). Hence, measuring displacement of architecture can provide a good approximation of the energy release and character of an ancient damaging earthquake.

The study of fault displacement using archaeology is outlined by Noller and Lightfoot (1997). This approach applies archaeological and geological stratigraphy within a paleoseismic study. Importantly, the use of a cultural strain marker or "piercing feature" of human production (e.g., wall) can produce equal or better results than the use of a natural feature (e.g., stream; cf. Grant and Sieh, 1994). An important component of applying this approach is in understanding how archaeological deposits will change shape, size, and spatial structure where offset by an active fault. Case studies in which cultural piercing features and other archaeological evidence figured heavily in study results are presented in Section 2.2.3.

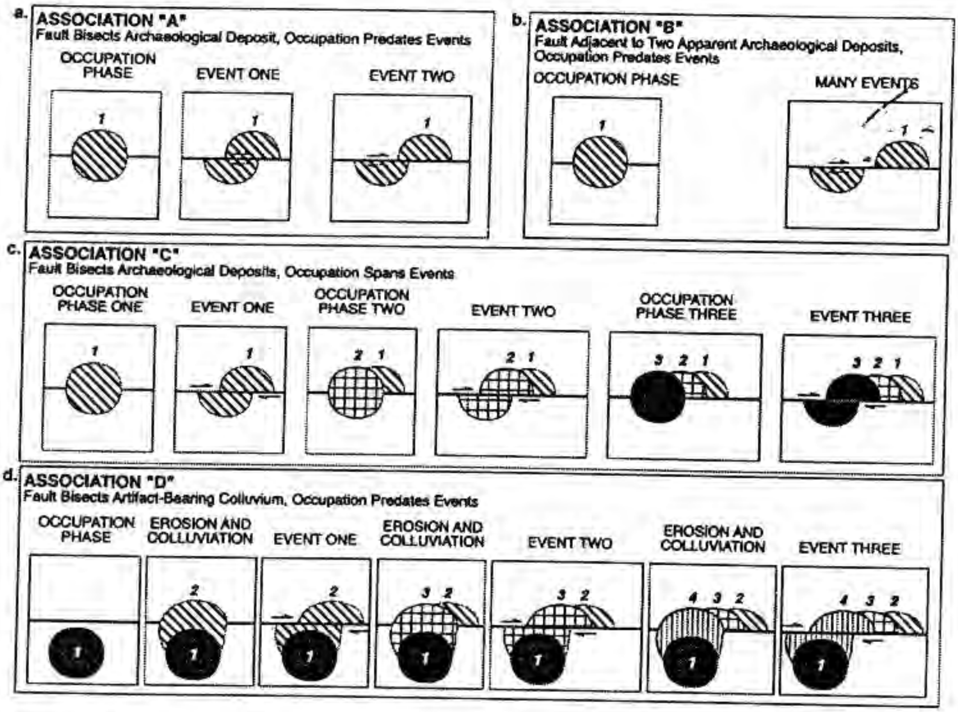
The piercing feature is a key concept in assessing the cumulative amount and rate of slip on a fault. In standard paleoseismic practice, a piercing feature is a datable linear geologic unit or its boundary, such as a stream channel (e.g., Grant and Sieh, 1994), that crosses a fault. The rate of slip on a fault is estimated by measuring the distance over which a piercing feature is displaced during a measurable period of time between two earthquake events. This measured period may include more than one event, hence the resultant amount and rate of slip are considered cumulative and mean, respectively.

Employing archaeological deposits to define cultural piercing features has several advantages. First, archaeological deposits may contain discrete linear, planar, or three-dimensional features, such as site boundaries, cultural lenses, or architectural structures, that may be used to measure offset along faults and the rate of displacement. For example, a wall, a house depression, or the outer margin of an artifact scatter that is offset by a fault may be a cultural piercing feature. Second, cultural piercing features may contain archaeological materials that can be directly dated. For example, unlike most geologic deposits, archaeological deposits may be dated by other methods, including obsidian hydration, written and oral histories, and archaeomagnetism. Artifact seriation may be well known and provide reasonable time constraints prior to obtaining numerical age estimates. Finally, the vertical and horizontal stratigraphy of cultural piercing features may be used to reveal complex fault histories.

2.2.2. Tectonic Reshaping of an Archaeological Site

The size and shape of the postearthquake archaeological site will depend on the (1) type of underlying fault; (2) the initial spatial configuration of the human settlement when it was occupied; and (3) the timing and slip of the earthquake starting with the time of the settlement's occupation. In tectonic zones characterized by strike-slip faults, one expects archaeological deposits to be displaced laterally during earthquake events. Along normal faults, deposits are exposed to erosion on one side of the fault and partially or wholly buried on the other. The fate of a site overlying a thrust fault depends on the surface and near-surface expression of the fault. In Quaternary basins, thrust faults commonly do not propagate to the surface. Instead they end at depth (e.g., >1 km) within the core of an anticlinal fold, and because of this character are referred to as "blind thrusts" (Lettis et al., 1997). Hence, a site astride a thrust fault may (1) not experience any deformation, other than change in elevation; (2) be deformed as the hanging wall (upper) block folds and/or ruptures; or (3) be eroded from the overriding block and tectonically and depositionally buried on the footwall (lower) block. To date, many examples of these tectonic settings have been studied, except for cases 1 and 3 of thrust faults (Table 6.1).

Strike-slip faults appear to present the most possible number of outcomes or associations of cultural materials and geologic setting. In many parts of the world human occupation is marked by a deposit of complex stratigraphy and little or no substantial architecture. Without a standing wall, such as the Crusader castle wall at Vadum Jacob, Israel (Marco et al., 1997; Ellenblum et al., 1998), strategies must be followed that will constrain model piercing features. An isoconcentration line (see section 3) is an example. Using the model of circular-shaped sites in the Fort Ross, California, region (Noller et al., 1993), Noller and Lightfoot (1997) proposed four categories of associations of archaeological deposits located above or adjacent to active strike–slip faults (Fig. 6.2). These categories (A–D) are briefly described as follows, along with some of the potential problems.



a. ASSOCIATION "A"
Fault Bisects Archaeological Deposit, Occupation Predates Events

b. ASSOCIATION "B"
Fault Adjacent to Two Apparent Archaeological Deposits, Occupation Predates Events

c. ASSOCIATION "C"
Fault Bisects Archaeological Deposits, Occupation Spans Events

d. ASSOCIATION "D"
Fault Bisects Artifact-Bearing Colluvium, Occupation Predates Events

Figure 6.2. Categories of associations of archaeological deposits with an active strike-slip fault include the following: (a) a single architectural feature or deposit belonging to a discrete phase of human occupation predating an earthquake event that is not reused or reoccupied; (b) a single architectural feature or deposit, like association (a), except that the two segments are separated; (c) a site, composed of many architectural features and/or deposits, with long use over a period of multiple earthquakes; (d) a single architectural feature or deposit, or site, located adjacent to a fault forms a point source for colluvium.

A. *A single architectural feature or deposit belonging to a discrete phase of human occupation predating an earthquake event that is not reused or reoccupied.* Following one or more displacements, the feature or deposit is split into two segments that are still touching each other. In the absence of knowledge of faulting, such deposit geometry normally would be interpreted to represent one contiguous and irregularly shaped site. Such is the case at Fort Ross (Noller and Lightfoot, 1997).

B. *A single architectural feature or deposit, like association (A), except that the parts are physically separated.* The two parts could be interpreted to represent two individual sites or discrete occupations, which could certainly be the case if the fault was not recognized. The study team must prove that the two "sites" are parts of one original site. To test this, one may use independently derived fault slip rates, geometry of cryptic compositional patterns in the deposit, and/or deposit age estimates.

C. *A site, composed of many architectural features and/or discrete deposits, with long use over a period of multiple earthquake events.* Repeated offsets of the deposit lead to a pattern of overlapping (A) associations and increased site circumference. The study team must show correspondence between the stratigraphic units and features of the site. A special case of this relationship is where one part of the site is repeatedly reoccupied resulting in a vertical stratigraphy of deposits that can be matched with the lateral stratigraphy of deposits on the other side of the fault.

D. *A single architectural feature or deposit, or site, located adjacent to a fault forms a point source for colluvium.* Archaeological materials are eroded and deposited across the fault. Here, earthquakes are recognized by host geologic deposits that are dated and correlated, in part, by contained artifacts. In a special case, the site is abandoned prior to erosion and is not reoccupied. The zone of redistributed artifacts is stretched along the fault by repeated offsets and is similar in this respect to the special case for association (C).

One or more of these associations may be present at the same site. The presence of one association does not automatically exclude another association. In fact, more than one association may be the consequence of changing environmental conditions as well as changes in site use.

2.2.3. Case Studies

Large, engineered masonry and earthen structures provide ideal piercing features with which to assess timing and amount of fault displacement, sense of slip, distribution of shear, and other important parameters of interest to paleoseismologists and to structural geologists. The Great Wall of China, one of the world's largest engineered structures, crosses a number of active faults, one of which ruptured during the 1739 A.D. Yiuchuan–Pingluo earthquake (Zhang et al., 1986). This event occurred on the Honggouzigou fault that offset the Great Wall by 2.7 m vertically and 3 m right laterally (Zhang et al., 1986). Such precise and accurate measures of displacement on the structure is one of the important and nearly unique contributions of faulted architecture to paleoseismology.

The Crusader castle Vadum Jacob was constructed on the Dead Sea Transform, along the Jordan River in modern Israel, and soon after was offset by an earthquake at dawn, May 20, 1202 (Ellenblum et al., 1998). Masonry castle walls cross the fault at a right angle, presenting ideal cultural piercing features. The trueness of the skillfully constructed wall is unequaled by any of the natural piercing features, (e.g., stream channel). Archaeological excavation of the walls provided the exposure with which to measure with high confidence its displacement (Fig. 2 of Ellenblum). Of the 2.1 m of left-lateral offset, 1.6 m is tied directly to the event in 1202. Earthquakes of 1759 A.D. and/or 1837 added another 0.5m to the total offset of the wall. This study is a good example of the type of results that a coordinated interdisciplinary archaeoseismological study can provide.

Earthquakes on the northern San Andreas fault at Fort Ross offset archaeological and colluvial deposits (Noller et al., 1992, 1993, 1994; Simpson et al., 1997). The last event at this site, the great San Francisco earthquake of 1906, produced 3.7m of offset on a nearby fence. Three cultural piercing features (Fig. 6.3) were used to measure slip rate on the San Andreas fault and include the northern and southern boundaries of the Emergent (500–1812 A.D.) archaeological deposit (Features 1 and 2, respectively) and the loci of Middle to Upper Archaic (3000B.C.–500A.D.) artifacts within the northern part of the midden deposit (Feature 3). Features 1 and 2 are offset by 22.9 ± 2.6 m and 25.6 ± 1.6 m, respectively. The location of Feature 3 is best constrained with an offset of 26 ± 4m. The Archaic deposit could be offset by as much as 6 m more than the Emergent deposit, given the uncertainty in their locations, implying that one to two 1906-size ruptures occurred between the deposition of the two units. This would be an example of association (C) (Fig. 6.2). The amount of offset of the cultural piercing features is consistent with that estimated using recurrence intervals at other sites on the San Andreas fault (Noller and Lightfoot, 1997).

2.3. When's the Next Earthquake?

2.3.1. Guessing the Future Based on the Past

Having some sense of when and how often earthquakes have occurred in the past is valuable information for assessing seismic risk in the future (Wyss and Dmowska, 1997). Predicting earthquakes remains an elusive quest, with hope for new methods ever on the horizon (cf. Geller, 1996; Varotsos et al., 1996). Much of our understanding of the history of humans and earthquakes comes from ancient sources and from archaeological investigations. The former is fraught with problems of communicating exactly what happened as we can get only snippets of an event that may, or in some cases, may not have occurred (Lee et al., 1988; Ambraseys, 1996). Yet resourceful catalogs of events can be assembled (Toppozada et al., 1981; Mart and Perecman, 1996). The five volume "Compilation of Historical Materials of Chinese Earthquakes" stands out among these catalogs because it hosts an impressive record dating from the 23rd century B.C. to A.D. 1980 (from Lin and Wu, 1993).

There is as yet no unifying concept or theory for fault behavior and the occurrence of earthquakes (Yeats et al., 1996). There are concepts that seem to work for some faults and not others. One concept that has seen widespread application is that of the *characteristic earthquake* (Schwartz and Coppersmith,

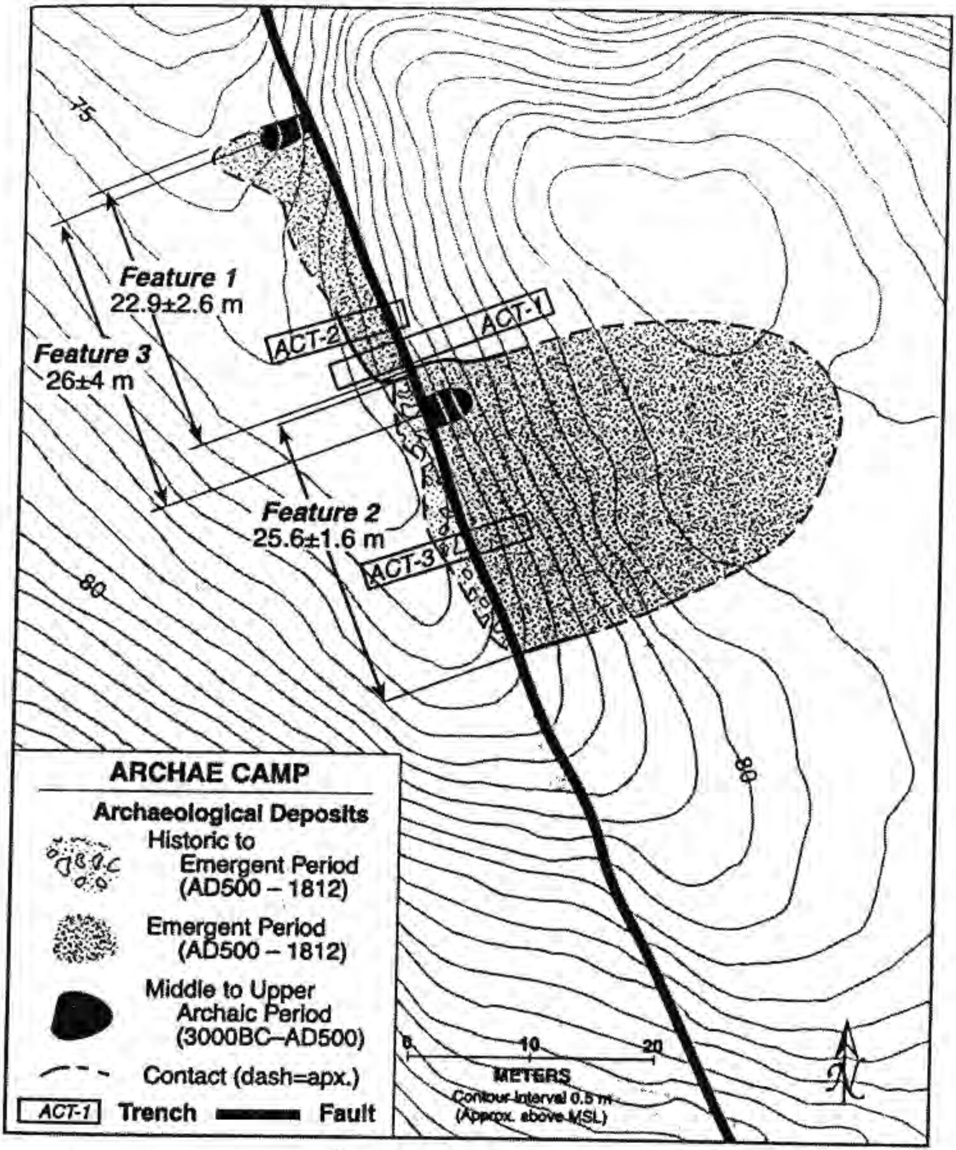


Figure 6.3. Map of the Archae Camp site showing distribution of archaeological deposits and trench locations. The Emergent and Archaic deposits are displaced along the San Andreas fault. Emergent and Archaic deposits west of the fault and northwest of trench ACT-3 are buried beneath fault-scarp-derived colluvium. A less than 25-cm-thick surficial deposit containing Historic to Emergent period materials drapes from the main site across the fault and into the swale. Paleoseismic trenches were excavated across the prominent southwest-facing fault scarp.

1984), in which large-magnitude earthquakes occur with same release of energy at a regular frequency. Another, and not necessarily competing, model is the *clustered earthquake* concept in which a number earthquakes occur followed by a long period of quiesence on the fault. Estimates of recurrence interval depend on the length and resolution of the record of past events. Taking the record on the Hierapolis fault, Turkey (Hancock and Altunel, 1997), as an example, the two events occurred within a period of about a thousand years, or on average every 500 years. If one uses the characteristic earthquake concept as their basis then this would seem to be a reasonable approach. In fact, most current estimates of earthquake recurrence and, by extension, predictions of when future events will occur are based on such short-term, imperfectly defined event chronologies (McCalpin, 1996). Using the clustered earthquake concept, some workers will argue that there is the strong possibility that, despite a geologically recent series of earthquakes, a fault may have entered a period of quiesence and hence will not quake again for another 100,000 or so years.

The historic record of earthquakes, such as that in China (from Lin and Wu, 1993), typically does not provide enough detailed information on earthquakes for recurrence to be calculated for individual faults. Linking historic felt and damage records to the causative fault requires further study in the field. However, such databases of historical seismicity are invaluable in determining the recurrence interval for damaging earthquakes in a region and as the basis for probabilistic seismic hazard studies.

2.3.2. Case Studies

The long use or occupation of tectonically active areas has presented ideal situations for revealing the long history of earthquakes. The chronology of paleoseismic events in the New Madrid Seismic Zone, central United States, is well supported by a sequence of liquefaction sand beds and prehistoric Native American occupation horizons (Saucier, 1991; Tuttle and Schweig, 1995, 1996; Tuttle et al., 1996). The abundance of lignite coal in deposits of the Mississippi River make radiocarbon dating of identical appearing charcoal highly suspect. The seriation of artifacts, although not completely removed from the problems associated with charcoal, provides a robust means of establishing ages of archaeological deposits and hence the liquefaction (earthquake) events that disrupt them (Tuttle et al. 1999b).

Sherds (pottery pieces) provide late Holocene age constraints on a thrice-faulted section of sediments at the Shama Gully sites along the southern border fault of the Weihe Graben, China (Zhang et al., 1995). Artifacts were found throughout the approximately 8 m section and thus bracket the surface fault ruptures at this site. The ages on two early events were established by ^{14}C and pottery seriation. Artifacts were collected from the base of depositional units, yet curiously not from the upper part of the units. The ages of the Weihe Graben earthquakes would be bolstered by collecting artifacts and radiocarbon samples from immediately below each event (stratigraphic) boundary. These samples would provide maximum constraints on the earthquake age estimates.

3. Case Study: Offset of the Seal Cove Archaeological Site by the San Gregorio Fault

3.1. Introduction

Archaeology was used to assess the recency of fault activity and fault slip on the San Gregorio fault at Seal Cove, California (Fig. 6.4; Noller et al., 1995; Simpson et al., 1997). The geological goal of this study was to obtain direct evidence of the date of the most recent earthquake, age estimates for earlier earthquakes, sense of fault displacement, and slip rate. The archaeological goal was to reveal the function and use of the site and its relation to local and regional trade and social

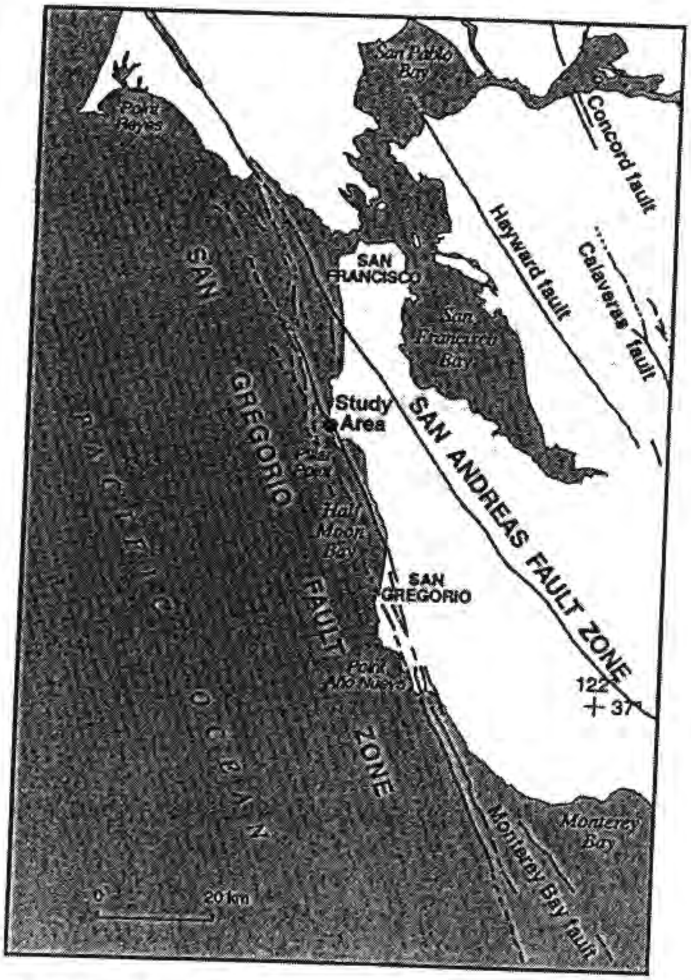


Figure 6.4. The San Gregorio fault lies offshore the California coast for much of its length, coming onshore at Seal Cove, about 20 km south of San Francisco.

organization. Most of these goals were met, providing valuable data for estimating earthquake parameters for the San Gregorio fault, specifically, and for seismic hazards assessments of central coastal California, in general.

The San Gregorio fault is westernmost of a series of faults that subparallel the San Andreas fault in central California. As such it is one of the largest potentially significant seismic source in the San Francisco and Monterey Bay areas. Compared to other faults in the San Andreas system, the San Gregorio fault has received little attention in the way of detailed paleoseismic studies (Weber and Lajoie, 1979) because of the offshore location of much of the fault and the paucity of suitable onshore sites with geologic piercing features (Weber et al., 1995).

The San Gregorio fault is part of a system of laterally continuous, late Pleistocene and Holocene active dextral slip faults, including (from south to north) the Hosgri, San Simeon, and Sur faults. The fault is geomorphically well expressed by features such as sag ponds, linear streams, fault scarps, and offset Pleistocene marine terraces. However, there is no record of surface rupture on this fault since the Spanish first occupied this part of the coast in A.D. 1770 (Monterey) to 1775 (San Francisco Santa María, 1775). Two historic earthquakes of moderate magnitude or greater have occurred that are attributed to the San Gregorio fault: an M $5\frac{1}{4}$ to $5\frac{1}{2}$ event near Pillar Point in 1856 and an M $5\frac{3}{4}$ to 6 event southeast of Point Año Nuevo in 1884 (Toppozada et al., 1981).

3.2. Approach: Identify an Archaeological Site on a Fault

Suitable geological sites were lacking for paleoseismic study of the San Gregorio fault. Having met recent success in locating and studying an archaeological site astride the San Andreas fault (Noller et al., 1993), I thought that the similar location of the San Gregorio fault along the Pacific coast might just yield a suitable archaeological site for investigation. The Seal Cove site was selected by overlaying a map of known archaeological sites in San Mateo County on a geological map showing active traces of the San Gregorio fault. Bill Lettis and I then went out to the site where, despite being a few hundred meters off the officially mapped trace of the fault, we found the site (California Registered Site CA-SMA-134) on a degraded scarp and bordering a sag pond.

The approach used in this study involves detailed mapping of the surface and subsurface distribution of archaeological features, concentrating on those features that are linear or have well-defined margins and therefore can provide strain gauges for evaluating fault displacement (Noller and Lightfoot, 1997). The distribution of ethnostratigraphic units and distinct archaeological features is determined by surface mapping and by a program of subsurface mapping involving shovel probes, hand-auger holes, test pits, and trenches. Cultural artifacts and other site materials also provide valuable information for assessing the age of stratigraphic units.

3.3. Methods: Excavate and Date

Field work consisted of preparing detailed geomorphic and archaeological maps of the Seal Cove site and vicinity, complemented by subsurface exploration consisting of shovel-probe and hand-auger surveys, archaeological test pits, and exploratory trenching (Fig. 6.5). Initially, several dozen random shovel probes were excavated to define the general limits of the archaeological deposits. Following the shovel-probe survey, 145 shallow (1 to 3 m) hand-auger holes were excavated over a 5 to 1.25m grid spacing to better define the margin of the site (Fig. 6.4). Samples were collected at 10 to 20 cm intervals until refusal. Test pits were hand excavated in the archaeological deposit to reveal stratigraphy and materials for dating (Fig. 6.5). The test pits were excavated along two transects

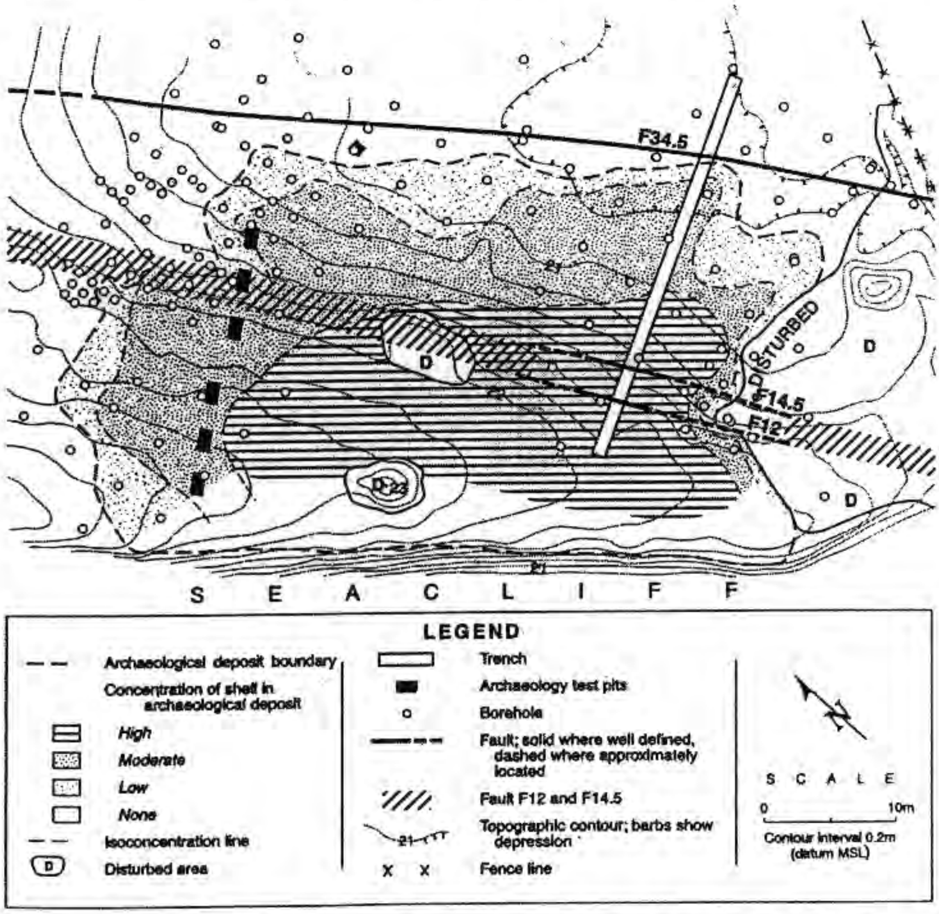


Figure 6.5. The archaeological deposit at Seal Cove is transected by three traces of the San Gregorio fault that underlie a northeast-facing scarp and bound a sag pond.

(northern and southern) across the archaeological deposit orthogonal to the fault. The three-dimensional position of each fire-cracked rock (FCR), bone, and artifact were mapped in the test units. A paleoseismic trench (1 m × 3 m × 36 m) was excavated and described along the southern transect of test pits (Fig. 6.5).

In addition to charcoal, we selected large (>10 cm) mussel shells (*Mytilus californianus*) from the archaeological deposit for radiocarbon dating (Noller et al., 1995). The large shells should maintain original stratigraphic context even if bioturbation (unrecognized) occurred, and thus their context would be better than charcoal sampled from the matrix of the archaeological deposit. Obsidian artifacts were analyzed for source, use, amount of wear and reuse, and measurement of hydration band width (Hylkema et al., 1995).

3.4. Results: Reading between the Fault Lines

The San Gregorio fault extends onshore near Seal Cove, California, where it transects an extensive, prehistoric archaeological deposit (CA-SMA-134) from Native Californian occupation of the site (Fig. 6.4). At the study site, the fault forms a distinct 1.5- to 3-meter-high east-facing scarp along the western margin of a closed depression (Fig. 6.4).

The archaeological deposit at Seal Cove covers 2,500 m^2, with a circumference of about 200 m around a roughly ellipsoidal boundary (Fig. 6.5). The deposit is about 1 m thick in the center and gradually thins towards its boundary. Where the northern part of the deposit crosses the fault, the boundary has an irregular shape (Fig. 6.5). This part of the deposit was chosen for further study. The southern part of the deposit was historically removed for earthfill, and thus was unsuitable for our study. An unknown amount of the western part of the deposit was removed by retreat of the sea cliff.

3.4.1. Ethnostratigraphic Units

Excavation of the archaeological deposit yielded a voluminous assemblage of stratified prehistoric Native Californian artifacts and refuse that provide a late period date of A.D. 1270–1400 (Table 6.3; Hylkema et al., 1995). Archaeological excavations, sea-cliff exposures, and paleoseismic trenching provide three dimensional control on the distribution of the units and included artifacts throughout much of the deposit. Four facies or ethnostratigraphic units (units A to D) were defined within the archaeological deposit on the basis of concentrations and depositional fabrics of shell, bone, stone handtools, and FCR in matrix materials consisting of black, organic sandy silt (Fig. 6.6). Unit A is shell and artifact poor and overlies an irregular basal and presumably anthropic surface with the underlying sterile soil and host deposits. Unit B is locally shelly, with many of the *Mytilus* fragments ventral side downward as they might have been deposited. Unit C contains a lens of abundant FCR, shell, bone, and stone tools that define a relic cooking hearth at least 7 m × 1 m in size. The base of unit D, a diffuse stone and bone line, is gradational with unit C.

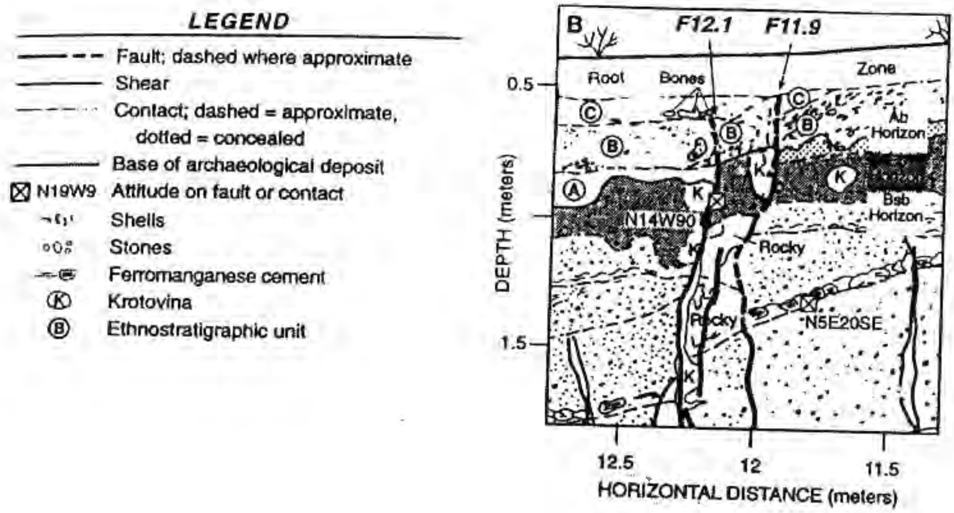


Figure 6.6. Ethnostratigraphic units and their relationship to strand 12.1 of the Seal Cove fault are shown in the south wall of the paleoseismic trench.

The upper 10 to 15 cm of site materials consist of black, organic-rich shelly sediment with few FCR and stone hand tools. Historic artifacts are common in this unit. This surface unit is bound by abundant roots that make calls on stratigraphic boundaries and faults uncertain. Charcoal and shell radiocarbon ages show that the deposit formed quickly. One charcoal fragment and one mussel shell from the core of the hearth feature were submitted for radiocarbon analysis (Noller et al., 1995). The age difference between that of coeval charcoal and shell is about 680 years and is within the range of reservoir ages (∂R) (100–800 yr BP) for marine mussel (*M. californianus*) shell along this coast (Berger et al., 1966; Hylkema, 1991; Robinson and Thompson, 1981). Correcting all shell ages using a ∂R value is not necessary because of the close correspondence of the charcoal-paired shell age with that of the other shells. Hence, the charcoal age is used as the age for all shell.

The archaeological deposit at Seal Cove is coherent in character, artifact assemblage, and age throughout. The uniformity of character and artifact assemblage, limited extent and depth of the deposit, and apparent single use of the site suggest many short periods of occupation. Nearly all of the bones within the deposit are from migrating animals (Table 6.3). On the basis of their historic migratory patterns, the temporal coincidence of these species in the Seal Cove region is April, plus or minus one month. Calibrated radiocarbon ages (2σ, calendric) overlap between A.D. 1270 to 1400, within the range of A.D. 960 to 1660. Given the volume and age range of the deposit it is permissible to suggest that Native Californians deposited the site materials within a period of one generation (20 years) of spring hunts.

Table 6.3. Inventory of Recovered Artifacts at the Seal Cove Site, Ca (CA-SMA-134)

Item	Number of specimen (or pieces)
Fire-cracked rock	2,028
Faunal bone	1,575
Bone tools	6
Pitted stones	152
Handstone/mano	3
Milling slab/metate	4
Incised cobble	2
Hand axe	2
Knapped cobbles	2
Obsidian debitage	11
Non-obsidian debitage	224
Obsidian points/bifaces	6
Chipped stone crescent	2
Olivella bead	1
Dietary shell	N/A

3.4.2. Faults in the Archaeological Deposit

It is vitally important that the discussion of the evidence of rupture of the surface by a fault (surface fault rupture) conform to the modes of description used by paleoseismologists (McCalpin, 1996). In this way, the results are of more immediate import to seismic hazard studies. The following description of stratigraphy and first-order interpretation should serve as an example of the discussion of a tectonically disturbed archaeological site. Other examples include Noller and Lightfoot (1997) and Ellenblum et al. (1998).

Faulted archaeological deposits were observed in the exploratory trench at Seal Cove (ethnostratigraphic units A, B, & C; Fig. 6.6). The northeast–southwest-trending trench crosses a 30-meter-wide zone of Holocene-active dextral faults that strike N15–20W. Three of the five Holocene fault strands in the trench (F4.5, F2.1, and F11.9) can be traced upward to or into the archaeological deposit.

The fault strand at meter 12.1 (F12.1 in Fig. 6.6) extends up to the base of, or possibly through, unit C. Beds of the Pleistocene sediments and the base of the overlying soil Eb horizon are vertically displaced by about 15 cm. Unit A is juxtaposed against the buried A/E/Bs soil profiles and unit B steps down to the east by less than 5 cm. Fault strand F12.1 is weakly expressed in unit B by rotated shell and juxtaposition of shell-rich (west) and shell-poor (east) facies, and is not evident in unit C. The upward termination of F12.1 is at the top of unit B, which is overlain by a floor level with unrotated bones. Because of the decrease in vertical throw going up section, more than one event on this strand may be inferred. It is plausible that this relationship is due to the penultimate event.

On the basis of these stratigraphic relations, one and possibly a second older event are inferred for faults transecting the archaeological deposit. The most recent surface-rupturing earthquake is identified by rotated clasts and changes in shell density in units B and C across F11.9. This earthquake is younger than unit C, which is dated to A.D. 1270–1400, yet must be older than the time of European contact and record-keeping A.D. 1770–1775.

3.4.3. Using the Archaeological Deposit to Determine Fault Slip

The northern boundary of the archaeological deposit is offset in a right lateral sense along the western fault zone (Fig. 6.5) and is used to constrain slip during the most recent, and possibly the penultimate, earthquake. The boundary of the archaeological deposit is diffuse and hence difficult to draw between areas of "low" and "no" shell detritus. The zone of low shell concentration is 2 to 5 m wide along the perimeter of the deposit, except along the fault scarp where the zone is less than 2 m wide (Fig. 6.5). The boundary of the archaeological deposit appears to have a cumulative offset of 8 to 9.5 m across the western fault zone (strands F14.5 and F12) (Fig. 6.5).

Confidence in the use of the northern site boundary is dependent on two key assumptions. First, it is assumed that the offset boundary was not deposited in its present shape by its occupants. Second, it is assumed that this boundary has undergone little or no postdepositional disturbance (e.g., erosion) since the time of fault offset. Disturbance of the northern boundary is ruled out because such disturbance is detectable by the methods employed.

3.5. Implications of Results from Seal Cove

Traces of the San Gregorio fault are identifiable in a 1270 to 1400 A.D. archaeological deposit at Seal Cove. Offset ethnostratigraphy in the deposit provides the basis for estimating the timing of events on this historically quiescent tectonic structure. The sense and magnitude of throw along these traces during the late Holocene are consistent with right lateral slip on the San Gregorio fault.

One and possibly two late Holocene earthquakes on the San Gregorio fault are evidenced in the archaeological deposit at Seal Cove. The most recent earthquake is constrained to between A.D. 1270 and 1775, and it quite possibly occurred while the site was occupied during a spring hunting season prior to A.D. 1400. This and possibly an earlier event produced a (cumulative) maximum right lateral offset of 8 to 10.5 m across the western traces of the San Gregorio fault. Unless more convincing evidence is found of previous displacement of the fault traces, a slip rate cannot be determined based solely on this offset archaeological deposit. Estimates of the timing, sense of throw, and amount of slip for the most recent earthquake were elusive at other sites (Weber and Lajoie, 1979; Weber et al., 1995), and thus there is no comparison for the results from Seal Cove.

These results demonstrate that archaeology can be used to complement standard geology-based paleoseismic studies. Clearly, after repeated unsuccessful attempts at a purely geologic site, for example, one in which stream channels are offset, it was the excavation of an archaeological site and its associated geologic context that provide the best and most complete results to date. The offset hearth was not recognized as such by the geological phase. Also, the block excavation of the exploratory trench did not fully reveal the number and amounts of offset on the other fault strands. Hence, the results also show that the wedding of the two disciplines and their methods are fully complementary: the unique view of one enhances the unique view of the other and vice versa.

4. Closing

Use of archaeology in studies of earthquake history is in its initial phase of development. The fields of paleoseismology and archaeoseismology are in the early stage of definition, as is demonstrated by the recent appearance of textbooks and reviews on these subjects (e.g., Stiros and Jones, 1996; Yeats et al., 1996; McCalpin, 1996). Archaeological evidence and sources have long been used to develop and refine the record of historical seismology (Ambraseys, 1996). The use of archaeology to characterize paleoearthquakes, including age and amount and direction of movement on a fault, began more as a function of describing oddities in archaeological excavations as well as explaining the accidental finds of cultural materials in geologic excavations. Not until the 1990s do we see a concerted effort to conduct truly interdisciplinary studies that provide a wealth of information on paleoearthquakes and fault behavior, as well as the significant contributions to archaeology. The breadth of archaeology-related studies covers the range of tectonic settings, types of active faults, and primary and secondary earthquake effects. The excavation of the Seal Cove site is one example of this new breed of archaeoseismological study. Archaeoseismology can answer the questions basic to seismology and paleoseismology: When did the earthquake occur? What did the earthquake do? Where did the earthquake occur? How big was the earthquake? When is the next earthquake? Archaeoseismologic studies provide additional sites for earthquake research as anthropogenic landscape change is altogether quite different from that due to other surficial processes. Finally, archaeoseismology, unlike purely geologic or geophysical studies, directly relates past human interaction with tectonic forces to that of present and future generations.

5. ACKNOWLEDGMENTS. Research at Seal Cove was supported by the U.S. Geological Survey, Department of the Interior, NEHRP Award 1434-94-G-2275 to the author. The author wishes to thank colleagues Gary Simpson, Stephen Thompson, Mark Hylkema, and Bill Lettis, who worked on the Seal Cove site. Certainly not least, my inspiration for this study is owed to years of discussion with Lisa Wells on the use of archaeology in geologic studies.

6. References

Aitken, M. J., 1990, *Science-based Dating in Archaeology*, Longman, New York.

Ambraseys, N. N., 1996, Material for the Investigation of the Seismicity of Central Greece, in *Archaeoseismology*, edited by S. C. Stiros and R. E. Jones, British School at Athens Fitch Laboratory Occasional Paper 7, pp. 23–36.

Anderson, W. A., Kelley, J. T., Thompson, W. B., Borns, H. W., Jr., Sanger, D., Smith, D. C., Tyler, D. A., Anderson, R. S., Bridges, A. E., Crossen, K. J., Ladd, J. W., Andersen, B. G., and Lee, F. T., 1984, Crustal Warping in Maine. *Geology* 12:677–680.

Armijo, R., Lyon-Caen, H., and Papanastassiou, D., 1991, A Possible Normal-Fault Rupture for the 464 B.C. Sparta Earthquake. *Nature* 351:137–139.

Berger, R., Taylor, R. E., and Libby, W. F., 1966, Radiocarbon Content of Marine Shells from the California and Mexican West Coast. *Science* 153:864–866.

Broster, B. E., Allen, P., and Burke, K. B. S., 1993, The Assessment of Postglacial Neotectonics; An Example of a Multidisciplinary Approach Involving Archaeology, Sedimentology and Historical Seismicity, Miramichi Area, New Brunswick. *Biennial Meeting of the Canadian Quaternary Association*, A8.

Caputo, R., Bravard, J.-P., and Helly, B., 1994, The Pliocene–Quaternary Tecto-Sedimentary Evolution of the Larissa Plain (Eastern Thessaly, Greece). *Geodinamica Acta (Paris)* 7:219–231.

Demitrack, A., 1986, The Late Quaternary Geologic History of the Larissa Plain, Thessaly: Tectonic, Climatic, and Human Impact on the Landscape. Ph.D. diss., Stanford University. University Microfilms, Ann Arbor.

Ellenblum, R., Marco, S., Agnon, A., Rockwell, T., and Boas, A., 1998, Crusader Castle Torn Apart by Earthquake at Dawn, 20 May 1202. *Geology* 26:303–306.

Flemming, N. C., and Webb, C. O., 1986, Tectonic and Eustatic Changes During the Last 10,000 Years Derived from Archaeological Data. *Zeitschrift fur Geomorphologie* 62:1–29.

Galadini, F., and Galli, P., 1999, *Faulting of a Roman Building in Northern Italy: Echo of an Ancient Earthquake from a Silent Area*, U.S. Geological Survey Paleoseismology Page http://geo.cr.usgs.gov/paleoseis/PPMain/Gall:FEM.

Ganas, A., and Buck, V. A., 1998, A Model for Tectonic Subsidence of the Allai Archaeological Site, Lokris, Central Greece. *Bulletin of the Geological Society of Greece* 32:181–187.

Geller, R. J., 1996, Earthquake Prediction; A Critical Review. *Geophysical Journal International* 131:425–450.

Grant, W. C., and Minor, R., 1991, Paleoseismic Evidence and Prehistoric Occupation Associated with Late Holocene Sudden Submergence, Northern Oregon Coast. *Eos, Transactions, American Geophysical Union* 72:313.

Grant, L. B., and Sieh, K., 1994, Paleoseismic Evidence of Clustered Earthquakes on the San Andreas Fault in the Carrizo Plain, California. *Journal of Geophysical Research* 99B4:6819–6841.

Guidoboni, E., 1996, Archaeology and Historical Seismology; the Need for Collaboration in the Mediterranean Area. In *Archaeoseismology*. edited by S. C. Stiros and R. E. Jones, British School at Athens Fitch Laboratory Occasional Paper 7:129–152.

Hancock, P. L., and Altunel, E., 1997, Faulted Archaeological Relics at Hierapolis (Pamukkale), Turkey. *Journal of Geodynamics* 24:21–36.

Harris, E. C., 1989, *Principles of Archaeological Stratigraphy*. Academic Press, New York.

Hylkema, M. G., 1991, Prehistoric Native American Adaptations along the Central California Coast of San Mateo and Santa Cruz Counties. M. A. thesis, San Jose State University, San Jose, CA.

Hylkema, M. G., Noller, J. S., and Thompson, S. C., 1995, The Archaeological Excavation of Prehistoric Site CA-SMA-134, Fitzgerald Marine Reserve, San Mateo County, California: *Final Technical Reports of the National Earthquake Hazards Reduction Program*, #1434-92G-2220, Reston, VA, U. S. Geological Survey, pp. 45–72.

Karcz, I., and Kafri, U., 1978, Evaluation of Supposed Archaeoseismic Damage in Israel. *Journal of Archaeological Science* 5:237–253.

Karcz, I., and Kafri, U., 1981, Studies in Archaeoseismicity of Israel: Hisham's Palace, Jericho. *Israel Journal of Earth Sciences* 30:12–23.

Kelson, K. I., Simpson, G. D., VanArsdale, R. B., Haraden, C. C., and Lettis, W. R., 1996, Multiple Late Holocene Earthquakes Along the Reelfoot Fault, Central New Madrid Seismic Zone. *Journal of Geophysical Research* 101B:6151–6170.

King, G., Bailey, G., and Sturdy, D., 1994, Active Tectonics and Human Survival Strategies. *Journal of Geophysical Research* 99B:20,063–20,078.

Lee, W. H. K., Myers, H., and Shimazaki, K. (eds.), 1988, *Historical Seismograms and Earthquakes of the World*, Academic Press, New York.

Lettis, W. R., Wells, D. L., and Baldwin, J. N., 1997, Empirical Observations Regarding Reverse Earthquakes, Blind Thrust Faults, and Quaternary Deformation: Are Blind Thrust Faults Truly Blind? *Bulletin of the Seismological Society of America* 87:1171–1198.

Lin, R., and Wu, Y., 1993, An Overview of Archaeo-Seismological Studies in China. In *Geophysical Exploration of Archaeological Sites. Theory and Practice of Applied Geophysics*, edited by A. Vogel and G. N. Tsokas, pp. 181–191. Vieweg, Bremen.

Marco, S., Agnon, A., Ellenblum, R., Eidelman, A., Basson, U., and Boas, A., 1997, 817-Year-Old Walls Offset Sinistrally 2.1 m by the Dead Sea Transform, Israel, *Journal of Geodynamics* 24:11–20.

Mart, Y., and Perecman, I., 1996, Neotectonic Activity in Caesarea, the Mediterranean Coast of Central Israel. *Tectonophysics* 254:139–153.

McCalpin, J. P., 1996, *Paleoseismology*, Academic Press, New York.

Michetti, A. M., Brunamonts, F., Serva, L., and Vittori, E., 1996, Trench Investigations of the 1915 Fucino Earthquake Fault Scarps (Abruzzo, central Italy): Geological Evidence of Large Historical Events. *Journal of Geophysical Research* 101B:5921–5936.

Morrison, R. B., 1991, Introduction, in *Quaternary nonglacial geology: Conterminous U. S. The Geology of North America, Volume K-2*. edited by R. B. Morrison, pp. 1–12 Geological Society of America. Boulder, CO.

Munson, C. A., Munson, P. J., and Garniewicz, R. C., 1992, Geoarchaeological Dating of Holocene-Age, Earthquake-Induced Paleoliquefaction Features in Southwestern Indiana. *Abstracts with Programs, Geological Society of America Annual Meeting* 24:162.

Nikonov, A. A., 1995, The Stratigraphic Method in the Study of Large Past Earthquakes. *Quaternary International* 25:47–55.

Noller, J. S., and Forman, S. L., 1998, Luminescence Geochronology of Liquefaction Features Near Georgetown, South Carolina, in *Dating and Earthquakes: Review of Quaternary Geochronology and its Application to Paleoseismology* edited by J. M. Sowers, J. S. Noller, and W. R. Lettis, pp. 4-49–4-57. U. S. Nuclear Regulatory Commission, NUREG/CR 5562. Washington, DC.

Noller, J. S., and Lightfoot, K., 1997, An Archaeoseismic Approach and Method for the Study of Active Strike-Slip Faults. *Geoarchaeology* 12:117–135.

Noller, J. S., and Simpson, G. D., Late Holocene Record of Large-Magnitude Earthquakes on the Northern San Andreas Fault, at a Prehistoric Native Californian village, Archae Camp, Fort Ross, California. *Journal of Geophysical Research*, in preparation.

Noller, J. S., Lettis, W. R., Kelson, K. I., and Lightfoot, K., 1992, Holocene Activity of the Northern San Andreas Fault as Determined by Paleoseismic and Archaeologic Methods. *EOS, Transactions, American Geophysical Union* 73:590.

Noller, J. S., Lightfoot, K. Wickens, K. A., Kelson, K. I., Wake, T., and Parkman, E. B., 1993, Preliminary Results of Geoarchaeological Investigations along the Northern San Andreas Fault Zone, Fort Ross State Historic Park, California. *Proceedings of the Society for California Archaeology* 6:249-256.

Noller, J. S., Lettis, W. R., and Simpson, G. D., 1994, Seismic Archaeology: Using Human Prehistory to Date Paleoearthquakes and Assess Deformation Rates of Active Fault Zones. *U.S. Geological Survey Open-File Report* 94–568:138–140.

Noller, J. S., Sowers, J. M., and Lettis, W. R., eds., 2000, *Quaternary Geochronology: Methods and Applications*, American Geophysical Union Reference Shelf Series 4, Washington, DC.

Noller, J. S., Thompson, S. C., Hylkema, M. G., Simpson, G. D., and Lettis, W. R., 1995, Use of Archaeology to Assess Holocene Activity on the San Gregorio Fault, Seal Cove, California. *Final Technical Reports of the National Earthquake Hazards Reduction Program*, #1434-92G-2220, U.S. Geological Survey, Reston, VA.

Noller, J. S., Wells, L. E., Reinhardt, and E., Rothaus, R. M., 1997, Subsidence of the Harbor at Kenchreai, Saronic Gulf, Greece, During the Earthquakes of A.D. 400 and A.D. 1928. *EOS, Transactions, American Geophysical Union* 78:636.

Noller, J. S., Wells, L. E., Reinhardt, E., and Rothaus, R., *Archaeoseismologic Evidence of Recent Episodic Subsidence at Kenchreai, Greece*, manuscript submitted for publication.

Nur, A. M., 1998, The Catastrophic End of the Bronze Age: Large Earthquakes of Sea People? *American Geophysical Union* 78:636.

Obermeier, S. F., Jacobson, R. B., Smoot, J. P., Weems, R. E., Gohn, G. S., Monroe, J. E., and Powars, D. S., 1990, *Earthquake-Induced Liquefaction Features in the Coastal Setting of South Carolina and in the Fluvial Setting of the New Madrid Zone*. U.S. Geological Survey Professional Paper 1504. Washington, DC.

Papageorgiou, S., and Stiros, S. C., 1996, The Harbour of Aigeira (North Peloponnese, Greece): an Uplifted Ancient Harbour. In *Archaeoseismology*. edited by S. C. Stiros and R. E. Jones, 211–214. British School at Athens Fitch Laboratory Occasional Paper 7.

Pavlides, S. B., 1996, Paleoseismology: A Branch of Neotectonics Linking Geological, Seismological and Archaeological Data—An Introduction. In *Archaeoseismology*, edited by S. Stiros and R. E. Jones. pp. 15–19. British School at Athens Fitch Laboratory Occasional Paper.

Pirazzoli, P. A., Stiros, S. C., Arnold, M., Laborel, J., Laborel-Deguen, F., and Papageorgiou, S., 1994, Episodic Uplift Deduced from Holocene Shorelines in the Perachora Peninsula, Corinth Area, Greece. *Tectonophysics* 229:201–209.

Rapp, G., Jr., 1986, Assessing Archaeological Evidence for Seismic Catastrophes. *Geoarchaeology* 1:365–379.

Reches, Z., and Hoexter, D. F., 1981, Holocene Seismic and Tectonic Activity in the Dead Sea Area. *Tectonophysics* 80:235–254.

Reinhardt, E. G., Easton, N. A., and Patterson, T. R., 1996, Foraminiferal Evidence of Late Holocene Sea-Level Change and Amerindian Site Distribution at Montague Harbour, British Columbia. *Geographie Physique et Quaternaire* 50:35–46.

Robinson, S. W., and Thompson, G., 1981, Radiocarbon Corrections for Marine Shell Dates with Application to Southern Pacific Northwest Coast Prehistory. *Syesis* 14:45–57.

Sangawa, A., 1989, Point of Contact Between Archaeology and Paleo-Earthquake Research. *The Quaternary Research (Japan)* 27:241–252.

Santa Maria, V., 1775, Diario de lo Acaecido en el Nuevo Descubrimiento del Puerto de S[a]n Fran[cis]co. In *The First Spanish Entry into San Francisco Bay* edited by J. Galvin, 1972, pp. 11–76. John Howell Books, San Francisco.

Saucier, R. T., 1991, Geoarchaeological Evidence of Strong Prehistoric Earthquakes in the New Madrid (Missouri) Seismic Zone. *Geology* 19:296–298.

Schwartz, D. P., and Coppersmith, K. J., 1984, Fault Behavior and Characteristic Earthquakes: Examples from the Wasatch and San Andreas Faults. *Journal of Geophyscial Research* 89:5681–5698.

Scranton, R., Shaw, J., and Ibrahim, L., 1978, *Kenchreai Eastern Port of Korinth I. Topography and Architecture*: E. J. Brill, Leiden.

Simpson, G. D., Thompson, S. C., Noller J. S., and Lettis, W. R., 1997, The Northern San Gregorio Fault Zone: Evidence for the Timing of Late Holocene Earthquakes near Seal Cove, California. *Bulletin of the Seismological Society of America* 87:1158–1170.

Soren, D, 1988, The Day the Earth Ended at Kourion. *National Geographic* 174:30–53.

Stiros, S. C., 1988, Archaeology: A Tool to Study Active Tectonics; the Aegean as a Case Study. *Eos, Transactions, American Geophysical Union* 69: 1633, 1639.

Stiros, S. C., and Jones, R. E. (eds.), 1996, *Archaeoseismology*. British School at Athens Fitch Laboratory Occasional Paper 7.

Stiros, S. C., and Pirazzoli, P. A., 1995, Paleoseismic Studies in Greece: A Review. *Quaternary International* 25:57–63.

Stiros, S. C., Marangou, L., and Arnold, M., 1994, Quaternary Uplift and Tilting of Amorgos Island (Southern Aegean) and the 1956 Earthquake. *Earth and Planetary Science Letters* 128:65–76.

Stiros, S. C., Pirazzoli, P. A., Rothaus, R., Papageorgiou, S., Laborel, J., and Arnold, M., 1996, On the Date of Construction of Lechaion, Western Harbor of Ancient Corinth, Greece. *Geoarchaeology* 11:251–263.

Toppozada, T. R., Real, C. R., and Parke, D. L., 1981, *Preparation of Isoseismal Maps and Summaries of Reported Effects for Pre-1900 California Earthquakes*. Open-File Report 81-11, California Division of Mines and Geology, Sacramento.

Tuttle, M. P., and Schweig, E. S., 1995, Evidence of Recurrent Large Earthquakes in the New Madrid Seismic Zone. *Geology* 23:253–256.

Tuttle, M. P., and Schweig, E. S., 1996, Recognizing and Dating Prehistoric Liquefaction Features: Lessons Learned in the New Madrid Seismic Zone, Central United States. *Journal of Geophysical Research* 101B:6171–6178.

Tuttle, M. P., Lafferty, R. H., Guccione, M. J., Schweig, E. S., Lopinot, N., Cande, R., Dyer-Williams, K., and Haynes, M., 1996, Use of Archeology to Date Liquefaction Features and Seismic Events in the New Madrid Seismic Zone, Central United States. *Geoarchaeology* 11:451–480.

Tuttle, M., Chester, J., Lafferty, R., Dyer-Williams, K., and Cande, R., 1999a, *Paleoseismology Study Northwest of the New Madrid Seismic Zone*. U.S. Nuclear Regulatory Commission, NUREG/CR-5730. Washington, DC.

Tuttle, M. P., Collier, J., Wolf, L. W., and Lafferty, R. H., 1999b, New evidence for a large earthquake in the New Madrid seismic zone between A.D. 1400 and 1670. *Geology* 27:771–774.

Umeda, Y., Murakami, H., Iio, Y., Cho, A., Ando, M., and Daicho, A., 1984, Earthquake Traces Impressed on the Yayoi-Age Dwelling Site. *Jishin* 37:465–473.

Varotsos, P., Eftaxias, K., Vallianatos, F., and Lazaridou, M., 1996, Basic Principles for Evaluating an Earthquake Prediction Method. *Geophysical Research Letters* 23:1295–1298.

Vita Finzi, C., and King, G. C. P., 1985, The Seismicity, Geomorphology and Structural Evolution of the Corinth Area of Greece. *Philosophical Transactions of the Royal Society of London A* 314:379–407.

Voltaire, F. -M., 1759, *Candide ou l'optimisme*.

Weber, G. E., and Lajoie, K. R., 1979, Evidence for Holocene Movement on the Frijoles Fault near Point Año Nuevo, San Mateo County, California. In *Coastal Tectonics & Coastal Geologic Hazards in Santa Cruz & San Mateo Counties, California, Field Trip Guide*, edited by G. E. Weber, K. R. Lajoie, and G. B. Griggs, pp. 92–100. Cordilleran Section, Geological Society of America, Boulder, Colorado.

Weber, G. E, Nolan, J. M., and Zinn, E. N., 1995, *Determination of Late Pleistocene–Holocene Slip Rates along the San Gregorio Fault Zone, San Mateo County, California*. Final Technical Report, U.S. Geological Survey National Earthquake Hazards Reduction Program. Reston, VA.

Wells, D. L., and Coppersmith, K. J., 1994, New Empirical Relationships Among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. *Bulletin of the Seismological Society of America* 84:974–1002.

Whitcomb, D., 1994, *Ayla: Art and Industry in the Islamic Port of Aqaba*. Oriental Institute Museum Publications, Chicago.

Winslow, M. A., and Johnson, L. L., 1989, Prehistoric Human Settlement Patterns in a Tectonically Unstable Environment: Outer Shumagin Islands, Southwestern Alaska. *Geoarchaeology* 4:297–318.

Wyss, M., and Dmowska, R., 1997, *Earthquake Prediction — State of the Art*. Birkhauser Verlag, Boston.

Yeats, R. S., Sieh, K., and Allen, C. R., 1996, *The Geology of Earthquakes*. Oxford University Press, Oxford, UK.

Zhang, B., Liao, Y., Guo, S., Wallace, R. E., Bucknam, R. C., and Hanks, T. C., 1986, Fault Scarps Related to the 1739 Earthquake and Seismicity of the Yinchuan Graben, Ningxia Huizu Zizhiqu, China. *Bulletin of the Seismological Society of America* 76:1253–1287.

Zhang, A., Yang, Z., Zhong, J., and Mi, F., 1995, Characteristics of Late Quaternary Activity Along the Southern Border Fault Zone of the Weihe Graben Basin. *Quaternary International* 25:25–31.

Zreda, M., and Noller, J. S., 1998, Ages of Prehistoric Earthquakes Revealed by Cosmogenic Chlorine-36 in a Bedrock Fault Scarp at Hebgen Lake. *Science* 282:1097–1099.