A. PROJECT SUMMARY

One of the most basic questions in earthquake physics, earthquake hazards, and neotectonics is “What controls the space-time pattern of seismicity?” (e.g., PBO Steering Committee, 1999). A more fundamental question that must be answered first is “What IS the space-time pattern of seismicity?” This question can only be answered by observing fault behavior at multiple temporal and spatial scales. Paleoseismic investigations provide data on the multi-cycle rupture history of a portion of a fault. This proposal outlines our plans to collect a multi-cycle rupture history from a proven paleoseismic site along one of the most scientifically important and hazardous faults in the world: the San Andreas fault (SAF).

The Carrizo Plain is one of the best places to study the rupture history of the SAF because it has a proven paleoseismic record with excellent slip rate and slip per event measurements, and the potential to significantly enlarge the data set by increasing the length of the earthquake record. The Carrizo Plain has been one of the most productive sections of the SAF for paleoseismic research, yielding multiple slip rates from different time intervals at Wallace Creek in agreement with geodetic measurements; slip per event measurements for the last 6 ruptures; and well-constrained dates of the last 5 major earthquakes at the Bidart Fan and Phelan Creeks . <u>The Bidart Fan site in the Carrizo Plain has the potential to produce a multi-cycle rupture history spanning at least 3000 years, with a minimum of 10 surface ruptures. We propose to exploit this record in the characterization of the rupture history of the south-central San Andreas Fault.</u> The record will be especially valuable because it can be combined with existing slip rates, slip per event data, and future measurements of slip per event at the Van Matre Ranch (VMR) site and the nearby Wallace Creek offset site of Sieh, Liu, and associates. We will also begin an exciting initiative by our team to refine radiocarbon dating methods for the Carrizo Plain by doing our own dating at UCI’s new Keck AMS facility, under the supervision of Dr. John Southon. Important improvements in applying radiocarbon dating to paleoseismology were made by G. Seitz (Fumal et al., 2002) while he was working under Southon at the LLNL C-AMS Lab. We will have a similar opportunity to improve the event record in the Carrizo Plain through long-term collaboration. Our proposed research at the Bidart Fan should allow us to double the temporal record of surface ruptures in the Carrizo Plain and provide a third major paleoseismic site on the San Andreas fault for developing and testing models of fault behavior.

Intellectual Merit of the Proposed Activity

Data on the rupture history of the SAF form the basis of numerous models of fault behavior and seismic hazard. Models of fault behavior range from simple, deterministic systems such as the time-predictable and slip predictable models of Shimazaki and Nakata (1980), to complex, non-linear, and/or chaotic systems that can be described as a group, but cannot be individually predicted (Liu, 2003). The high slip rate, short recurrence interval, great length and accessibility of the SAF make it the best target in the U.S. (and perhaps the world) for observational testing of fault behavior models. Paleoseismic data are essential for such testing, because they are the only type of observations that span multiple earthquake cycles.

Broader Impacts Resulting From the Proposed Activity

The SAF dominates seismic hazard assessments in California (WGCEP, 1988). Its proximity to densely populated regions makes the risk associated with this fault a major threat to the U.S. The proposed research will provide additional insights on the magnitude and dates of past earthquakes in the Carrizo Plain and thereby help to assess the potential magnitude, location, and date of future damaging earthquakes.

C. PROJECT DESCRIPTION

C.1 Overview

One of the most basic questions in earthquake physics, earthquake hazards, and neotectonics is “What controls the space-time pattern of seismicity?” (e.g., PBO Steering Committee, 1999). A more fundamental question that must be answered first is “What IS the space-time pattern of seismicity?” This question can only be answered by observing fault behavior at multiple temporal and spatial scales. Paleoseismic investigations provide data on the multi-cycle rupture history of a portion of a fault. This proposal outlines our plans to collect a multi-cycle rupture history from a proven paleoseismic site along one of the most scientifically important and hazardous faults in the world: the San Andreas fault (SAF).

The Carrizo Plain is one of the best places to study the rupture history of the San Andreas fault because it has a proven paleoseismic record with excellent slip rate and slip per event measurements, and the potential to significantly enlarge the data set by increasing the length of the earthquake record. The Carrizo Plain (Figure 1) has been one of the most productive sections of the San Andreas fault for paleoseismic research, yielding multiple slip rates from different time intervals at Wallace Creek (Sieh and Jahns, 1984) in agreement with geodetic measurements (Lisowski et al., 1991); slip per event measurements for the last 6 ruptures (Liu and Sieh, in Liu, 2003; Grant and Sieh, 1993; Grant and Donnellan, 1994); and well-constrained dates of the last 5 major earthquakes at the Bidart Fan and Phelan Creeks (Grant and Sieh, 1994; Sims 1994) (Figure 2). The Bidart Fan site (Figures 3 and 4) in the Carrizo Plain (Grant and Sieh, 1994; Sieh and Prentice, in Yeats et al., 1997) has the potential to produce a multi-cycle rupture history spanning at least 3000 years, with a minimum of 10 surface ruptures. We propose to exploit this record in the characterization of the rupture history of the south-central San Andreas Fault. The record will be especially valuable because it can be combined with existing slip rates, slip per event data, and future measurements of slip per event at the Van Matre Ranch site (Figures 1-3; Arrowsmith and Grant, in progress), and the nearby Wallace Creek offset site of Sieh, Liu, and associates. Our long-term goal is to document this record, working as a team, and as part of a larger group of Carrizo researchers.

We are currently resuming work at a Carrizo Plain site (Van Matre Ranch) to measure displacement per rupture over multiple ruptures. At Van Matre Ranch and in this proposed project, we will also begin an exciting initiative by our team to refine radiocarbon dating methods for the Carrizo Plain by doing our own dating at UCI’s new Keck AMS facility devoted to carbon isotopes, under the supervision of Dr. John Southon (see his supporting letter in the supplemental documents section of this proposal). Important improvements in applying radiocarbon dating to paleoseismology were made by Gordon Seitz (Fumal et al., 2002) while he was working under Dr. Southon at the LLNL C-AMS Lab. We will have a similar opportunity to improve the event record in the Carrizo Plain through long-term collaboration. Our proposed research at the Bidart Fan should allow us to double the temporal record of surface ruptures in the Carrizo Plain and provide a third major paleoseismic site on the San Andreas fault for developing and testing models of fault behavior.

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(1980), to complex, non-linear, and/or chaotic systems that can be described as a group, but cannot be individually predicted (Liu, 2003). The high slip rate, short recurrence interval, great length and accessibility of the SAF make it the best target in the U.S. (and perhaps the world) for observational testing of fault behavior models. These models form the basis for all estimates of seismic hazard, and in turn, seismic risk. Paleoseismic data are essential for such testing, because they are the only type of observations that span multiple earthquake cycles (Grant and Gould, in press).

C.1.2 Broader Impacts Resulting From the Proposed Activity

Because of its great length and high slip rate, the San Andreas fault is the largest source of seismic hazard in California (WGCEP, 1988). Its proximity to densely populated and economically vital regions makes the risk associated with this fault a major threat to the U.S. However, the past behavior of the fault is the best indicator of earthquake potential, including the location and magnitude of future earthquakes. The proposed research will provide additional insights on the magnitude and dates of past earthquakes in the Carrizo Plain and thereby help to assess the potential magnitude, location, and date of future damaging earthquakes.

C.2 Paleoseismic data from the southern San Andreas fault

The longest multi-cycle earthquake sequence in North America is a record of 14 well-dated earthquakes from the Wrightwood paleoseismic site (Figure 1) near the southeastern boundary of the Mojave segment of the San Andreas fault in southern California (Fumal et al., 2002). A record of 10 surface ruptures has been reported from the Pallett Creek site (Biasi et al., 2002; Sieh et al., 1989), also on the Mojave segment of the SAF in southern California. The record of ruptures from these two sites has formed the primary data set for testing models of fault behavior and earthquake recurrence (Biasi et al., 2002) because the length of the record, precision of dating, and potential for extending the data set are unparalleled. Significant resources have been, and will continue to be, invested in these sites because of their proven record and rich potential.

However, there are many important questions about earthquake recurrence and fault behavior that cannot be adequately addressed at these sites. For example, although the sites are only about 20 km apart (Figure 1), correlation of individual ruptures between sites has been problematic (Biasi et al., 2002; Fumal et al., 2002; Sieh et al., 1989). The rupture pattern of the San Andreas fault, and its potential for generating large earthquakes, cannot be understood from such a limited geographic area. Rupture extent and slip variation remain essential fault-system parameters that can only be answered with improved spatial coverage. Several sections of the fault must be well-characterized to understand the potential for the largest earthquakes. The potential to correlate events diminishes with distance and slip observed at a given site (e.g., Biasi et al., 2003). Therefore, a comparable paleoseismic record is needed from another site beyond the Mojave section of the SAF, to characterize the magnitude and spatial extent of ruptures recorded at Pallett Creek and Wrightwood, and other paleoseismic sites along the SAF. Furthermore, observations of slip variation are important in understanding fault friction and mechanical properties, and slip rate measurements are critical for characterizing deformation patterns and quantifying seismic hazard. The characteristics of the Wrightwood and Pallett Creek sites that make them such goldmines for dating earthquakes makes them less suitable for measuring slip per event or slip rate. Reported Holocene slip rates for the Mojave segment of the San Andreas fault range from a minimum of 9 mm/yr at Pallett Creek (Sieh, 1984) to a maximum of 38 mm/yr (Schwartz and Weldon, 1987). Slip per event data is available from both Pallett Creek (Sieh, 1984; Salyards et al., 1992) and Wrightwood (Weldon et al., 2002), but there are large uncertainties in the measurements due to the structural complexity of the fault zone at these sites, and the potential for unrecognized soft-sediment deformation.

C.2.1 San Andreas fault models and hypothesis testing

A recent special issue of *BSSA* was devoted to Paleoseismology of the San Andreas Fault System (Grant and Lettis, Eds., 2002). However, despite the large amount of new data published in this volume, questions remain about the validity of segmentation models of the San Andreas fault, the rupture patterns of individual prehistoric earthquakes, and reasons for variation in earthquake characteristics. For example, as shown in **Table 1,** average recurrence intervals of San Andreas ruptures vary by more than a factor of two. The pattern of variation is surprising. The most recent Working Group reports characterized the Cholame segment as having a relatively short recurrence interval, and the Carrizo segment as having one of the longest recurrence times (WGCEP 1988; SCECWG, 1994). Neither characterization appears to be correct, as the most recently published paleoseismic data indicate that the LY4-Cholame site ruptures infrequently (Stone et al., 2002; Young et al., 2002; Runnerstrom et al., 2002) while the Bidart Fan site in the Carrizo Plain ruptures almost as frequently as Pallett Creek (Grant and Sieh, 1994; Sieh et al., 1989; Biasi et al., 2002; and Table 1 below).

Table 1. Average recurrence intervals through AD 2000 for selected sites along the southern San Andreas fault. (Modified from Stone et al., 2002; with additions from Grant and Lettis, 2002).

Paleoseismic site	Number of ruptures	Average Recurrence (years)
Cholame LY4	4	236
Bidart Fan[1]	5	156
Frazier Mountain[2]	2	257-397
Pallett Creek[3]	10	135
Wrightwood[4]	14	105
Thousand Palms[4]	5	215
Indio[5]	4	238

References: [1] Grant and Sieh (1994) [2] Lindvall et al (2002) [3] Biasi et al., (2002) after Sieh et al. (1989); [4] Fumal et al., (2002) [5] WGCEP (1988)

Chronologies of earthquakes spanning at least 10 ruptures are important for testing recurrence models (clustered, Poisson, lognormally distributed etc.). Large earthquakes in the Carrizo Plain and at Pallett Creek have been proposed to occur in temporal clusters (Grant and Sieh, 1994; Sieh et al., 1989). Quantitative testing of recurrence models for the Wrightwood and Pallett Creek chronologies suggest a pattern of accelerated activity in the early 600s to early 800s A.D., although a random distribution of events cannot be ruled out (Biasi et al., 2002). Although the 5 well-dated earthquakes at the Bidart Fan suggest a pattern of temporal clustering (Figure 2), the number of dated earthquakes is too small to test this hypothesis

(Grant and Sieh, 1994). A minimum of 10 dated ruptures would be required (Biasi et al., 2002).

Segmentation models of the San Andreas fault were developed largely from the distribution of surface slip and an inferred rupture pattern derived from paleoseismic data (WGCEP, 1988; Schwartz and Coppersmith, 1984; Sieh, 1978). One of the most influential models of fault behavior, the characteristic earthquake model (Schwartz and Coppersmith, 1984), was based on limited paleoseismic data from the San Andreas and Wasatch fault zones. More recent studies in the Carrizo Plain suggest that the multi-cycle rupture history of the SAF is inconsistent with the characteristic earthquake model (Grant, 1996; Liu, 2003). Additional paleoseismic data from the Carrizo Plain could confirm this interpretation - or possibly refute it for a longer time scale.

A longer record of surface ruptures at the Bidart Fan site would also be helpful for correlating ruptures between the Carrizo Plain and sites on the adjacent Mojave and Cholame segments and therefore estimating the magnitude of earthquakes previously documented at other sites. Magnitude is an important parameter in earthquake simulation models (e.g. Ward et al., 2003). Although correlations will never be perfect because of uncertainties inherent in dating the earthquakes, a better record of ruptures from the Carrizo Plain will help constrain the magnitude and extent of ruptures recorded at other sites. This is particularly true for the Carrizo Plain, because there are unusually precise measurements of slip for several previous ruptures. For example: Recent work by Liu and Sieh (Liu, 2003) demonstrates that slip per event at Wallace Creek was approximately 8 m, 7.5 m, 5.5 m, 1.5 m, 8 m and 5.5 m in each of the last 6 ruptures. Grant and Sieh (1994) had previously suggested that at least one of the last 5 events had significantly less slip than the others, and proposed that their event "D" might correlate with a rupture (event "T") at Pallett Creek. From Liu and Sieh's work (Liu, 2003), it appears that Event D had the least amount of slip (1.5 m) in the Carrizo Plain. Recent work by Biasi et al. (2003) shows that lower slip events are less likely to correlate with ruptures at distant sites. If Carrizo Event "D" does correlate with Event T at Pallett Creek, it would be one of the longest rupture earthquakes in the Carrizo record. This type of testing of magnitude hypotheses and rupture correlations is only possible when there are multiple, good paleoseismic sites. Results from the Bidart Fan site, alone or in combination with slip measurements at Van Matre Ranch, will make the existing data more valuable as well as contribute new data.

C.3 Previous Work in the Carrizo Plain

In part because of its spectacular geomorphic expression (Figures 3 & 4), the San Andreas fault in the Carrizo Plain has received significant attention from researchers. In this section we briefly summarize only those studies that are relevant to our proposed work. **Table 2** and **Figure 2** provide summaries of selected paleoseismic sites and data from the Carrizo Plain. Relative to other paleoseismic sites on the southern SAF, the Carrizo Plain has yielded a rich data set. The success of previous investigations in the Carrizo Plain suggests that future efforts will be productive, and worth the investment.

TABLE 2 - Selected paleoseismic sites and data from the Carrizo Plain. See Figure 1 for site locations.

Paleoseismic Site	Reference	Data
Wallace Creek (WC)	Sieh and Jahns, 1984	1) late Holocene slip rate

		33.9 ± 2.9 mm/yr 2) early Holocene slip rate 35.8 ± mm/yr
Wallace Creek (WC)	Liu (2003)	8 m, 7.5 m, 5.5 m, 1.5 m, 8 m, and 5.5 m slip in the last 6 ruptures
Phelan Creeks (PH)	Sims, 1994	1) Holocene slip rate 34 mm/yr 2) average recurrence 150 - 300 yrs*
Phelan Fan	Grant and Sieh, 1993	~ 7 m slip in 1857 A.D.
Bidart Fan (BF)	Sieh and Prentice in Yeats et al., 1997	6 or 7 ruptures since 3000 BP
Bidart Fan (BF)	Grant and Sieh, 1994	5 ruptures since 1218 A.D.* At least 7 ruptures since 2200 BP
Van Matre Ranch (VMR)	Sieh, 1977 and 1978	Channels displaced 8 ± ½ m, 7½ ± 1 m and 10 ± 1m by at least 3 earthquakes

*See Figure 2 for plot of event (rupture) dates at each site.

C.3.1 Significance of the Bidart Fan site

The Carrizo Plain is one of the best places to study the Holocene activity of the San Andreas fault. The excellent geomorphic expression (Figure 3) and structural simplicity of the fault zone make it relatively easy to plan paleoseismic investigations and the fault zone is easily mapped (Figures 3 and 4). The recent designation of the Carrizo National Monument ensures that the paleoseismic record will not be destroyed by development - unlike many other areas along the fault. Therefore, the Carrizo Plain is an important natural laboratory for long-term studies of the San Andreas fault and its rupture potential.

As shown in Table 1, there are only 4 sites along the southern San Andreas fault (>500 km) that have a rupture chronology of at least 5 events. One of these sites is the Bidart Fan, and its proximity to other sites with rupture data (see Figures 1-4 and Table 2) make it a tempting target for future research. Our previous work at the Bidart Fan indicates that it is an excellent place to develop a long chronology of earthquakes for several reasons:

1) It has good stratigraphy for discriminating individual earthquakes and preserving material for radiocarbon dating. An example of the stratigraphy is shown in Figure 5, from Grant and Sieh (1994). Sedimentation consists of areally extensive alluvial fan deposits, including debris flows, fluvially deposited sand and gravel beds, laminated silts, and clay lenses.

2) It has datable material. Measurable sedimentation has occurred on the active lobe of the fan (see below) approx. every 1 - 2 decades, on average. Detrital charcoal and other datable organic material is commonly embedded in the deposits. More importantly, micropaleosols a few centimeters thick form on the surface of the active fan between depositional events (Grant and Sieh, 1994). Most organic material in the micropaleosols is not detrital and is therefore a good resource for dating. We will work with John Southon and the UCI Keck AMS facility to refine radiocarbon dating methods for the paleosols.

3) Geomorphic expression of the fault is clear and simple. This should allow us to accurately locate traces across most of the fan (Figures 3 and 4)

4) The pattern of deposition and geomorphic offsets indicates that the active lobe of the fan has shifted around, thereby preserving ruptures at different time intervals in different places on the fan. The surficial pattern of sedimentation and channel incision on the Bidart fan suggests that the area of active sedimentation has swept across the fan from northwest to southeast over the time period of several recent earthquake cycles (Grant and Sieh, 1994). This is clearly visible in Figure 4. This pattern of sedimentation will allow us to correlate between different chrono-stratigraphic levels laterally across the fan, without having to excavate too deeply.

Previous work at the Bidart Fan shows that it contains a lengthy, datable record of surface ruptures (Table 3). A total of four trenches have been excavated in the SAF zone on the Bidart Fan. The locations are shown on Figure 4. The first trench (#1) was excavated, logged and interpreted by Prentice and Sieh in 1989. (This was the first fault trench that Grant ever worked on as a first year geology graduate student.) The study has not been formally published in a journal, but the unpublished data and interpretations of up to 7 ruptures were summarized (by Sieh) in Yeats et al., 1997. They are reproduced in the first column of Table 3, below. The record in Trench #1 showed at least 6, and probably 7 earthquakes since 3000 BP. The most recent earthquake is assumed to be the historic 1857 Fort Tejon earthquake that caused extensive surface rupture in the Carrizo Plain (Sieh, 1978). The dates of previous earthquakes are poorly constrained by the ages of detrital organic material in the sediments.

An important feature observed in the first trench is a "gap" in the record of earthquakes. The gap is a massive, featureless zone caused by bioturbation of the fan surface while that portion of the fan was depositionally inactive. As seen on Figure 4, the surface of the Bidart fan beyond the active depositional lobe has a smoother, more uniform appearance due to bioturbation (churning of the surface by plants, insects and animals). Bioturbation disturbs the sedimentary record and thereby causes a "gap" in the earthquake record during the time period when the site is on the inactive lobe of the fan. At the same time, the record of surface ruptures is preserved on the active depositonal lobe of the fan. <u>Therefore, a long chronology of earthquakes can be obtained by placing multiple trenches across the fan to "capture" the spatio-temporal record of earthquakes created by the interplay of surface rupture and spatially varying deposition.</u>

An example is shown in Table 3. The middle column shows the results from three additional trenches (#2-4) excavated, logged and interpreted by Grant and Sieh (1994). Grant and Sieh (194) also reported 7 earthquakes, although only the youngest five are commonly reported in the literature because they are reasonably well dated. When the record of 7 earthquakes and depositional gaps at the first Bidart trench is compared with the record of 7 earthquakes and depositional gaps from the other trenches, it yields a composite chronology consisting of 10 surface ruptures of the Bidart Fan over the last 3000 years, as shown in the third column of Table 3. The most recent 5 earthquakes are reasonably well dated, but uncertainty in the dates of the five earlier ruptures is much greater. *Therefore, these five early earthquakes are the primary target of our proposed data acquisition.* Additional trenches placed across the Bidart Fan may reveal more than these 10 ruptures since 3000 BP.

TABLE 3 - Dates of ruptures and gaps in the depositional record recorded at the 4 previous Bidart Trench excavation sites. A composite rupture sequence of approx. 10 earthquakes is displayed in the 3rd column. This sequence of events is the primary target for research.

Trench 1*	**Trenches 2 - 4****	**Bidart Fan Earthquakes**
1857 A.D.	1857 A.D.	1857 A.D.
during or before the 15th century	"sometime after a date within the range 1405-1510 A.D."	approx. 1405 - 1510 A.D.
gap	1277 - 1510 A.D.	1277 - 1510 A.D.
gap	1277 - 1510 A.D.	1277 - 1510 A.D.
gap	1218 - 1276 A.D.	1218 - 1276 A.D.
approx. 1000 BP	gap	~ 1000 BP
before 1000 BP	gap	~ 1200 BP†
between 1800 - 3000 BP	after 2200 BP	1800 - 2200 BP
between 1800 - 3000 BP	after 2200 BP	1800 - 2200 BP
approx. 3000 BP	gap	~ 3000 BP

*From Sieh and Prentice unpublished data presented in Yeats et al. (1997)
**From Grant and Sieh (1994)
† Sims (1994) reports a rupture event at Phelan Creeks circa 1200 BP.

C.4 Project plan

- **C.4.1 Proposed work** Due to our previous work at the site and in the region, the proposed project is well defined.
  1. We plan to excavate trenches at several locations on the Bidart Fan to capture evidence of earthquakes preserved by the shifting lobe of deposition across the fan.
  2. We will correlate chrono-stratigraphic units across the fan to develop a multi-cycle composite record of earthquakes for the Carrizo Plain.
  3. We will develop sampling and analysis methods for improving the application of radiocarbon dating to the Carrizo Plain.
  4. We will test the results against proposed models of fault segmentation, earthquake recurrence and seismic hazard for the southern San Andreas fault.
  5. We will write-up the results for publication in several major journals.

For the 2004 project year we plan to excavate three new trenches (A, B, and C on Figure 4) between the existing trenches (#s 1, 2, 3 and 4) to develop a better spatial and temporal model of deposition across the fan. We propose to identify and date surface ruptures in the 3 new trenches and correlate them with previously dated ruptures. (See C.4.2 Age Control for description of dating efforts and their significance.) We will also attempt to improve dates of previously documented earthquakes by radiocarbon dating of previously collected samples still in Grant's possession from trenches 2,3 and 4. In the first year of effort, we will also develop a plan for second year excavations based on data from the 3 new trenches and 4 previous trenches. The trenches will be excavated with a backhoe and propped open with hydraulic shoring. Standard safety procedures including hard hats and a trench escape/rescue plan will be applied. We will first locate the fault and then evaluate the stratigraphy before excavating further. We expect that the excavations will be staged and we will incorporate field reviews (see below in project management plan) so that we minimize the potential for destruction of important relationships by inadvertent digging. All surfaces will be scraped, cleaned, and gridded. Important control features will be surveyed with the total station into the site coordinate system. We will log at 1:10 for detailed portions of the exposures and 1:25 for broader stratigraphic coverage. We will use USGS-"Trenchomatic" low distortion mosaic photography of the exposures in the logging and for archival purposes.

In the 2005 project year, depending on first year results, we will either reopen and deepen excavations at two or more trench sites to expose the oldest events, or we will place additional shallow trenches between the previous trenches to obtain better spatio-temporal coverage of the rupture sequence. The locations of these trenches cannot be determined at this time. We would do additional radiocarbon dating and complete the stratigraphic correlations required to construct a composite rupture history. Testing of fault models against the rupture data will require 2 - 3 months of effort, depending on the number of ruptures that we will be able to date, and the dating uncertainty. The type of hypothesis testing (quantitative or qualitative) cannot be determined until we know what the data set will be. The last few months will be devoted to writing up results for publication.

C.4.2 Age control

Radiocarbon dating is essential to the success of this project, and indeed all paleoseismic research in the Carrizo Plain. Although the Carrizo Plain is in many respects an ideal place for studying the San Andreas fault, the semi-arid environment does not encourage the growth of the type of vegetation (peat) that has made Pallett Creek and Wrightwood such paleoseismic gold mines. In contrast, age control is the Achilles heel of the Carrizo paleoseismic record. Grant and Sieh (1993) described some of the problems of applying radiocarbon dating in this area including: inherited age from detrital wood, the high cost of AMS dating (which is required for the typically tiny samples of organic material), the presence of shrubs that can live more than 800 years and therefore yield dramatically different dates from different portions of the same shrub, and common flora with both C-3 and C-4 pathways resulting in substantially different fractionation of carbon isotopes. Liu and Sieh (Liu, 2003) also discovered evidence of climatic variation leading to episodes of non-deposition near Wallace Creek.

To successfully apply radiocarbon dating in such a challenging environment, it is essential to know what you are doing! We already have the benefit of experience with the field conditions, and knowledge of the problems they may present. We will have the opportunity to improve age control by learning how to do the actual radiocarbon dating under the supervision of Dr. John Southon, who has recently moved to UCI to establish an AMS facility dedicated to carbon isotopes. (See attached letter, and technical description in the facilities section.) This facility is only available to UCI researchers, and at greatly reduced cost. We will have the opportunity to learn from some of the world's most recognized experts in radiocarbon dating and its applications in field research. John Southon previously supervised Gordon Seitz at the LLNL CAMS lab, and this resulted in a significant improvement in dates at the Wrightwood paleoseismic site (Fumal et al., 2002). We anticipate similar improvements in dates of events in the Carrizo Plain, beginning with the Van Matre Ranch site in the southern Carrizo, and continuing to the Bidart Fan site as we become more experienced. With access to the radiocarbon dating lab, and the expertise of John Southon and other AMS facility staff, we should be able to experiment with different types of samples, and pretreatments to explore the best pathways to improved radiocarbon dating of Carrizo Plain earthquakes.

We have also found palynology to be a useful analysis method for distinguishing historic from prehistoric sediments in the Carrizo Plain (Stone et al., 2002; Young et al., 2002). If conditions warrant it, we will send samples to Paleo Research (http://www.paleoresearch.com/) for corroboration of selected radiocarbon dates.

C.4.3 Project management plan and cost effectiveness

As we have done in the past, we will work collaboratively on all aspects of the project and jointly supervise the postdoc and students. We have found joint supervision to be effective because it allows us to bring our complementary expertise (paleoseismology for Grant; active tectonics, imaging methods and geomorphology for Arrowsmith) to the project, and to continuously supervise research by trading off responsibilities when we are traveling or involved in other projects. This approach has allowed us to publish results fairly quickly.

This project is somewhat expensive because it is very labor intensive, and most of the labor must be done by people trained in paleoseismology or radiocarbon geochronology. . Ideally, we will recruit a postdoc who already has some training in paleoseismology so that s/he can quickly become familiar with the existing Bidart fan / Carrizo data and then devote some time to learning about radiocarbon dating. Some training is included in the research cost, and the training contributes to the broader value of the research project. The field research requires many person hours to work in the trenches; compile the stratigraphic data and correlate ruptures spatially and temporally across the fan; as well as learning to do the radiocarbon dating and prepare results for publication. The PIs both have significant experience working in the Carrizo Plain, and Grant is intimately familiar with the Bidart Fan site. However, both are also committed to teaching and other academic responsibilities during much of the year. If they were to work on the project alone, it could easily take a decade or longer to complete the proposed work. Although this is not uncommon (for example: Grant first visited one of the Wrightwood trenches as a first year geology grad student in 1989, and then edited the manuscript for publication in *BSSA* in 2002!) the required time can be shortened significantly by assigning a postdoc to work exclusively on the project for two years, with additional “hands” to help with the field work, and the PIs to supervise the overall effort and assist with the scienceThis management plan should be more cost effective in the long run, since everyone can work synergistically over a shorter, more focused time interval. It will also allow more rapid dissemination of results.

C.4.4 Dissemination and Training

Our proposed research is a continuation of a successful 8-year collaborative investigation of the rupture history of the south central San Andreas fault between Cholame and the Carrizo Plain by P.I.s Arrowsmith and Grant. We have conducted research in the area since graduate school, and have recently published 3 papers (Stone et al., 2002; Young et al., 2002;

Runnerstrom et al., 2002) on the results of collaborative research in the northern Carrizo Plain, and participated in and contributed to numerous informal and formal (Grant and Lettis, 2002) discussions of SAF rupture patterns and history. We expect to continue a comparable level of productivity and plan to prepare several major journal articles on the results of this research, in a timely manner. The project will provide opportunities for training students (undergraduate and graduate) and a postdoctoral researcher in paleoseismic field research methods. The PIs and postdoc will also be trained in radiocarbon dating methods, and thereby increase this knowledge resource in the paleoseismic research community. As a team, the PIs have an excellent record in training and mentoring women and underrepresented minorities, including Native American, African American and Latina. This is one way in which our research program has had a broader impact on society.

C.4.5 Related efforts

In this proposal we have already described several other research projects in the Carrizo Plain. These investigations have either been conducted by us (individually or jointly), or by our close associates (e.g. Sieh was Grant's Ph.D. supervisor, Sims collaborated with Arrowsmith, Prentice was Sieh's graduate student and Grant's contemporary: Stone, Young and Runnerstrom are current or former students jointly supervised by PIs). In addition, Arrowsmith is currently working with Sims to publish the record of earthquakes and fluvial response recorded at Phelan Creeks. The Phelan Creeks record has previously been summarized in grey literature (e.g., Sims, 1994) and abstracts. Liu and Sieh are in the process of writing up Liu's dissertation for publication. Sieh has expressed tentative plans to begin excavations to measure offsets at a site a few km northwest of Wallace Creek. As we train our students in the Carrizo Plain, we envision the development of a Carrizo Plain Working Group of close associates and friendly competitors to unravel the mysteries of the San Andreas fault.

Other related efforts include projects to model fault behavior based on paleoseismic data. Grant is currently collaborating with Steve Ward and Tom Rockwell to develop Ward's earthquake simulator, "tune" it with paleoseismic data, and apply it. Initial results are described by Ward et al. (2003). Grant is also working on the QuakeSim project to develop numerical simulations of active tectonic processes, with an emphasis on earthquakes and faults. Grant and Gould (in press) describe some of the issues associated with assimilation of paleoseismic data into numerical models.

Field consultation and review

We recognize the importance of field review in paleoseismologic investigations. We have had field reviews at the LY4 site (Stone et al., 2002; Young et al., 2002) by T. Fumal, H. Stenner, T. Dawson, D. Schwartz, T. Rockwell, G. Seitz, and J. Lienkaemper among others. These reviews provided us motivation and inspiration to modify our investigations and further test the interpretations. We expect to schedule field review with scientists in both Southern and Northern California several times during the project. In particular, we will seek feedback from other researchers who have recently worked in the Carrizo Plain, such as Kerry Sieh, Jing Liu (if she is available), John Sims, Carol Prentice and other interested parties.

C.5 Results from most related prior NSF support--Arrowsmith

Collaborative Research: Magnitude of slip, slip rate, and slip distribution along the Cenozoic Altyn Tagh Fault system

NSF Award Number: EAR-9805319 $180,000, 7/1/98-6/30/01. Part of Continental Dynamics project with University of Arizona, Lawrence Livermore National Laboratory, and UCLA colleagues. Web site: http://activetectonics.la.asu.edu/atf/atf.html.

In three field seasons, we studied a 585 km--long reach of the central Altyn Tagh fault (ATF) in Xinjiang, China to document the fault trace geometry and evidence for recent ruptures along this major structure. Efforts included:

- *Earthquake geology investigations*. We excavated ~15 trenches including three sets of large ones (~100 cubic meters) to determine the timing of the most recent and penultimate earthquakes along the Altyn Tagh Fault. We also measured more than 135 offset landforms to estimate the slip distribution in the last earthquakes. In the eastern 250 km, we identified three geometric segments bounded by left steps along the ATF and determined that the last earthquake produced 2--7 m minimum offsets. ^{14}C and infrared stimulated luminescence dates and trench logs of disrupted sediments from sites 140 km apart indicate that the central ATF produced two to three earthquakes (M7.1 -- 7.6) in the last 2000-3000 years.
- *Compilation of instrumental and Chinese historic and paleoseismic earthquake records* (http://activetectonics.la.asu.edu/atf/seismicity).

<u>*Publications (not including abstracts or thesis; * indicates student coauthor)*</u>

Cowgill, E., Yin, A., Arrowsmith J R., Xiaofeng, W., Zhang, S., The Akato Tagh bend along the Altyn Tagh fault, NW Tibet 1. Cenozoic structure, smoothing by vertical-axis rotation, and the effect of topographic stresses on borderland faulting, *Geological Society of America*, accepted pending revisions (9/2003).

Cowgill, E. Arrowsmith, J R., Yin, A., Xiaofeng, W., Zhengle, C., The Akato Tagh bend along the Altyn Tagh fault, NW Tibet 2. Active deformation and the importance of transpression and strain-hardening along the Altyn Tagh system, *Geological Society of America*, accepted pending revisions (9/2003).

Washburn*, Z., Arrowsmith, J R., Dupont-Nivet, G., Feng, W. X., Qiao, Z. Y., Zhengle, C., Paleoseismology of the Xorxol segment of the Central Altyn Tagh Fault, Xinjiang, China, Annals of Geophysics, *in press*, 2003.

Washburn*, Z., Arrowsmith, J R., Forman, S. L., Cowgill, E., Wang, X. F., Zhang, Y. Q., and Chen, Z. L., Recent earthquake geology of the central Altyn Tagh Fault, China, *Geology*, 29, No. 11, p. 1051–-1054, 2001.

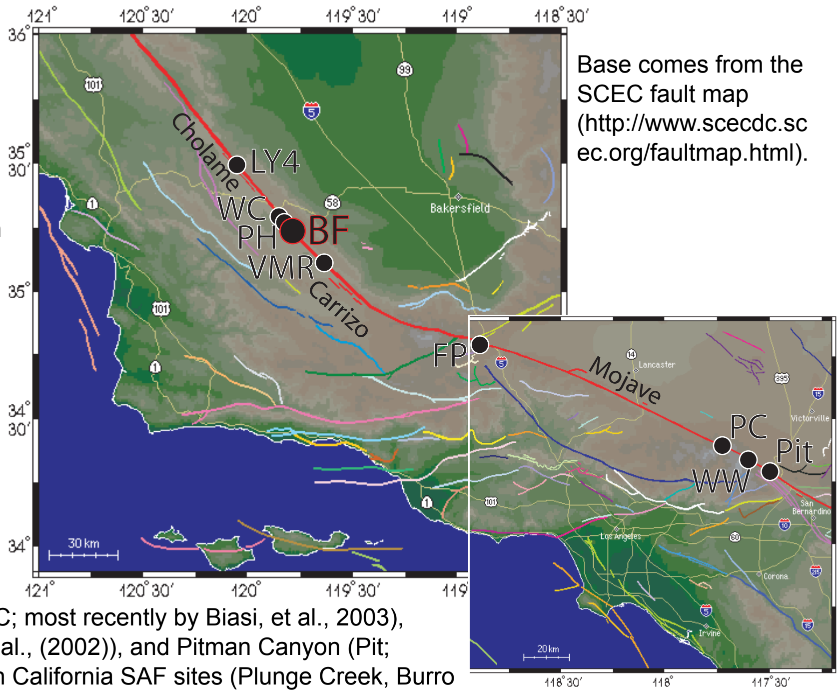
C.5.1 Results from most related prior NSF support--Grant

Grant received prior NSF support only as flow-through funds via the Southern California Earthquake Center (an NSF Science and Technology Center). Since these were not contracted directly with NSF, a full report is not included here, although 2 of 7 resulting journal articles are listed below because they are not listed elsewhere in this proposal:

Grant, L. B., J. T. Waggoner, C. von Stein and T. Rockwell, Paleoseismicity of the North Branch of the Newport-Inglewood Fault Zone in Huntington Beach , California, from Cone Penetrometer Test Data. Bulletin Seismological Society of America, v. 87, no. 2, p.277 - 293, 1997.

Grant, L. B. L. J. Ballenger, and E. E. Runnerstrom. Coastal uplift of the San Joaquin Hills, Southern Los Angeles basin, California, by a large earthquake since 1635 A.D. Bulletin Seismological Society of America, v. 92, no. 2, p.590-599, 2002.

Figure 1. Location map of major paleoseismic sites along the south-central SAF (red line). The Bidart Fan site (BF; Grant and Sieh, 1994 and this proposal) is located in the north-central portion of the Carrizo section of the SAF; south of LY4-Cholame, near the Wallace Creek study site of Liu, 2003 (WC), Phelan Creeks (PH; Sims, et al.), and northwest of Van Matre Ranch (VMR; where we currently are working). The Frazier Park site of Lindvall, et al. (2002) is along the northern portion of the Mojave section which is well characterized to the southeast at Pallet Creek (PC; most recently by Biasi, et al., 2003), Wrightwood (WW; Fumal, et al., (2002)), and Pitman Canyon (Pit; Seitz, et al.). Other Southern California SAF sites (Plunge Creek, Burro Flat, and Thousand Palms) are located southeast of this map.



Base comes from the SCEC fault map (http://www.scecdc.scec.org/faultmap.html).

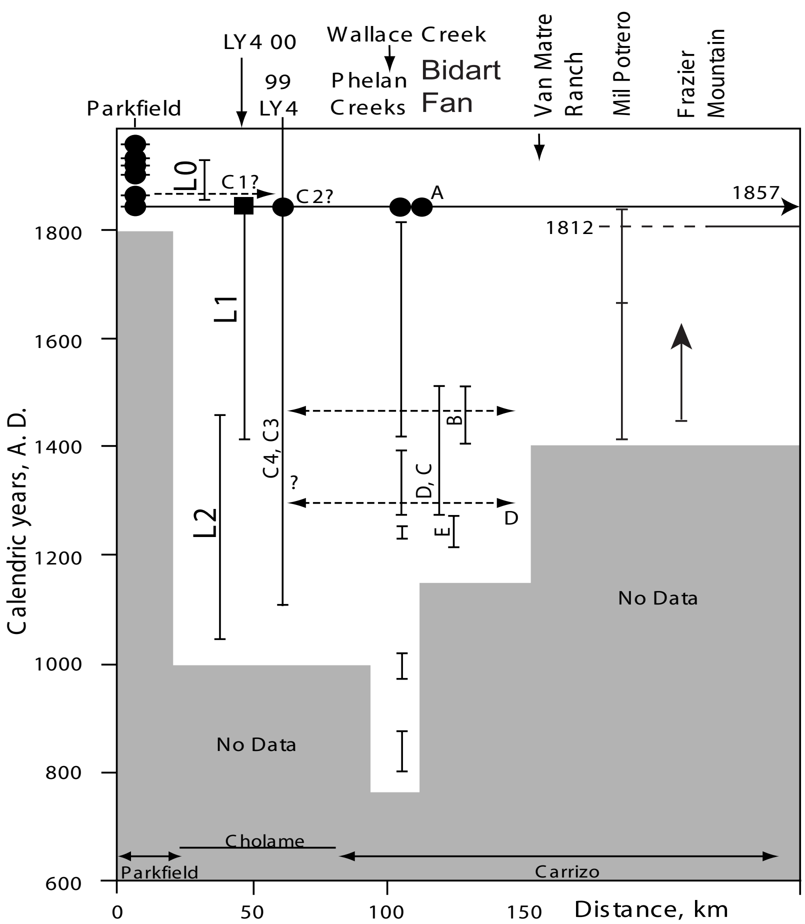


Figure 2. Event correlation diagram for the Parkfield, Cholame, and Carrizo segments of the SAF (modified from Young, et al., 2002 and Liu, 2003). Results from this project will lengthen and thus anchor the paleoseismic record for this important section of the SAF. Data are from: The historic Parkfield record (e.g., Bakun and Lindh, 1985), LY4-99 (Stone, et al., 2002), LY4-00 (Young, et al., 2002), Phelan Creeks (J. D. Sims, personal comm.), Bidart Fan (Grant and Sieh, 1994), Mil Potrero (Davis, 1983), and Frazier Mountain (Lindvall, et al., 2002).

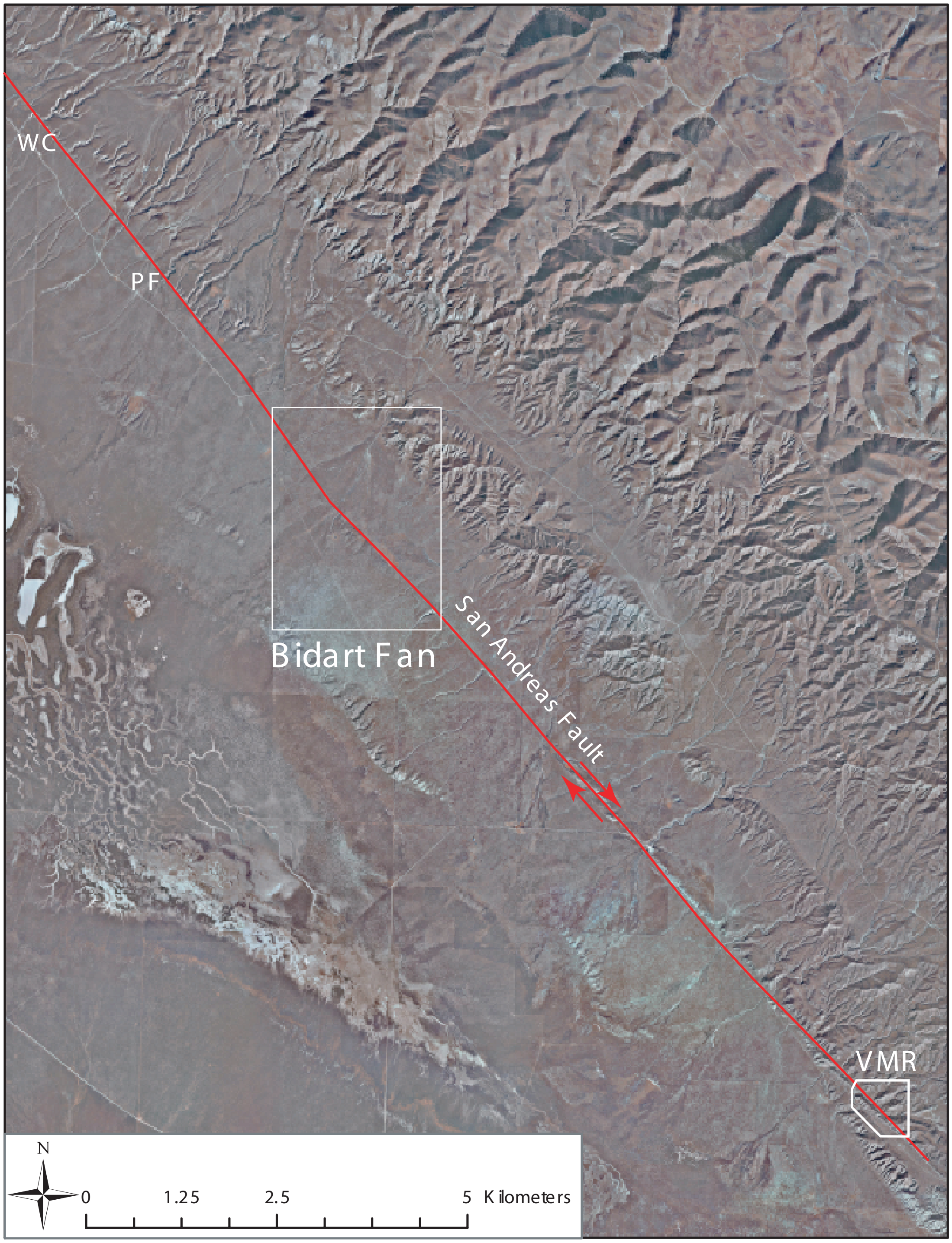


Figure 3. A) Aerial photography (from AirPhoto USA) of the central Carrizo Plain showing the locations of major paleoseismic study sites (WC, Wallace Creek; PF, Phelan Fan; Phelan Creeks; PH; BF, Bidart Fan; and VMR, Van Matre Ranch). Note the spectacular tectonic landforms along this portion of the SAF in the Carrizo Plain. Figure 4 outline is shown as the Bidart Fan rectangle.

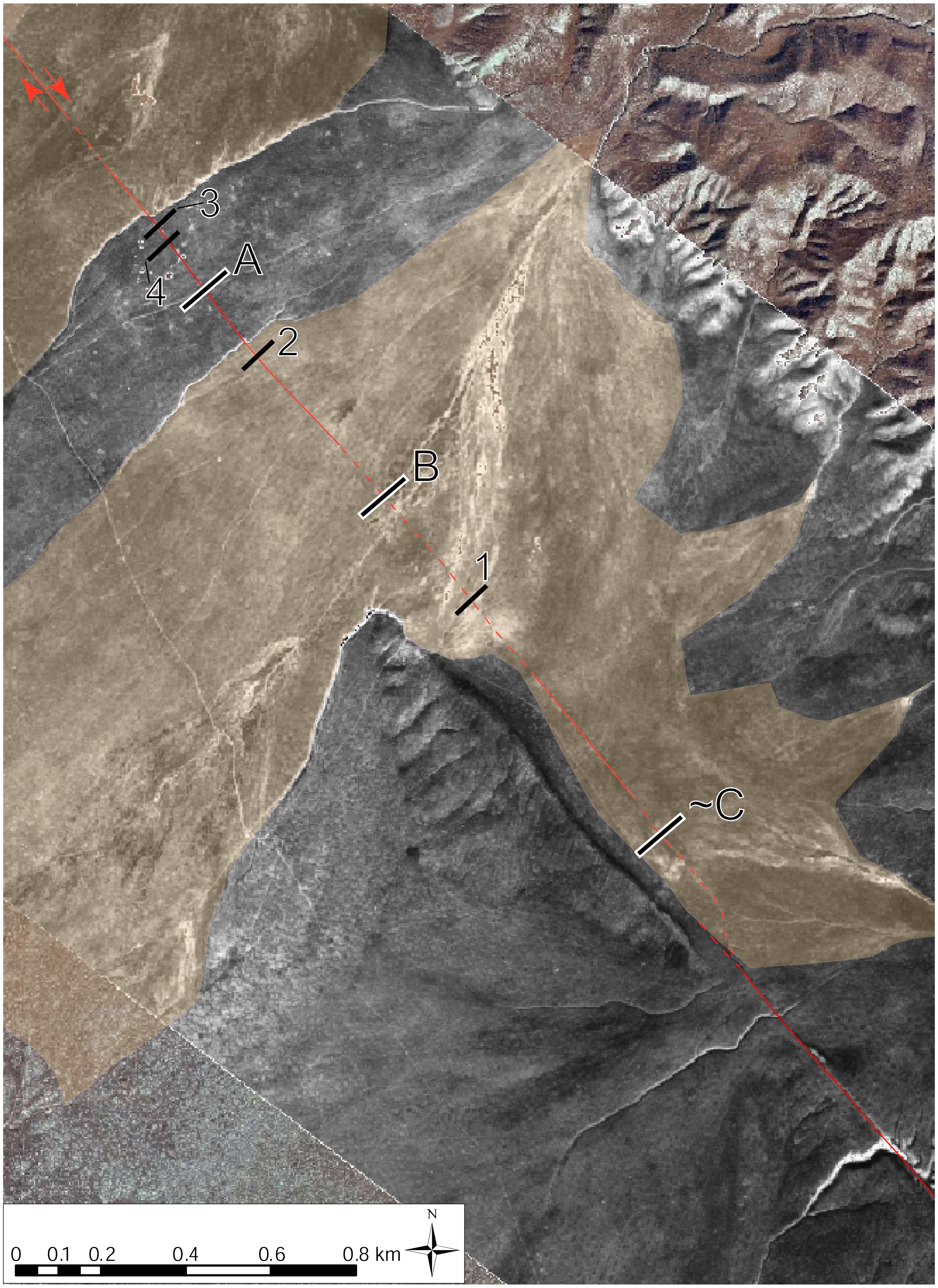


Figure 4. 1936 aerial photograph (from the Fairchild Aerial Photography Collection) showing the clear 1857 (and earlier) rupture traces at the Bidart Fan. Numbered trench locations are from Grant and Sieh, 1994. Lettered excavations are those proposed in this study. Trench C's location will be determined after examining the record from A and B.

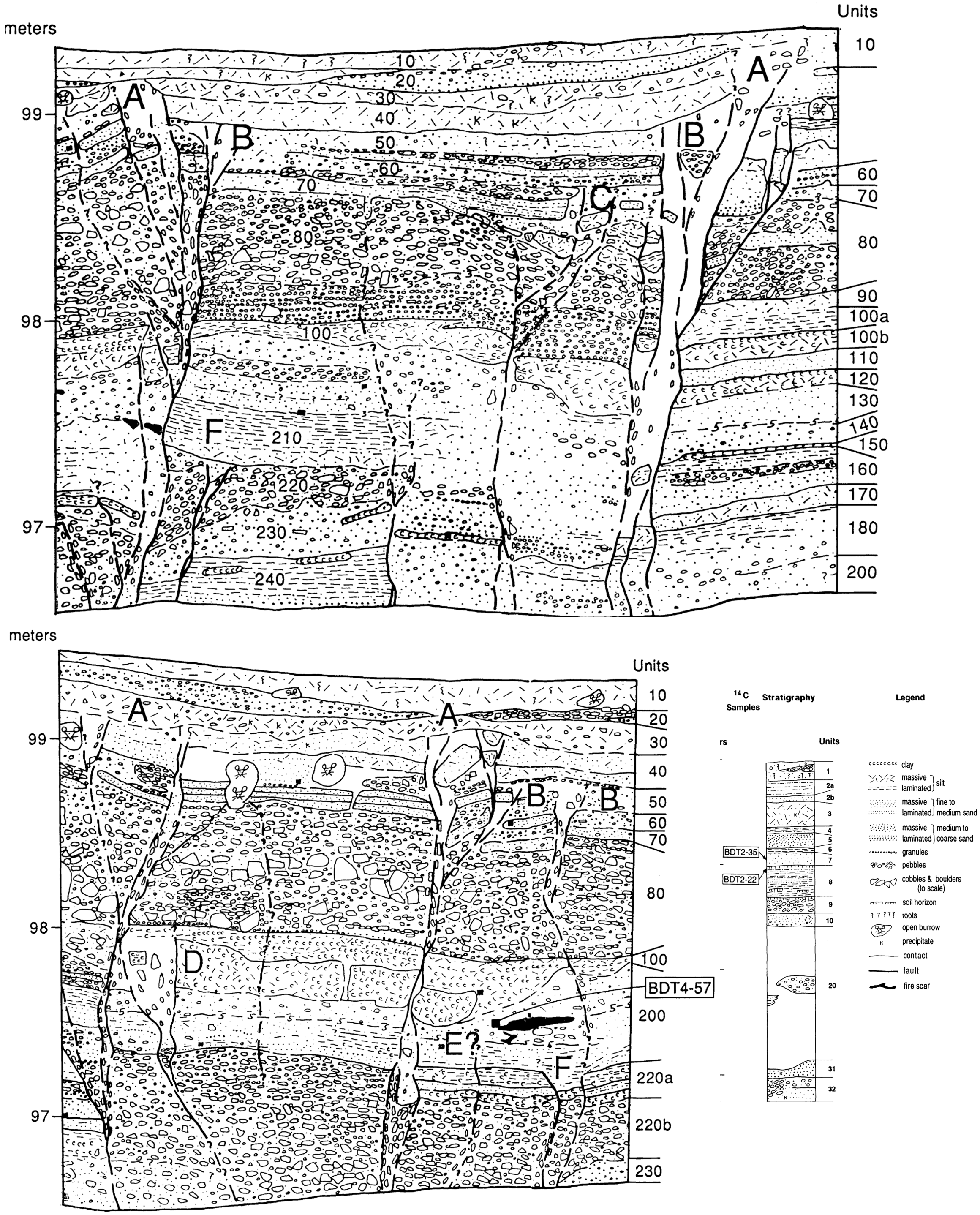


Figure 5. Logs of portions of the southeast (A) and northwest (B) walls of trench 4 from Grant and Sieh, 1994. Capital letters make the appoximate locations of stratigraphic evidence for the events. Units are numbered. View is toward the southeast. Blank areas are fault-zone breccia or bioturbated zones. Inset stratigraphic columnshows main units and presents the explanation for the logs.

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