The Oak Creek Post Fire Debris and Hyperconcentrated Flows of July 12, 2008 Inyo County, California: A Geologic Investigation

By

David L. Wagner, Jeremy T. Lancaster, and Margie B. DeRose

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JOHN G. PARRISH, Ph.D.
STATE GEOLOGIST

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Author Affiliations

David L. Wagner, PG #3440, CEG #1028, California Geological Survey, Independence, CA

Jeremy T. Lancaster, PG #7692, CEG #2379, California Geological Survey, Sacramento, CA

Margie B. DeRose, PG #8576, Formerly Geological Society of America, GeoCorps Program, Inyo National Forest and Bureau of Land Management; Currently, Inyo National Forest

THE OAK CREEK POST FIRE DEBRIS AND HYPERCONCENTRATED FLOWS OF JULY 12, 2008 INYO COUNTY, CALIFORNIA: A GEOLOGIC INVESTIGATION

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ABSTRACT

On July 12, 2008 remnant moisture from hurricane Bertha moved from the Gulf of Mexico across the southwestern United States bringing tropical moisture to the Eastern Sierra Nevada. Rainfall intensities reportedly as high as 97 mm/hr (3.8 in/hr) occurred for a period of 39 minutes on the Oak Creek drainage north of Independence, in Inyo County, California. This area had been burned during the Inyo Complex fire of July 6, 2007. The storm generated debris and hyper-concentrated flows ran out 6 to 7 km (~3.8 to 4.4 mi) from the mountain front, reportedly damaging or destroying 50 residential structures, severely damaging the historic Mt. Whitney Fish Hatchery, and disrupting traffic on State Highway 395 for nearly a week. Although slopes were extensively rilled, most of the estimated 1.5 million cubic meters (~2.0 million yd^3) of transported sediment was scoured from channels and deposited over an area of more than 3 km^2, mostly on younger alluvial fans. Surges moved down the North Fork of Oak Creek at estimated velocities of 2 m/sec (~4.5 mi/hr) to 5.4 m/sec (~12 mi/hr) and were one to three meters high. Sand-rich, hyper-concentrated flows followed the active channel of the North Fork of Oak Creek and filled the channel where it debouched on the alluvial fan surface, spreading sediment and debris laterally across the distributary fan interfluves. Several avulsions occurred as the result of either channel plugging and flow redirection, or as channel overflow. On the South Fork of Oak Creek, boulder-rich debris flows clogged the active channel, and created a boulder field of at least 1,500 m (4,600 ft) long and 75 m (230 ft) wide on the upper portion of the young alluvial fan surface. The channel of the South Fork was forced to a new course to the west. Boulders ranging from less than one meter to over three meters across, weighing up to ~26,000 kg (~57,000 lbs) were moved by the flows. Flooding and debris deposition occurred within the active stream channels and on significant portions of the young alluvial fan surfaces; older alluvial fan surfaces were unaffected, supporting the hypothesis that younger fan surfaces are the ones most likely to be affected by post-fire debris and hyper-concentrated flows.

INTRODUCTION

As is well documented in southern California, fires greatly increase runoff as well as both the probability and volume of debris laden flows issuing from mountain canyons on to alluvial fan surfaces (See Chawner, 1934; Troxell and Peterson, 1937; Rowe et al. 1949; Wells, 1987; Spittler, 1995; Cannon, 2001, Cannon and Gartner, 2005; and Cannon et al., 2010). Research in recently burned areas in California, Colorado and Utah (Santi et al., 2007) shows that most post-fire debris flows are initiated by runoff and erosion and grow in size through erosion and scour in channels by moving debris. Most commonly, post-fire debris flows occur within two years after a fire (USGS, 2005) and can be triggered during storm events with return periods of two years or less (Cannon, 2008).

The July 12, 2008 rainfall event occurred on the Oak Creek drainage as the remnants of hurricane Bertha moved from the Gulf of Mexico across the Southwest to the Eastern Sierra Nevada (Jayko, 2009), causing thunderstorms and local pockets of intense rain (DeGraff et al., 2011). In the late afternoon, a cell of intense rain centered on the Oak Creek drainage that had been burned two years prior in a lightning-sparked range fire in July 2007. Between 4:00 and 5:00 P.M., water, sediment, and debris began moving down tributaries in the Oak Creek drainage area, eventually concentrating in the North and South forks of Oak Creek (Figures 1,2, and 3). At about 5:30 P.M. a hyperconcentrated flow (a flow consisting of water, sediment and debris) destroyed a motor home parked at the Oak Creek campground on the North Fork of Oak Creek, and its sole occupant managed to survive by “body surfing” over a 1.6 km (1 mile) (Figures 4a,b). About the same time, sediment ranging in size

Figure 1: Aerial view of the Owens Valley and the Eastern Sierra Nevada showing the location of the Oak Creek tributaries near the town of Independence, CA. Note deposition features on the younger fan of the North Fork, see Plate 1 for mapped extent of debris and hyperconcentrated flow deposits. (Map base: 2009 USDA NAIP, and 10-Meter USGS digital elevation model)

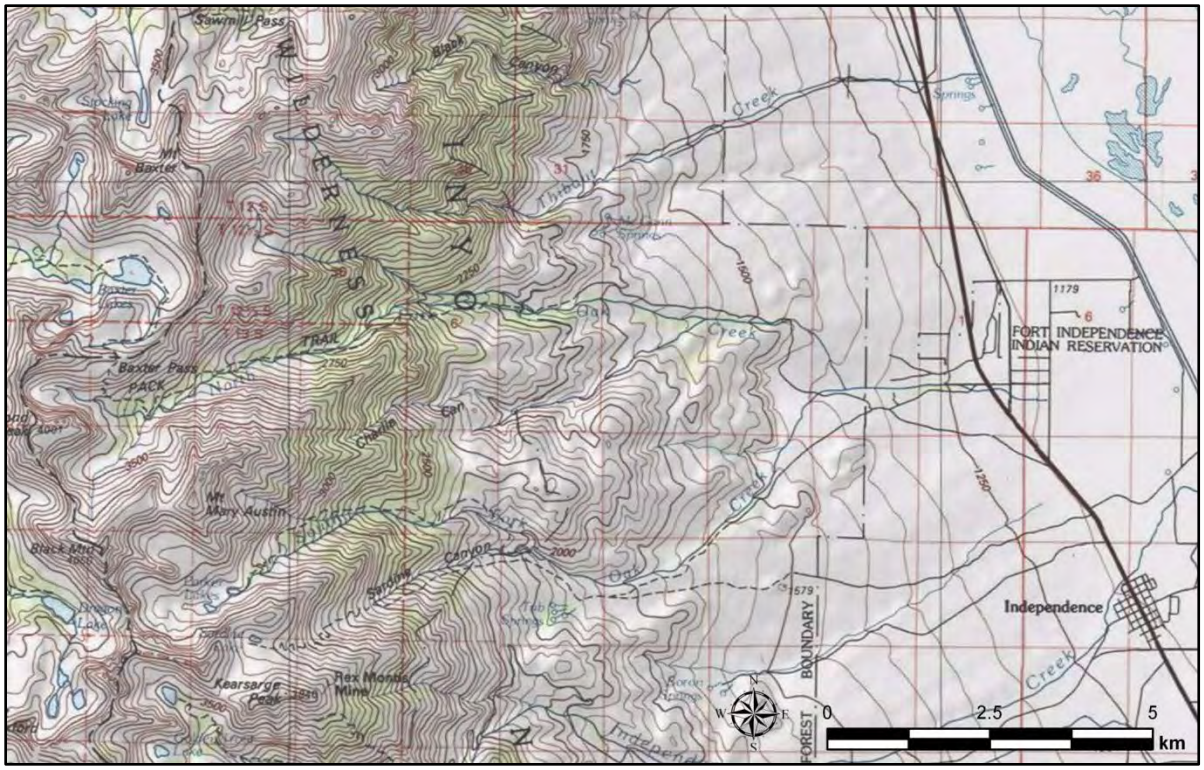

Figure 2: Part of the topographic map of the USGS Mount Whitney 30X60 Minute Quadrangle showing the Oak Creek and surrounding watersheds situated near the town of Independence, CA.

Figure 3: Hyperconcentrated flow on the younger fan of the North Fork of Oak Creek. (Photo by Ken Babione)

Figure 4a: Remains of motor home at Oak Creek Campground.

Figure 4b: Pickup truck that was transported down-fan by the hyperconcentrated flow.

up to boulders larger than 2 m (~6 ft) in diameter moved down the South Fork of Oak Creek, destroying the Bright Ranch (Plate 1). Fortunately, no one was there at the time. Flows from the North and South forks combined in a fan coalescing zone and continued down the main stem Oak Creek, severely damaging the Mt. Whitney Fish Hatchery as well as several State Department of Fish and Game employee residences. According to news reports, 25 homes were destroyed and another 25 were damaged to some extent (Inyo Register**,** July 15, 2008). Relatively few people were in the homes, and luckily there were no serious injuries or fatalities among the residents. At 5:30 P.M., the Independence Volunteer Fire Department received reports of flooding and responded along with Cal Fire personnel to find sediment and debris flowing across Highway 395. At 6:30 P.M. the California Highway Patrol closed the highway. At 11:45 P.M., the California Highway Patrol began escorting motorists across the still flooded portion of the highway; escorts continued for nearly a week. Most of the sediment and debris that intersected Highway 395 flowed south along the highway to a topographic low point and then turned eastward, almost reaching the Los Angeles Aqueduct.

Flows from the North and South forks merged near the fish hatchery and filled the channel of Oak Creek, forcing it to incise a new channel south of the old one. The South Fork of Oak Creek was also diverted by boulder debris into a pre-existing more northerly channel west of the fish hatchery. This sudden cutting off of an existing channel and the formation of a new flow path is called avulsion, and is a characteristic component of distributary flow patterns on alluvial fans.

Well preserved evidence of flow behavior, channel scour, and deposition found in the Oak Creek drainage following the event, provide a wealth of evidence for scientific observation. This report presents the results of observations and mapping to document size and nature of this flood event, as well as the physical factors contributing to the event.

Terminology

Common terms used to describe flow behavior include but are not limited to streamflow, hyperconcentrated flow, debris flow, mudflow, debris torrent, mud flood, and debris avalanche (Pierson and Costa, 1987). This event has been described as a flash flood, as a mudslide (Inyo Register, July 15, 2008), and as a debris flow (DeGraff, 2008). One witness observed the distal portion of the flow, saying “It reminded me of volcanic lava. It was black and that’s

how it moved. It was moving forward, but at a very slow rate of speed. What caught my attention was a tree floating across the road upright" (Inyo Register, July 15, 2008). A flow that can support an upright tree is viscous, behaving as a non-Newtonian fluid and would likely be classified as a debris flow. Conversely, mud spatters on buildings, trees, and rock outcrops were observed reaching several meters high, indicating portions of the flow exhibited turbulent flow behavior.

The term 'flood' is commonly, and sometimes mistakenly mixed with terms used to describe flow behavior (e.g. mud flood). Flooding has a geomorphic context, and the term flooding may be defined as: the result of flow exceeding channel bankfull capacity through overflow (Graf, 1988). Flooding in the alluvial fan environment is similar to flooding in the riverine environment – only in that in both cases, water "accumulates" in a channel as a result of rainfall, and runoff from overland flow. However, on alluvial fans, flow is tributary in the uplands, but becomes distributary below the fan apex, and flow behavior is more variable in runoff from mountainous watersheds on to alluvial fans than in most riverine systems. The National Research Council (NRC, 1996) developed the term "alluvial fan flooding" that captures the distinct geomorphic process of flooding on alluvial fans, and the term now has a basis in the National Flood Insurance Program. The NRC definition includes the entire continuum of flow behavior, typically subdivided into the terms streamflow, hyperconcentrated flow, and debris flow. These types of flow behavior are discussed below.

Streamflows typically exhibit turbulent behavior, and have sediment concentrations below 20 percent by volume. The transition from turbulent Newtonian streamflow to non-Newtonian flow is strongly dependent on sediment concentration and particle size distribution because of particle interactions (Cannon et al., 1995). Sediment concentrations in hyperconcentrated flows generally range from about 20 to 60 percent by volume (depending on grain-size distribution), overlapping in range with debris flows (Pierson and Costa, 1987; Costa, 1988). Clay concentrations as low as 3 to 13 by volume may cause particle interactions and suspension to occur, the dampening of turbulence, and the development of yield strength in the flow. In contrast, streamflows absent of fines may not develop particle interaction and yield strength at sediment concentrations as high as 50 percent by volume (Pierson and Costa, 1987). Sediments are deposited from hyperconcentrated flows while the remaining fluid continues to flow resulting in clast-supported deposits that exhibit some sorting (Cannon et al., 1995) (See descriptions in Table 1). Hyperconcentrated flow seems to apply to most of the sediment-water mixtures that flowed down the North Fork of Oak Creek.

Sediment concentrations generally above 60 percent by volume are defined as debris flows (Pierson and Costa, 1987). Debris flows are a form of mass wasting which may initiate as landslides along steep slopes, or in stream channels as a result of scour and bank collapse, and progressive entrainment of sediment (in-channel bulking) in floodwaters. Flow behavior varies with water and clay content as well as grain size distribution (Costa, 1984; Pierson and Costa, 1987; Costa, 1988; Cannon et al., 1995). Thick viscous granular flows with a wide range of particle sizes, but very little fines content, contrast with fluid flows, dominated by fine-grained matrix (Iverson, 2003). In viscous granular debris flows only the largest particles (i.e. boulders) are deposited from suspension and the mixture comes to rest en masse (Cannon et al., 1995).

Observations during this investigation indicate that the leading edges of all the flows were bulked with sediment and

TABLE 1:
General classification of flow behavior related to sedimentary structures and geomorphology (modified after Costa, 1984; Costa, 1988, and Giraud, 2005).

Flow Type	Sediment Load‡		Sedimentary Structures	Deposits and Landforms
	By weight*	By volume†		
Streamflow	1-40%	0.4-20%	Well to moderately sorted, stratified to massive; weak to strong imbrication; cut-and-fill structures; ungraded to graded	Bar and swale, fans, sheets, splays; channels have high width-to-depth ratios
Hyperconcentrated flow	40-70%	20-60%	Poorly sorted and weakly stratified to massive; thin gravel lenses; clast supported; normal and reverse grading	Similar to streamflow; transitioning to sheets, splays and lobes at the higher end of the sediment/water continuum
Debris flow	70-90%	>60%	Very poor to extremely poorly sorted; no stratification; weak to no imbrication; matrix supported; inverse grading at base; normal grading near top	Marginal levees, terminal lobes, boulder fields (in coarse-grained viscous flows); sheets, lobes, and splays (in finer-grained fluidized flows with lower viscosity)

‡These values are general guidelines used to classify flow types in a continuum of sediment, debris and water mixtures.
***Values are provided in Costa, 1984, reportedly assuming <10% clay content.**
†Values from Pierson and Costa, 1987

were in fact debris flows that in some cases were trailed by hyperconcentrated flows. This is consistent with the findings of Iverson (2003) that no single flow type can describe the variation that occurs during one event and is a logical reason why the term debris flow is used to describe debris laden flows (hyperconcentrated flows and debris flows) that leave behind deposits of poorly sorted sediment and debris (Giraud, 2005). For this report, the terms debris flow and hyperconcentrated flow, are used, or are generically termed 'flow(s),' keeping in mind that as sediment content increased in settings such as the flow front or where material overflowed channels, debris flow behavior was dominant. Determination of debris flow versus hyperconcentrated flow is based on field observation of geomorphic features and the sedimentological nature of the deposits.

Despite the complex nature of flow behavior observed, the July 2008 flows resulted in wide spread flooding, as well as mobilization, transport, and deposition of large amounts of debris.

Methods

To aid in understanding the context of the July 12 debris and hyperconcentrated flows, Wagner compiled a geologic map of the Quaternary deposits in the Oak Creek drainage (Plate 1). Boundaries of the flow source areas, including areas of erosion and concentrated flow were mapped by DeRose (Plate 2) from field observations as well as reviews of black and white and natural color aerial photographs taken both

before and after the July 12, 2008 event. Natural color aerial photographs (nominal scale 1:6,000) taken for the California Department of Transportation (Caltrans) shortly after the event provided the most useful information. The extent of the mapped flow is depicted on the geologic map (Plate 1) as geologic unit, Qdh.

Profiles of the major sediment-producing channels of Oak Creek drainage were measured to determine cross-sectional area of channels for use in estimating the debris yield rate (Hungr, 2005), which is expressed as volume of sediment, soil and organic material yielded per meter of channel. The profiles were measured with a laser range finder. Errors due to this measuring technique are estimated at ± 1 meter (± 3 ft). Number and spacing of the profiles were based on amount and variability of channel dissection. Dissection of the North Fork and South Fork of Oak Creek is relatively uniform compared to the middle fork, so debris yield could be estimated using far fewer profiles. On the middle fork, 19 profiles were measured as opposed to seven for the North Fork and four for the South Fork. Spacing of the profiles was dictated by changes in channel morphology so extrapolation of debris yield between profiles was based on a similar depth and width of dissection.

PHYSIOGRAPHIC AND GEOLOGIC SETTING

The Oak Creek watershed is approximately 61.5 km^2 and is drained by two major tributary systems, the 33.2 km^2 North Fork of Oak Creek, and the 22.8 km^2 South Fork of Oak Creek (tributary drainage area measured to fan apex). Oak Creek

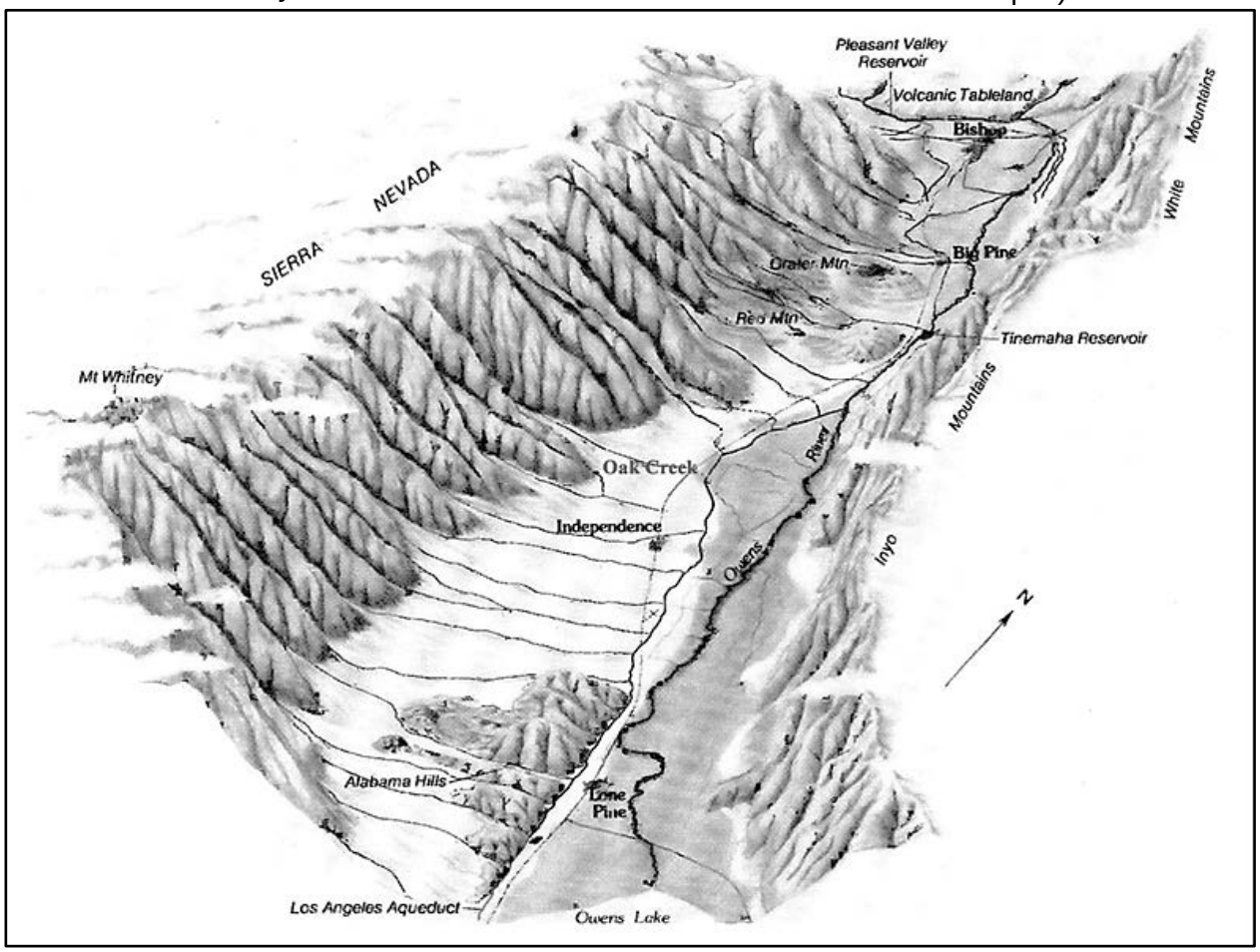

Figure 5: Oblique view of Owens Valley. Vertically exaggerated to show topographic relief between the valley and surrounding mountains (from Hollet et al., 1989).

drains part of the great eastern escarpment of the Sierra Nevada on the west side of Owens Valley just north of the town of Independence. Owens Valley is the westernmost internally draining graben (down-dropped fault block) of the Basin and Range geomorphic province, and lies in the southwestern part of the Great Basin of North America. The distinctive physiography of north to northwest-trending mountain ranges separated by fault-bounded valleys that formed in response to crustal extension is characteristic of much of the Basin and Range province. Crustal blocks west of Owens Valley, including the Sierra Nevada, move to the northwest relative to the Colorado Plateau, pulling apart the earth's crust to form north-trending mountain ranges and intervening basins including the Owens Valley. The south-southeast trending Owens Valley is about 30 km (20 mi) wide and extends for about 120 km (75 mi) from the Volcanic Tableland near Bishop, to Owens (dry) Lake (Bierman and others, 1991). Mountains rise steeply on both sides of the valley to 3,000 to 4,000 m (9,100-12,200 ft) above the valley floor, which is just over 1,000 m (3,000 ft) elevation in the south to 1,300 m (4,000 ft) north of Bishop (Figure 5). To the west is the Sierra Nevada, a west-tilted, fault-block mountain range with a steep, rugged eastern escarpment and a relatively gentle western slope. To the east is the White-Inyo Range, equally rugged, but quite arid because of the rain shadow effect of the Sierra. Displacement along range front faults that bound both the Sierra and the White-Inyo Range drops the valley down relative to the mountains. Faults making up the Sierra Nevada frontal fault zone cut Pleistocene alluvial, glacial, and colluvial deposits (Gillespie, 1982; Le et al., 2007; Zehfuss et al., 2001; Slemmons et al., 2008). On the east side of the valley, discontinuous range front faults include the Inyo Mountains and White Mountains faults which both have lateral and vertical movement (Bacon et al., 2005; dePolo, 1989). A third fault zone, the Owens Valley fault zone, transects the valley floor displaying right-lateral movement though there is a component of vertical, down-to the-east displacement (Slemmons et al., 2008). In 1872, a devastating earthquake occurred on the Owens Valley fault. It is the largest earthquake to strike the Great Basin in historic time (Bacon et al., 2006), producing at least 110 km (69 mi) of surface rupture (Beanland and Clark, 1994). Scarps along the Owens Valley fault can be traced across Owens Lake to Lone Pine and from Lone Pine to just south of Tinemaha Reservoir.

During the latest Miocene and earliest Pliocene, what is now Owens Valley was probably a shallow basin on a broad, low-relief plateau (Phillips, 2008). At about 4-3 Ma, rapid subsidence was initiated and the long, straight Owens Valley we see today began to take shape (Phillips, 2008). As the valley subsided, streams cut deep, steep-walled canyons into the eastern slope of the Sierra Nevada. Bouldery sediment derived from the mountains emanated from the rugged canyons as debris flows and hyperconcentrated flows, forming broad fans extending 10 or more km (6 mi) from the range front into Owens Valley. A broad belt of coalesced fans called a bajada (Trowbridge, 1911; Gillespie, 1982) extends from Lone Pine to Big Pine. Bajada morphology is best displayed between Onion Valley and the Alabama Hills (Figure 6). In the Oak Creek drainage, the bajada is interrupted by bedrock foothills that blocked transport of sediment until the late Pleistocene. Gillespie et al. (1991b) proposed that fan development correlates with glacial advances when the glaciers produced large amounts of unstable sediment susceptible to mobilization as debris flows. However, Dűhnforth et al. (2007) have demonstrated that fan-forming debris flows also occurred during interglacial periods and that fans that do not have deeply incised (entrenched) heads can be mantled with Holocene debris flow deposits.

Figure 6: Photo of the great bajada (coalesced alluvial fans) looking south from Onion Valley Road with the Sierran escarpment in the right background and the Alabama Hills in the left background.

From a distance the bajada looks smooth (Figure 6) but the surface has many features such as boulder fields, debris flow channels with boulder levees, and debris flow lobes composed of boulders. Channels are often plugged with boulders where debris flows came to rest, forcing the stream to abandon the channel. Abandoned channels are relatively straight, have U-shaped cross sections with width-to-depth ratios of 7 to 12 and decrease in cross section area downstream (Whipple and Dunne, 1992). Whipple and Dunne (1992) concluded that channels on the bajada were cut by streams, not debris flows. They further concluded that some debris flows stopped near the heads of fans and formed plugs and lobes while others continued down the fans, spread out, and left thin, tabular deposits. Whipple and Dunne (1992) evaluated the textural, rheological and morphological aspects of these deposits and identified that: (1) "high-sediment" debris flows with a greater percentage of coarse clasts (>32 mm) are typically restricted to the steeper upper parts of the fans where they leave boulder levees, snouts, and lobes, and (2) "low-sediment" debris flows, with much lower viscosities and yield strengths (and with a lower percentage of coarse clasts), respond to the channel systems they encounter, and have longer runout distances. They described these lower viscosity flows as being highly mobile, moving rapidly in unblocked channels, and when they exceed the capacity of the channels they spread out onto terraces of the fan surface leaving thin, sand-rich overbank deposits.

Bedrock of the Owens Valley consists of Proterozoic and Paleozoic sedimentary and metamorphic, Mesozoic granitic, and Cenozoic volcanic rocks (Knopf, 1918; Moore, 1963; Bateman, 1965; Nelson, 1966, Ross, 1965; Stone et al., 2000). Proterozoic and Paleozoic rocks consist of marine limestone, dolomite, shale, siltstone, sandstone and other minor rock types, principally found in the White-Inyo Range, but they also occur in the Alabama and the Poverty hills. Plutons of Mesozoic granite form the core of the Sierra and are also present the White-Inyo Range as well as in the Alabama and Poverty Hills. Presumably the granite also forms the bulk of the bedrock beneath Owens Valley as well. Cenozoic volcanic rocks include the basaltic and rhyolitic lava of the Big Pine Volcanic field and the Bishop Tuff, which forms the Volcanic Tableland at the north end of Owens Valley (Figure 5).

The Big Pine volcanic field encompasses approximately 1,000 square km of basalt flows at the surface with an unknown volume interbedded with valley fill in the subsurface. At least 40 cinder cones and one rhyolite dome (Gillespie, 1991a) were, for the most part, erupted along faults bounding the Owens Valley. Basalt lava flows issued from the cinder cones and flowed over the alluvial fans toward the center of the valley. Volcanism occurred episodically through most of the Quaternary but most dated flows are between 100 and 500 ka, though some of the flows may be as young as 10 ka (Gillespie, 1991a).

Valley fill is a mixture of gravel, sand, silt and clay deposited by fluvial, lacustrine, and aeolian processes. Fluvial sediment deposited by the Owens River in its meander belt overlies lacustrine deposits of Pleistocene Owens Lake, and interfingers

with alluvium from the Sierra and the Inyo ranges as well as with lava flows of the Big Pine volcanic field.

Geology of the Oak Creek Drainage

Plate 1 is a geologic map showing the distribution of Quaternary deposits in Oak Creek drainage that overlie the Mesozoic granitic and older metamorphic bedrock mapped by Moore (1963). Quaternary deposits overlying bedrock include alluvium, basaltic lava flows, glacial outwash and moraines, landslide deposits, colluvium, and the sediment and debris deposited during the flow of July 12, 2008. Alluvial fan deposits are divided into three units, very old fan, old fan (North and South Fork fans on Plate 1) and younger fan (North and South forks of Oak Creek on Plate 1).

Very old alluvium is the oldest surficial unit overlying the bedrock. It underlies the older fans of both the North Fork and South Fork of Oak Creek and crops out in isolated areas along North Fork and South Fork of Oak Creek. Virtually all of the granitic clasts have weathered away leaving only more resistant rocks, which are stained a deep red color. The very old alluvium is early Pleistocene to late Pliocene in age (Gillespie, 1982).

Basaltic lava flows along the North Fork of Oak Creek and in the foothills were erupted from sources higher in the mountains. These flows are among the oldest of the Big Pine Volcanic field (Darrow, 1972; Gillespie, 1982). Gillespie (1982) divided the flows of the Big Pine field into four of subdivisions. Undivided lava flows are shown on Plate 1 as Qv and two of the subdivisions are shown as Qv1 and Qv2. Qv caps the ridge between the North and middle forks of Oak Creek. Isotopic dates on the ridge-capping flows range from approximately 1.2 Ma to 208 ka (Blondes, 2008; Gillespie, 1982, Gillespie et al., 1983). A second group of flows (Qv1 and Qv2) are interbedded with fanglomerate of the older fan of the North Fork of Oak Creek (Plate 1). Isotopic dates on these flows range from 420 ka to 100 ka (Bierman et al., 1991; Blondes et al., 2007). These dates provide important time constraints on the abandonment of the older fan of the North Fork of Oak Creek and the initiation of the younger fans of the North Fork and South Fork of Oak Creek.

Older fanglomerate (Qvof, Qof), consisting of boulders, cobbles and pebbles in a clay-rich, sand and silt matrix makes up the older fans of the North and south forks of Oak Creek. Granitic boulders and cobbles are deeply weathered. The older fan has a smooth surface underlain by a well developed, reddish soil rich in grus, making it distinct from the younger, gray-colored fans (Qyf). All but the largest granitic boulders on the fan surface have been weathered to the level of the fan or disintegrated completely, leaving only the most resistant rocks. The older fans formed during the late Pleistocene when the North Fork of Oak Creek flowed more northeasterly, and the South Fork of Oak Creek flowed more southeasterly than their present courses (Plate 1) (Gillespie, 1982). At that time, there was a continuous bedrock ridge extending from the old fan of the North Fork to the old fan of the South Fork that effectively blocked sediment transport directly to the east (Gillespie, 1982). Basalt lava flows, erupted from sources in the mountains from 420 ka to 100 ka (Bierman et al., 1991), flowed down stream channels on the old fan (Qof) of the North Fork of Oak Creek. After eruption of the youngest lava flow at 100 ka the North Fork of Oak Creek overtopped the bedrock ridge, rapidly eroding a gap allowing sediment transport to the lower area between the older fans (Plate 1). Adjusting to a new, lower base level, the North Fork cut a new channel, nearly due east, and 15 to 20 m (46 to 61 ft) lower than the old fan surface (Gillespie, 1982). Thus it appears that the older fan (Qof) of the North Fork of Oak Creek was abandoned and the younger fan began to form less than about 100,000 years ago. The South Fork of Oak Creek

also eventually overtopped the bedrock ridge and established a new, more northeasterly course that flowed into the topographically lower area between the older fans. The abandonment of the older fan of the South Fork of Oak Creek apparently occurred later than older fan of the North Fork judging by the smaller size and more youthful appearance of the topography of the younger fan of the South Fork of Oak Creek. Both forks of Oak Creek drain similar size watersheds with similar relief and geologic source materials.

The younger fans (Qyf) consist of large (0.2 -1 m) to very large (>1 m) boulders, cobbles and pebbles in a coarse sandy to silty, micaceous matrix. Granitic boulders are fairly fresh to moderately weathered, giving the younger fan a gray color on aerial photos. Abandoned stream channels with boulder levees, boulder debris flow snouts, as well as boulder fields are present on their surfaces. Isotopic dating indicates that the younger fans of the North and South forks of Oak Creek are about the same age as the bulk of fans forming the great bajada between Independence and the Alabama Hills near Lone Pine (Figure 6). Cosmogenic dating indicates the older parts of the fans of the bajada are 80 to 60 ka but are in some areas mantled with Holocene (<11,000 years) debris flow deposits (Dűhnforth et al., 2007; Le et al., 2007). Dating of the lava flows interbedded with the older fan of the North Fork of Oak Creek discussed earlier indicate the older parts of the young fans are the same age and are also mantled with Holocene debris flow deposits.

Glacial moraines (Qmw) occur in the upper reaches of the Oak Creek drainage and glacial outwash (Qow) occurs in the middle parts of the drainage. Moraine sediment, composed of rock fragments ranging in size from pebbles to slabs several meters across, in a clay-rich, silty, sandy matrix, is material transported by glacial ice. Outwash is bouldery sediment that was transported below the limits of glacial ice by water. Both types of glacial sediment are coeval and are also coeval with the younger fans. A rock avalanche deposit on the slope of Kearsarge Peak on the southwest side of the South Fork of Oak Creek is composed of angular boulders of granitic and metamorphic rock. Cosmogenic dating of this deposit by Le et al. (2007) gives an exposure date of ~19 ka, suggesting the avalanche occurred during the Tioga glaciation.

Sediment and debris deposited by the hyperconcentrated flow (Qdh) during the July 12, 2008 storm along the North Fork of Oak Creek is poorly sorted, pebbly, granitic sand, silt, and clay. It is light gray at the surface and brownish gray beneath the surface. Pebbles are mostly granite, angular, up to three centimeters across; set in a matrix comprised of clayey-silty sand that is rich in weathered biotite. Less common are larger pebbles, 3 to 6.4 cm across and cobbles 6.4 to 20 cm across. Grain size analyses of six samples reported by Colburn (2010) showed an average of 15 percent clay and silt, 64 percent sand, and 21 percent gravel. The sediment is notably vesicular. Colburn (2010) reported the presence of air pockets 1-2 mm in diameter in the clayey matrix, and that these vesicles make up about 10 percent by volume of his samples. Granitic and basalt boulders over 1 cubic meter were moved by

Figure 7: Granite slab (volume 9.6 m^3; weight 26,000 kg; 11,800 lbs.) that came to rest gently against a small tree. This is characteristic of debris flows (Costa and Jarrett, 1981).

the hyperconcentrated flow. Boulders up to half a meter across were lodged in tree crotches 1 to 3 meters (3 to 9 ft) above the ground. One slab (1.3 x 2.3 x 3.3m [4 x 7 x 10ft]) came to rest against a tree (Figure 7). The sediment that was deposited by the flow typically occurs as thin sheets that blanket the pre-existing surface. Along stream banks they are commonly thin, 2 to 4 cm (0.78 to 1.6 in), but locally thicken in surface irregularities and in buried former stream channels and swales. The sheets are lobate with sharp bases and concentric flow bands on the upper surfaces, similar to those commonly found on lava flows. The margins of the flow are also lobate, about 40 cm (16 in) thick, and usually lined with tree limbs, bark, twigs and refuse. Flows splashed up trees and over boulders leaving a cement-like crust. Burned vegetation and ash from the Inyo Complex Fire of July 2007 can be seen beneath these deposits along the middle fork of Oak Creek.

Extensive deposits of moderately well stratified sand and gravel underlie the deposit of July 12, 2008 along the North Fork and middle fork of Oak Creek. For the most part, these sediments appear to be overbank deposits from previous flood events. The many springs in this area support lush riparian vegetation and have resulted in interbeds of peat and lignite within the flood deposits, as well as other organic layers that contain charcoal that are likely the result of previous fires. These deposits can be traced along the middle fork of Oak Creek from its confluence with the North Fork up to its confluence with Charlie Canyon. In a few exposures, burned vegetation from the Inyo Complex fire can be seen between the stratified sediments and the recent hyperconcentrated flow deposits.

Three sections of the stratified sediments were measured (Figure 8a,b,c, located in Appendix A). Two of the measured sections (field stations 62 and 63, Figure 9) are near the confluence of the North and middle forks of Oak Creek and the third (field station 15, Figure 9) is about 2.5 km (1.6 mi) upstream on the middle fork of Oak Creek.

The upper part of the sequence at station 62 is stratified, coarse-grained, fluvial, pebbly granitic sand, 0.5 to one meter (1.5 to 3 ft) thick. This sand is interpreted to be overbank deposits laid down during water floods. Below that is an interval of organic-rich sediment composed of both matrix-supported diamictons that appear to be debris flow deposits, as well as, stratified pebbly granitic sand typical of fluvial deposits. The organic layers include horizons of charcoal, 1 to 2 cm (0.63 to 0.78 in) thick, sometimes containing ash, that appear to be in situ burned vegetation. Elsewhere in the section, disseminated organic material occurs in the fine-grained sandy matrix of the diamictons and is likely reworked, and burned branches and twigs as well as charcoal horizons occur in the fluvial deposits. In the area near the confluence of the North Fork and middle fork of Oak Creek, peaty layers several cm thick of decayed riparian vegetation are interbedded with granitic sand that likely buried the vegetation during floods (Figures 8a,b and 11). These peat layers are considered to be black mats typical of spring-fed wetlands in the Great Basin (Quade et al.,1998). The organic-rich intervals, which are 1 to 1.2 m (3 to 3.7 ft) thick, represent a series of fluvial and debris flow deposits associated with one or more prehistoric fires. Radiocarbon dates indicate the youngest organic-rich sediments at station 62 are less than 630 years old at the top, becoming in excess of 1,370 years before present (BP) at the bottom of the exposed section.

At field station 15 the organic-rich section looks similar but it is much older. Radiocarbon dates show the organic-rich section is between 2,200 and 2,400 years old. A 2 m (6 ft) thick cobble-boulder-rich polymict diamicton with a brownish-gray, silty sand matrix lies below the organic-rich

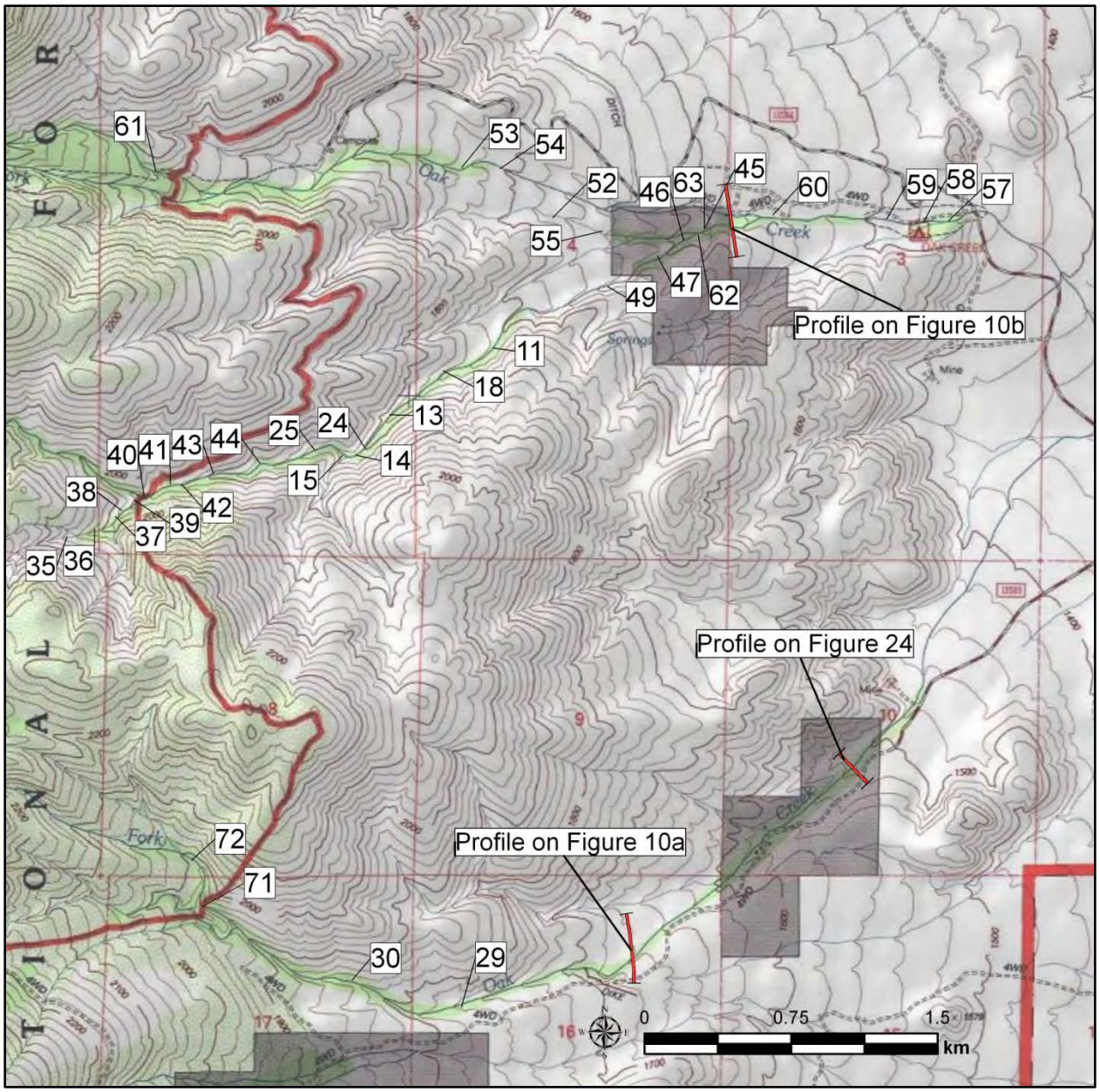

Figure 9: Maps showing the locations of profiles in the Oak Creek drainage. Profile locations for Figures 10 and 24 are indicated by red lines and text boxes.

interval. There is a 1 to 2 cm (0.63 to 0.78 in) thick layer of burned vegetation at its base. This is interpreted to be a large debris flow that moved down the middle fork of Oak Creek after a fire that occurred more than 2,200 years BP. This distinctive deposit can be traced about one km downstream where it pinches out so it does not occur in the measured sections of stations 62 and 63 (Figure 8a,b in Appendix A).

Channel Morphology of the Oak Creek Drainage

The North Fork of Oak Creek drains 33.2 square km of the Eastern Sierra. Its headwaters are at about 3,300 m (10,300 ft) elevation and the stream flows about 18 km

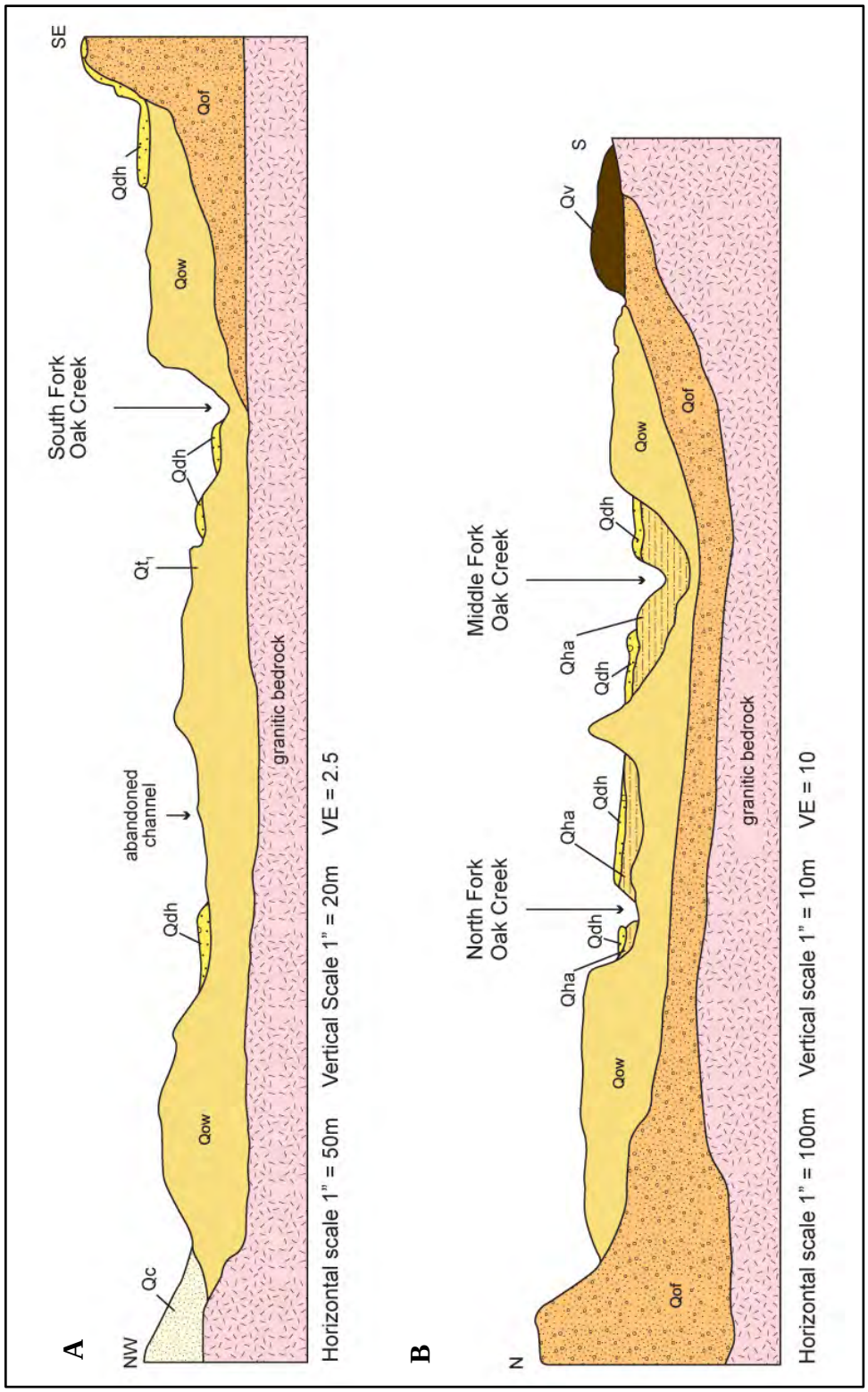

Figure 10a and b: Schematic cross sections across the North and South forks of Oak Creek. Location of profiles is shown on Figure 9. (Qof=Older fan deposits; Qow=Glacial outwash; Qha= alluvium; Qdh=Debris flow and hyperconcentrated flow deposits; Qv=Lava flow; Qc=Colluvium; Qt_1=Terrace surface) Note: the channel of the North fork of Oak Creek contains alluvium that is not present in the channel of the South Fork. The sand-rich alluvium in the North Fork channel system was source of the sand-rich hyperconcentrated flows. The source of the boulder-rich debris flows of the South Fork were the boulder glacial outwash deposits. The more complex channel morphology of the South Fork of Oak Creek resulted in avulsions forcing the debris flows out of the main channel.

(11 mi) east to the floor of Owens Valley to an elevation of about 1,170 m (3,840 ft). The slope of the channel ranges from about 5 degrees in the lower elevations to 7 degrees in the higher elevations. There are two main tributaries; the middle fork which drains the southern part of the basin and an unnamed northern tributary that drains the northernmost part of the drainage basin. Both of these tributaries were major sediment sources for the July 12, 2008 flow. In addition, two smaller unnamed tributaries between the North Fork and middle fork yielded lesser but significant amounts of sediment. The North Fork of Oak Creek contributed modest amounts of sediment compared to its tributaries. With the exception of the unnamed tributary in the northernmost part of the basin, the tributaries converge with the North Fork at 1,600 m (4,900 ft) elevation where the channel confluence is 260 m (800 ft) across and incised into the older fan of the North Fork of Oak Creek (Plate 1; Figure 10b).

Incision into the older fan appears to have begun after the deposition of the youngest lava flow at about 100,000 years ago, forming a broad channel partly filled with glacial outwash (Figure 10b). The glacial outwash deposits slope toward Owens Valley at about 6 degrees. An older part of the alluvium of the younger fan of the North Fork of Oak Creek (Plate 1) appears to be the downstream equivalent to the glacial outwash. Glacial outwash deposits have planar tops that slope toward Owens Valley whereas the younger fan has a radial contours, and a convex-upward surface. Sedimentological characteristics and composition are so similar that the two cannot be separated solely by observing outcrops. Flat-topped glacial outwash deposits extend down to the confluence of the middle fork and North Fork of Oak Creek (Plate1). Deposits of pebbly sand occur along the modern channels of the North Fork of Oak Creek (Figure 11). Stratification and poor sorting indicate these are overbank water flood deposits of fluvial origin. Though most of these sediments were deposited during water floods there are interbeds of matrix-supported debris flow deposits. The most extensive accumulations of the sand-rich sediments are along the middle fork of Oak Creek. These are the major source of the sand in the 2008 flows.

The South Fork of Oak Creek drains just over 22.8 square km. Its headwaters are at about 3,300 m (10,800 ft) and it flows 11.5 km (7.2 mi) east to its confluence with the North Fork immediately west of the Mt. Whitney Fish Hatchery (Plate 1; Figures 1,2) at elevation 1,330 m (4,400 ft). In its lower reaches the channel slope is about 5 degrees but in the upper part of Little Onion Valley the slope increases to 9-10 degrees. An unnamed southern tributary drains Sardine Canyon (Plate 1; Figure 2). Glacial geology of the South Fork of Oak Creek is more complex than the North Fork. Gillespie (1982) mapped several ages of glacial moraines which are shown as one unit on Plate 1. Moraines are thick, steep-sided deposits of unstable material that is easily eroded. In addition to the moraines there are glacial outwash deposits that extend far lower than the moraines. Both types of glacial deposits are composed of boulders set in a pebbly matrix of silt and sand, and are major sediment sources that collectively rival those of the middle fork of Oak Creek. Erosion of the boulder-rich glacial deposits resulted in a fine-grained slurry that carried a greater percentage of larger boulders down the South Fork than in the North Fork (Figure 12).

At its widest point, the channel of the South Fork of Oak Creek is just over 300 m wide (Figure 10a). It is incised into older fan deposits on the south side and into granitic bedrock on the north side. As discussed earlier, the incision of South Fork channel occurred after incision of the North Fork.

Figure 11: Photo of stratified overbank fluvial deposits exposed along the North Fork of Oak Creek. The uppermost gray sand was deposited during the July 12, 2008 event. The black layers are carbon rich sediment from previous fires, reworked charcoal, and peaty black mat deposits of decayed wetland vegetation.

The South Fork channel had nearly reached its present configuration when glacial outwash was deposited in the channel. Along the active stream channel are at least two terraces cut into the outwash deposits. These terraces were most likely the result of base level changes downstream that affected the South Fork. Since terraces are lacking along the active stream channel of North Fork, the base level changes appear to be restricted to the South Fork. This suggests that the channel and fan of the North Fork have reached a level of equilibrium between sediment supply, uplift, and erosion, not yet achieved by the South Fork channel and fan.

Another indication of the relative youth of the South Fork is that major changes in the channel took place during the July 12, 2008 storm. According to members of the Bright family, most of the boulder fields that are now downstream from the Bright Ranch, formed during the storm. Prior to the storm, the channel upstream from the Bright Ranch was as bouldery as it is now but down stream there were far fewer boulders. Near the center of Section 10 (See Plate 1), a small bridge across the stream piled up debris during the storm, forcing the stream to change its course to the west and flow along the mountain front until it intercepted a small drainage.

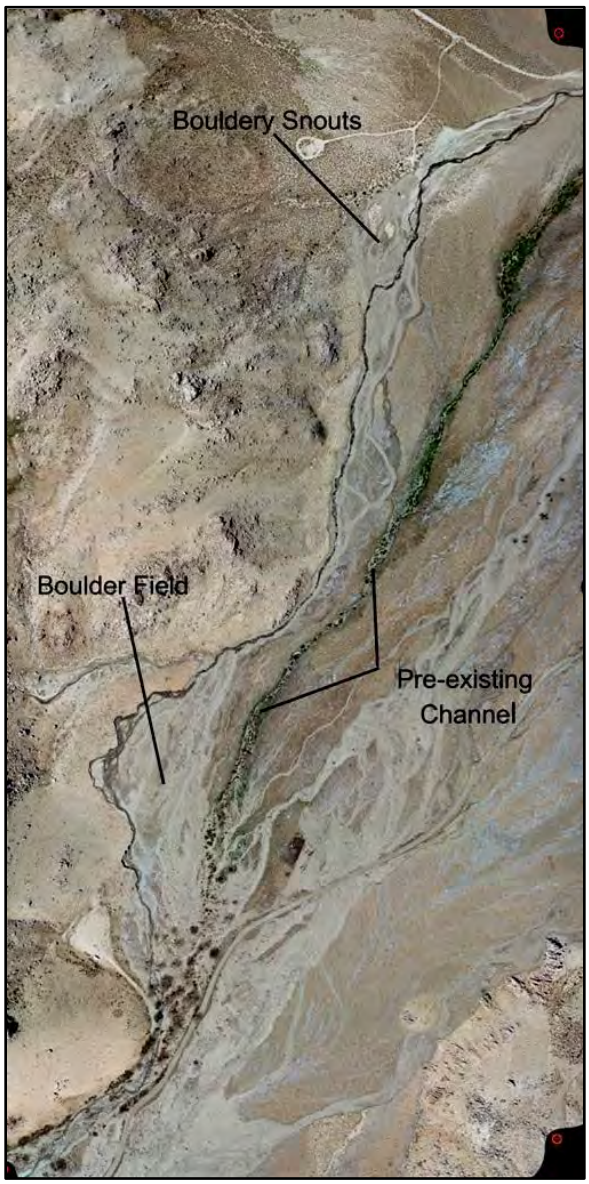

Figure 12: Air photo showing the boulder field left behind by the debris flow along the South Fork of Oak Creek. In the upper part of the photo there are boulder snouts where lobes of the debris flow came to rest. (Photo by Caltrans)

A large boulder field that was not present before the storm now exists between this new course and the now abandoned older course (Figure 12).

WILDFIRE

Lightning ignited the Inyo Complex fires on July 6, 2007, burning 35,151 acres (142 km^2, 54.9 mi^2) between Independence and Big Pine. Burn severity mapping conducted by the Monitoring Trends in Burn Severity program jointly implemented by the USGS and USFS (2012), utilized 30 meter resolution Landsat Thematic Mapper satellite imagery from August 5, 2006 and July 25, 2008. The Inyo Complex Fire burn severity data is replotted on Figure 13 and shows the distribution of areas within the fire boundary with burn severities categorized as unburned to low, low, moderate, and high. In the North Fork of Oak Creek drainage, 40.5 percent of the basin was burned at moderate to high severity. In the South Fork of Oak Creek drainage, 26.8 percent of the basin was burned at moderate to high severity. According to DeGraff (2007), the fire doubled the normal predicted discharge for the burned area.

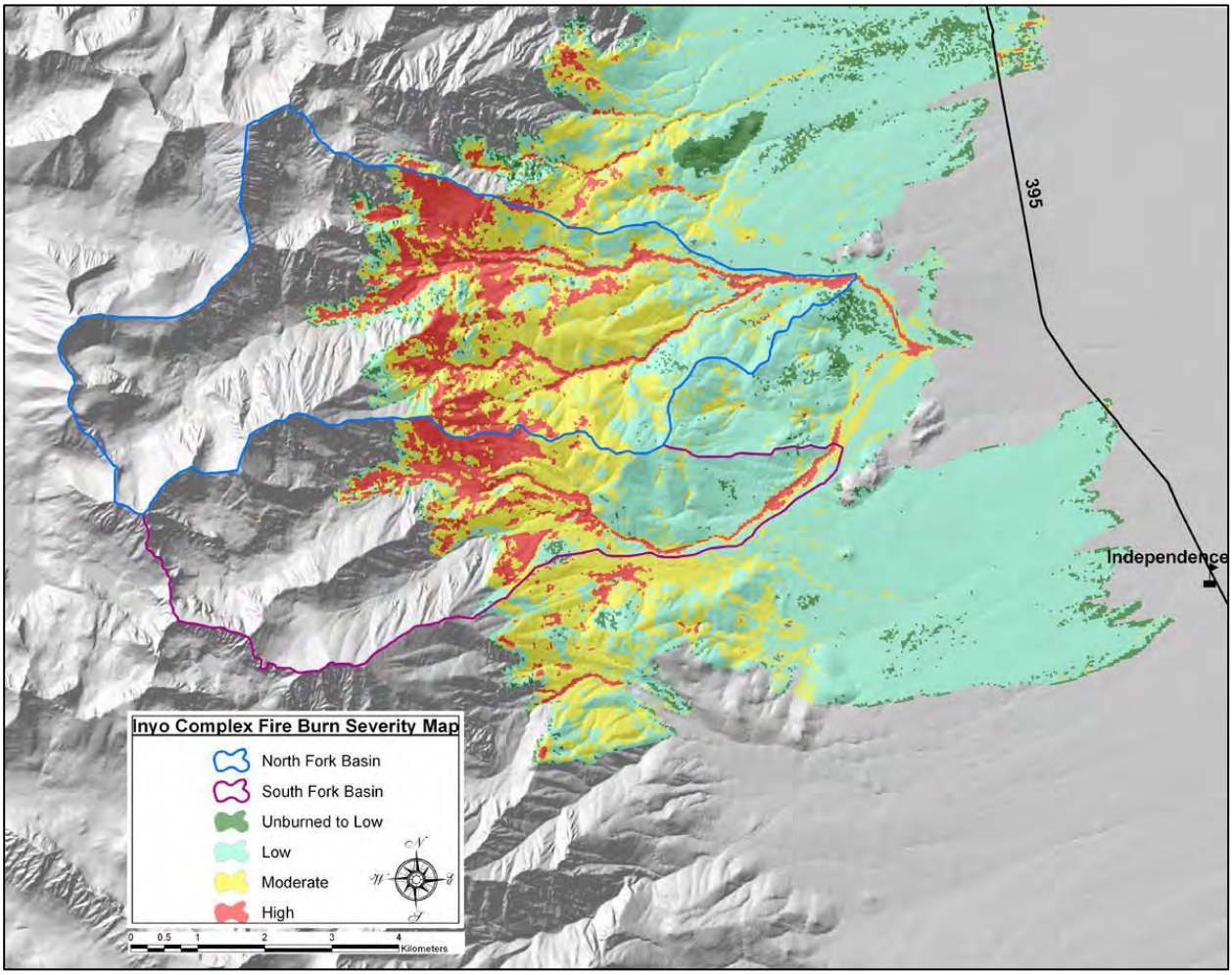

Figure 13: Burn severity map of the July 2007 Inyo Complex Fire and affected area of the North and South Forks of the Oak Creek drainage basin. (Data Sources: USGS and USFS Monitoring Trends in Burn Severity; USGS 10-Meter digital elevation model.)

RAINFALL

On July 12, 2008 tropical moisture moved into southern California from the east. This moisture was the remnants of Hurricane Bertha which had moved inland across the southwestern United States from the Gulf

of Mexico causing locally intense thunderstorms Jayko (2009). One local storm cell stalled over the Oak Creek drainage, dropping heavy rain and hail. National Oceanic and Atmospheric Administration (NOAA, 2012) NEXRAD (Next Generation Radar) doppler radar in the San Joaquin Valley (Station ID# KHNX) recorded rainfall intensity and storm totals over the Oak Creek watershed on a 1 km grid (Figure 14). Doppler radar data indicate precipitation occurred from 4:37 to 5:16 P.M. (a duration of 39 minutes) with rainfall totals in the range of 7.6 to 63.5 mm (0.3 to 2.5 in). This would give an average intensity of 11.7 mm/hr (0.48 in/hr) at the margins of the cell to 97.7 mm/hr (3.84 in/hr) in the central portions of the cell. However, while it has been well established that doppler radar data can both under and overestimate rainfall intensity with distance, and require validation with physical rainfall gages (Mazari et al., 2009), these data are all that are available for the immediate area. A rain gauge at the Oak Creek Campground was destroyed by the flow just before it was scheduled to report at 4:42 P.M. (DeGraff, 2008). This rainfall intensity is at the high end of the range of peak intensities that resulted in debris flows observed by Wells (1987) in small, burned watersheds at the San Dimas Experimental Forest near Los Angeles. As the storm began to subside, the slopes above the Oak Creek drainage were observed to be white with hail which quickly melted, possibly by subsequent rain that continued to fall on the hail.

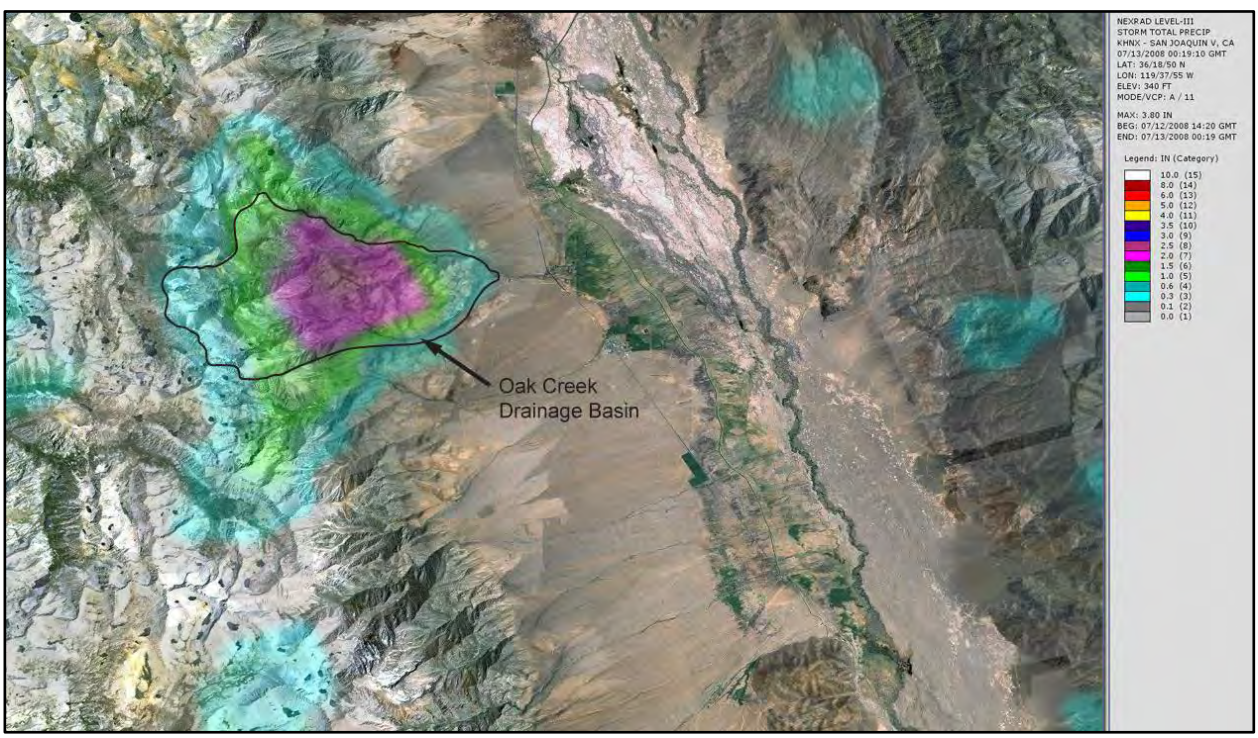

Figure 14: NEXRAD doppler radar data showing storm rainfall totals after the terminus of the July 12, 2008 cloud burst. Note: Lightest turquoise is equal to 7.6 mm (0.3 in), and dark purple is equal to 63.5 mm (2.5 in). Data Source: National Oceanic and Atmospheric Administration Next Generation Radar (NEXRAD).

DEBRIS FLOW MODELS

Empirical models that estimate the probability and volume for post-fire debris flows (Cannon et al., 2010) have been used to aid floodplain managers and emergency response personnel in reducing risks to lives and property should the burned watersheds be affected by post-fire storms. The USGS postfire probability model for southern California (Rupert et al., 2008; Cannon et al., 2009) uses an empirical database to develop regression against several factors found to have a strong correlation to the occurrence of debris flows. These factors include average rainfall intensity, percentage of basin burned at moderate to high severity, basin slope, ruggedness, relief ratio, and soil erosion factor (k) (Table 2). Average rainfall intensity is calculated as the measured depth divided by duration normalized to a

TABLE 2:
Summary of fire, rainfall, and morphometric data from the Oak Creek drainage basin.

Measured Variables		North Fork Basin	South Fork Basin
Basin Area‡		33.18 km^2	22.80 km^2
Rainfall Intensity		11.7-97.7mm/hr	11.7-97.7mm/hr
Rainfall Duration		39 minutes	39 minutes
Percent of Basin Burned		54.9%	44.3%
Burn Severity	**Low**	14.4%	17.5%
	Moderate	24.8%	15.2%
	High	15.7%	11.6%
Area of Basin with Slopes 30% - 50%		24.4%	25.0%
Area of Basin with Slopes > 50%		58.0%	52.6%
Melton's Number		0.45	0.53
Relief Ratio		0.18	0.19
Soil Erosion Factor (K Factor)†		0.05-0.10 (Hillsides and Moraines) 0.15 (Alluvial Fans and Fan Terraces)	0.05-0.10 (Hillsides and Moraines) 0.02-0.15 (Alluvial Fans and Fan Terraces)
Estimated Debris Volume		900,000m^2	600,000m^2

‡**Basin areas are measured upstream of fan apex discharge (deposition) locations as a function of the area contributing to postfire runoff on the North and South Forks of Oak Creek.**

†**K Factor taken from US Department of Agriculture Soil Survey (Seney and Gallegos, 1995)**

one hour period. Melton's number (ruggedness) is calculated as the difference in basin elevation divided by the square root of the basin area. Relief ratio is calculated as the change in elevation from the basin mouth to the basin crest along the longest channel extending to the drainage divide, divided by the length of channel. Soil erosion factor is typically based on maps and data provided by US Department of Agriculture, Soil Survey, and is used to quantify the detachment of soil due to runoff and rain drop impact (USDA, 2011).

Comparison of rainfall intensity, burn severity, erosion factor, basin slope, and relief ratio for the North and South Fork Oak Creek basins (Table 2) to empirical regression described in the USGS probability model (Cannon et al., 2009) indicate a strong postfire debris flow potential, with probabilities for both basins equal to 1.

NATURE AND EXTENT OF THE DERBIS AND HYPER-CONCENTRATED FLOWS

Erosion of slopes and scouring of stream channels extend up to 3,000 m elevation on the escarpment of the Sierra. The flows traveled over 16 km (25.6 mi) with more than 1,800 m (5,500 ft) of relief as they moved through the Oak Creek drainage, onto alluvial fans and out into Owens Valley. As is the case with most debris and hyperconcentrated flows in small, burned watersheds (Santi et al., 2007), these flows were due to rainfall, runoff, and in-channel erosion rather than landslide-initiated debris flows. The July 12, 2008 storm cell was centered over the divide separating the North and South Fork drainages of Oak Creek (Figure 14). Flows traversed both drainages of Oak Creek until they merged just west of the Mt. Whitney Fish Hatchery (Figure 15).

Figure 15: Photograph showing the merging of the debris flow from the South Fork (left) with the hyperconcentrated flow from the North fork of Oak Creek (right). In the far background is the new course of the South Fork after the avulsion at the bridge (Figure 28). The old channel is marked by green riparian vegetation that has since died due to lack of water. The part of the debris flow forced onto the fan below the Bright Ranch is in the middle left of the photo. Note how debris was diverted along the road in lower left. (Photo by Ken Babione).

Figure 16: View to the northeast of the confluence of Charlie Creek (from the left) and the middle fork of Oak Creek. The slopes are extensively rilled, particularly those above Charlie Creek. Charlie Creek shows the effects of overbank streamflow while the middle fork of Oak Creek was deeply scoured and shows the effects of a hyperconcentrated flow. Charlie Creek delivered mostly water from the rills not sediment. The middle fork of Oak Creek is incised into sandy wetland deposits which were extensively scoured supplying copious amounts of sandy sediment. (Photo by Jerry DeGraff)

Slope Erosion

Extensive rill networks (Plate 2; Figures 16 and 17) developed on the steep slopes above the stream courses. Undisturbed forest and range soils typically have relatively high infiltration rates (Ice et al., 2004). After a major wildfire, these soils often include a surface layer of highly-permeable loose material underlain by an impermeable soil layer formed during the fire. The impermeable layer is composed of soil particles coated with organic compounds derived from the burning of surface litter (DeBano, 1980, Ice et al., 2004). Wells (1987) studied rill networks in the San Dimas experimental forest and proposed a model for rill formation. Rain quickly wets the loose upper layer but does not penetrate the water repellant layer, resulting in pore pressure increases until a small slope failure occurs and a mini-debris flow forms. Once the rill forms behind the debris flow, it fills with water which moves rapidly downslope. Wells (1987) observed that once the rill forms, it fills with clear water. This would help explain why burned slopes have not typically been found to be the major source of sediment in post fire flows, but are responsible for the increased

Figure 17: Closer view of some of the rills on a slope shown on Figure 16. Rills have distinct side levees.

Figure 18: Small braided rills within a larger (~1 m) gully.

runoff. For example, Morton (1989) documents eight times more hillslope-derived soil slips (debris flows) per unit area in unburned portions of the San Timoteo Badlands in southern California produced by a major rainstorm in 1969 than there were in areas that were recently burned. Santi et al. (2007) compiled data for 46 debris flows from burned areas in the western U.S., and found the average contribution of sediment from rills was 3 percent.

Rills in the Oak Creek drainage vary in size with the smallest about 10 cm across and 7 cm deep and the largest about 80 to 100 cm (32 to 39 in) across and 40 cm (16 in) deep. Usually there is a levee 5 to 10 cm (2 to 4 in) high along the rills. Rills are single straight tracks or more complex with small braided rills within a larger one (Figure 18). Above the middle fork of Oak Creek, rills on 34 degree slopes have marginal levees, stalled mini-debris flows with well-formed snouts, and fan deltas at the base of the slopes where they flatten out to 8 degrees. Nearly all of the sediment excavated from the rills could be accounted for in these features. A few are more than a meter deep and more properly should be called a gully. Once the rills empty into well developed channels, scouring becomes prominent (Figure 19). These observations are consistent with the Wells (1987) model for rill formation on burned slopes and provide corroborating evidence they are conduits for rapid movement of water and not major sources of sediment.

Figure 19: Rills emptied water into a tributary of the middle fork of Oak Creek where channel scouring began.

Channel Scour

All three forks of Oak Creek as well as many of their tributaries were extensively scoured. Two notable exceptions where little scour was observed are the North Fork of Oak Creek above the confluence with an unnamed tributary about one and half miles from the Baxter Pass trailhead (Figure 2) and the unnamed tributary to the middle fork that drains Charlie Canyon (located in the southeast corner of section 5 [Plate 1]). Both of these streams are within the high

rainfall area and the slopes above them are extensively rilled but there is relatively small amounts of erodible material in the channels. In Charlie Canyon there is little channel scour but there is abundant evidence of water flooding. Additionally there are virtually no mud splatters on the trees and rocks nor was there sediment deposited on the terraces. This is more evidence that the rills deliver considerable water but relatively little sediment to the streams.

Channel scour along the middle fork of Oak Creek are truly spectacular (Figure 20 a,b). The most detailed field observations were made along this fork where the stream channel is inclined about 5 degrees. Nineteen cross sections were measured along a 3.5 km (2.2 mi) section of the middle fork of Oak Creek (Figure 9). Cross sections are not evenly spaced, but were located at or near knickpoints that tend to mark channel segments that are similar and where measurements were feasible.

Figure 20a: Deep scour of the lower part of the middle fork of Oak Creek. Scour ranges from 17 to 22 m across and 8 to 9 m deep. Boulders on left are older glacial outwash deposits.

Figure 21 (a,b) shows cross sections at two sites where remnants of the preexisting channel are preserved, and cross section data are shown in Table 3 (keyed to locations shown on Figure 9). The upper cross section on Figure 21a is at site 13 and shows the lowest measured downcutting, while Figure 21b is at site 14 which displays more typical scour and downcutting. Site 13 is within a 200 meter (600 ft) reach where a new 1 m (3 ft) deep channel formed. Both up and down stream from this reach, scour depths were similar to or greater than shown at site 14. High mud lines on the cross sections were determined by matching the margins of overbank deposits which are usually marked by wood, bark and forest litter. Along straight reaches they match evenly on the opposing stream banks and on tree trunks. Battering of the upstream side of tree trunks also matches the mud lines. Mud spatters on trees and rocks were observed one to three or more meters above the mud lines. We interpret the mud line to be height of the largest, second surge. The even matching of high mud lines across the straight stretches of the channel indicates that the top of the flow was relatively planar, indicative of a hyperconcentrated flow as opposed to a debris flow.

Figure 20b: Scour farther up the middle fork of Oak Creek. Scour here is 10 to 17 m across and 7 to 10 m deep. Bouldery deposits on the stream banks are older glacial outwash. Foundation in the lower left of photograph is the remains of a private home burned during the Inyo Complex fire of July 2007. (Photo by Jerry DeGraff)

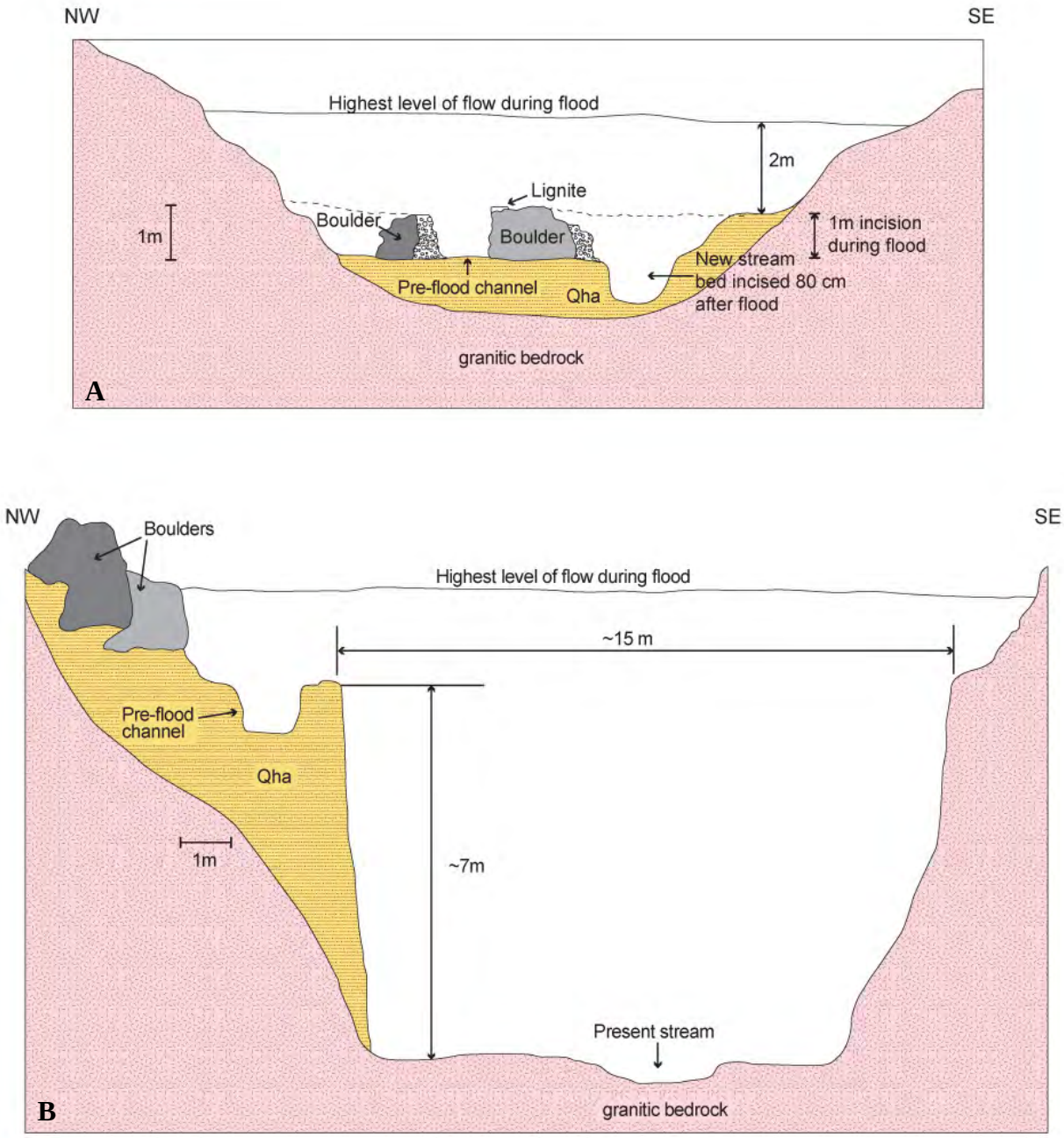

Figure 21a and b: Examples profiles on the middle fork of Oak Creek. The upper profile is at site 13, a locality where there was a minimum of scour. A small remnant of lignite on top of the boulder is all that remains of the wetland deposit that once filled the drainage. Both of the localities had remnants of the old channel which allows determination of the scour depth during this storm. The lower profile shows a more typical scour cross section found at site 14.

Debris yield from scouring of the channel of the middle fork is calculated to be on the order of 538,000 cubic meters (Table 3). Two of the three significant tributaries that enter the middle fork, the unnamed stream that drains Charlie Canyon and an unnamed tributary entering the middle fork from the south at elevation 1,820 m (5,500 ft), apparently contributed water but little sediment. The middle fork is increasingly

incised at the confluences of both tributaries. A third tributary entering the middle fork from the south at elevation about 2,000 m (6,100 ft) was significantly scoured. Based on a cross section near its mouth, the debris yield is estimated to be on the order 50,000 m^3. Above stations 35 and 36 on Figure 9 the middle fork bifurcates into three tributaries which show channel scour up to an elevation of 2,800 m (8,500 ft). A rough estimate of the yield of these tributaries is 20,000 m^3. Based on these estimates the debris yield of the tributaries is about 60,000 to 70,000 m^3. The yield from the rills is considered negligible so the total debris yield for the middle fork of Oak Creek is estimated to be nearly 600,000 m^3. Channel scouring contributed a bulk of the sediment (~90 percent) and tributaries contributed the remaining ~10 percent.

TABLE 3:
Estimated debris yield form the middle fork of Oak Creek based on profiles (See figure 9 for profile locations).

Profile Location	Flow Width (meters)	Flow Depth (meters)	Flow Area ($meters^2$)	Channel Segment (meters)	Segment Volume ($meters^3$)
35[1]	7	3	101	---	---
36	8	5	20[2]	90	1,800
37	10	6	60	50	3,000
38	11	9	99	100	10,000
39	11	8	88	50	4,400
40	13	11	143	130	19,000
41	9	6	54	50	2,700
42	15	10	150	150	22,000
43	10	11	110	165	18,000
44	24	23	552	350	190,000
25	15	10	150	300	45,000
14	20	15	300	200	60,000
24	5	1	5	200	1,000
13	7	12	84	300	25,000
18	15	10	150	320	48,000
11	3	20	60	400	24,000
49	10	15	150	300	45,000
47	24	3	72	140	10,000
46	18	12	180	50	9,000
	Average	**Average**	**Average[3]**	**Total**	**Total**
	12	10	130	3,400	538,000

[1] **The stream flows across bedrock at this location, significant scouring began downstream.**

[2] **The scored channel is v shaped here, therefore flow area is one half the depth times the width.**

[3] **Average flow area is calculated as the arithmetic mean.**

Channel scour along the North Fork of Oak Creek was variable. Channel scour ranged from 1 x 4 m to 6 x 14 m (3 x 12 ft to 18 x 43 ft) immediately upstream from the apex of the younger fan of the North Fork of Oak Creek. In a straight stretch between stations 59 and 60 on Figure 9, the channel was incised only 1-2 m (3-6.1 ft) deep, and the width appears relatively unchanged. Near the confluence of the middle fork and North Fork, scour widened to 17 m (52 ft) and deepened to 7-8 m (21-24 ft). The channel scour was variable and was generally less where the streams flowed through bouldery glacial outwash deposits than in areas underlain by sand-rich deposits. Estimated debris yield for the North Fork of Oak Creek is over 250,000 m^3, and estimated yield for the unnamed tributaries is about 50,000 m^3 for a total of approximately 300,000 m^3. Again, the main channel contributed most of the sediment (~85%) while the tributaries contributed ~15 percent.

The total debris yield for the entire drainage of North Fork of Oak Creek is on the order of 900,000 m^3, with most scoured from the main channels. These yields fit the pattern reported by Santi et al. (2007), where scour of the main channel is the greatest, and scour of tributaries is much more important than sediment derived from rills.

Channel scour along the South Fork of Oak Creek is more evident in the upper reaches of the drainage that are underlain by erodible glacial moraines. Moraines contain boulders set in a sandy matrix that are sources of both sand-rich sediment and boulders. There are no extensive sandy wetland deposits in the South Fork drainage as there are in the North Fork, so here the ratio of boulders to sandy sediment is much higher. The tributaries that drain the south-facing slopes and join the South Fork of Oak Creek at about 2,000 m (6,100 ft) are the source of much of sand-rich sediment that flowed down the South Fork in the July 2008 event. These south-facing slopes were extensively rilled and individual tributaries were scoured two to three meters wide and one to two meters deep. An estimated 9,000 m^3 of sand-rich sediment was scoured from these tributaries. Profiles at stations 72 and 71 (Figure 9) show the channel scour increased downstream to 10 m wide and 4 m deep (30 x 12 ft), and the estimated debris yield is 8,000 m^3. Between stations 71 and 30 the channel was incised about 5 m deep and 14 m wide (15 x 43 ft), yielding approximately 60,000 m^3 of debris. Between stations 72 and 30, the channel follows the contact between glacial moraines and outwash and granitic bedrock (Plate 1). Moraines provided both sand and boulders while the outwash provided mostly boulders. Between stations 30 and 29 the channel widens from its V-shape to an open channel with terraces and abandoned stream courses. In this part of the South Fork of Oak Creek, scour is less evident or lacking and is no longer a viable indicator of debris yield. According to the Bright family, most of the boulders from the ranch house downstream to the fan of the South Fork were emplaced during the July 12, 2008 storm. Assuming an average thickness of one meter, the estimated volume of the boulder deposits is almost 400,000 m^3. The upper reaches of the South Fork of Oak Creek contributed an estimated 70,000 m^3 of sand -rich material based on the profiles discussed above. The amount of sediment deposited on the fan of the South Fork as a result of overflow from the main channel is difficult to estimate. On Plate 1, it appears to be a little less than a quarter of the area of the South Fork fan so an estimate of about 200,000 m^3 seems generally reasonable. The total estimated debris yield for the South Fork of Oak Creek is then on the order of 600,000 m^3.

Summing the estimated debris yields for the entire drainage gives about 1½ million cubic meters. This sediment was deposited as a sheet that follows the local topography. Thickness varies, ranging from <2 cm to over a meter (0.78 in to over 3 ft),

so an average of about 50 cm (20 in) seems reasonable. A GIS estimate of the mapped extent of the flow on Plate 1 results in 3.12 km^2 giving a total estimated volume of the deposit of 1.56 million m^3, which is in good agreement with estimate of debris yield based on field measurements.

Debris flows on the South Fork of Oak Creek

There are no eyewitness reports for flow on the South Fork of Oak Creek but geomorphic evidence observed indicates debris flows were the dominant mode of flow. The ratio of boulders to sandy sediment is far higher here than in the North Fork. There are boulder levees along abandoned channels, plugs of boulders and logs choking abandoned channels, as well as abundant evidence of intense grinding on any obstruction. Figure 22a shows a tree that was severely abraded by grinding action. Also noted at this locality are pebbles hammered into the tree trunks like nails, apparently by boulders (Figure 22b).

Figure 22a: Abraded tree trunk on the South Fork of Oak Creek. This tree is near the active channel where the debris flow was the thickest and most forceful. It is not apparent in this photograph, but this tree was nearly cut in half by the debris.

Figure 22b: Close up of pebbles driven into the tree trunk like nails.

Tree trunks around the Bright Ranch were battered to about 1.4 m (4.3 ft) above the ground on their upstream sides. Mudlines at 1-1.2 m (3-3.7 ft) on the downstream sides of some trees suggest that there were eddies of watery sediment leeward of some of the trees. Boulders perched in tree crotches 1.7 m (5.2 ft) (Figure 23) above the ground near the main channel of the South Fork suggest that the flow was thicker at the center of the channel and decreased outward. This is consistent with the profile of a debris flow (Figure 24).

Figure 23: Boulder perched 1.7 m above the ground near the center of the debris flow.

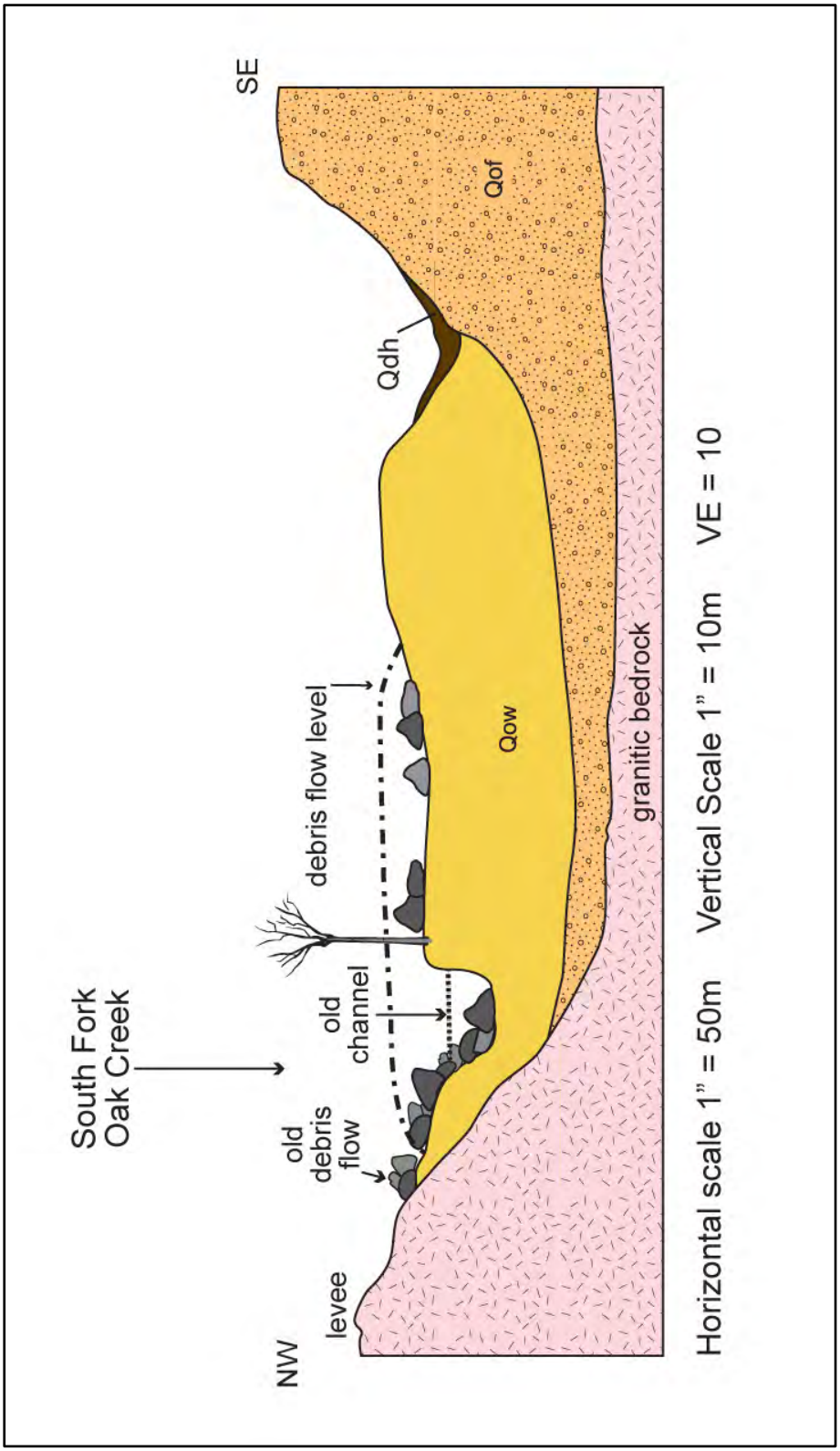

Figure 24: Cross section showing the inferred geometry of the debris flow below the Bright Ranch on the South Fork of Oak Creek. (Qof=Older fan deposits; Qow=Glacial outwash; Qdh=Debris flow and hyperconcentrated flow deposits)

The Bright Ranch house, a mobile home with a concrete front porch and a substructure of steel girders, was pushed off the substructure and pulverized as it moved downstream (Figure 25). The largest piece observed was part of the roof with a stove pipe about 2 km (1.3 mi) downstream from the house site. Although severely mangled, the steel substructure remained at the site, buttressed by the concrete porch. The porch and floor of the mobile home were about one meter above the ground. It appears from the battering of nearby trees and perched boulders, the debris flow was about 1.7 m (5.2 ft) thick and carried boulders up to a meter or more across and possibly much larger logs when it struck the mobile home, pushing it off the foundation. It is unclear how far up above the Bright Ranch the debris flow was initiated, but the point of origin is somewhere above a diversion ditch (sec. 16 on Plate 1) near the major confluence of tributaries in the north half of sec. 17 (Plate 1). The concrete abutment of a diversion was partially swept away (Figure 26); which would have required the impact force of a debris flow. Exposed rebar from the remaining concrete structure was smoothly polished on the upstream side, while the ridges on the downstream/underside still remained. Figure 24 is a profile of the channel of the South Fork downstream from the Bright Ranch showing the inferred cross section of the debris flow. Boulders and tree trunks are piled against upright trees to a height of 1.7 m (5.2 ft). There is a prominent boulder levee (Figure 27) on the north bank of the creek as well as an older boulder levee marking the margin of a previous, higher debris flow. In this area there many large, intensely abraded logs and tree stumps in the debris. The largest log is a trunk of a yellow pine that is 1.3 m (4 ft) in diameter at its base and is 30 m (91 ft) long.

Figure 25: Remains of the mobile home on the Bright Ranch. The twisted steel substructure of the mobile home lies behind the stone porch that was in front of the home.

Figure 26: Remains of the concrete abutment of the diversion structure on the South Fork of Oak Creek that was partially swept away by the debris flow.

Figure 27: Boulder levee left by the debris flow along the South Fork of Oak Creek. Older boulder levee occurs behind and higher than the younger levee, and is marked by two large boulders in contact with each other in the upper middle portion of the photograph.

At this point (just below the Bright Ranch) the debris flow was about 75 m (230 ft) across and about 1.7 m (5.2 ft) thick on stream banks and over twice that thick in the stream channel. The debris flow's leading edge likely would have looked like a moving pile of boulders and logs. Near the center of section 10 (Plate 1), at the apex of the fan of the South Fork of Oak Creek the debris flow encountered a bridge. Debris quickly choked the channel at the bridge, forcing the flow to move to a new course to the west along the mountain front (Plate 1). A large boulder field formed below this avulsion point as the debris flow came to rest. This boulder field extends along the new channel to the southeast corner of section 3 (Plate 1; Figure 12). After the boulder snout of the debris flow came to rest, finer sediment from the trailing part of the debris flow surged over the boulders. A later avulsion occurred above the bridge where the debris flow partially blocked the stream (Figure 28) forcing the remaining part of the flow onto the upper part of the fan to the southeast where it flowed a more direct course to its confluence with the flow from the North Fork of Oak Creek near the Mt. Whitney Fish Hatchery (Figure 15).

Figure 28: Photograph showing the avulsion of the debris flow along the south fork upstream from the bridge. The channel became clogged with boulders (the lighter colored material on the right side of the photo) forcing the debris flow out onto the fan. This part of the debris flow contained more sandy material that appears brownish on this photo. The Bright Ranch was in the grove of trees in the upper left of the photo. In lower left there is a fiberglass spa from the Bright Ranch (Photo by Jerry DeGraff).

Figure 29: Boulders and debris piled against trees to over 3 m high on the middle fork of Oak Creek.

Hyperconcentrated Flows on the North Fork of Oak Creek

The height of the hyperconcentrated flow is indicated by a remarkably consistent mud line, along with wood, bark, and forest litter along the North Fork and middle fork of Oak Creek. Caked mud and battering of upstream-facing tree trunks within the channel are generally 3 m (9 ft) (Figure 29) above the ground and match the mudlines on the stream banks. Mud splashed up tree trunks 1 to 2 m (3 to 6 ft) above the level of the battering suggesting turbulent flow, indicative of water content higher than that of a debris flow. Coarse, sand-sized sediment shows some sorting and is clast supported but lacks or has very weak stratification, characteristic of hyperconcentrated flows (Table 1).

Velocity of the Hyperconcentrated Flow on the North Fork of Oak Creek

The velocity of debris and hyperconcentrated flows varies dramatically with factors related to flow behavior, such as particle size distribution, sediment and debris concentration, and yield strength. Factors related to the channel system, such as channel width, depth, and slope also affect flow velocity (Costa, 1984). Given constant channel geometry, the rate of movement of a flow will decrease with

increased viscosity and yield strength. Superelevation of flow is commonly used to back calculate the flow velocity at locations where mud lines exist in channel bends. While these features were observable in the North Fork, the debris flow that traversed the South Fork behaved as a viscous granular flow, leaving little superelevation evidence behind, thus no velocity calculations were conducted.

On the North Fork of Oak Creek, Don Rockwood, the man who "body surfed" the flow to escape it, described the event as coming in three "waves." Two were about 1 m (3 ft) high and were separated by one that was 2.6 to 3.9 m (8 to 12 feet) high. Along the middle fork and North Fork of Oak Creek and on the alluvial fan below Oak Creek Campground there is evidence for two surges; the larger, middle surge would have destroyed evidence of the first smaller one. Material from the second surge is overlain by deposits of the smaller third one (Figure 30). According to Rockwood, the three surges were followed by sustained flow of "mud". Accounts of the July 26, 1952 debris-flows from Milner and Cottonwood canyons in the nearby White Mountains described a series of waves or surges that moved "…as fast as a man can dog trot…"(Beaty, 1963).

Figure 30: Photograph of the hyperconcentrated flow on the fan of the North Fork of Oak Creek. There were three surges in the flow, two of them evident on this photo. The darker, outer part was the second and largest surge that buried the first smaller one. The lighter colored, inner part was deposited by the smaller, third surge (Photo by Jerry DeGraff).

On the middle fork of Oak Creek the flow passed through an S-curve, causing the flow to surge up the outside banks. This phenomenon can be used to estimate the velocity of the flow by measuring the difference in elevation between the mud lines on the outside and inside banks, the radius of curvature and width of the channel (Figure 31). According to Costa (1984), if the channel slope is less than 15 degrees, the velocity can be estimated by the equation:

$$V = (r_c g \tan\Phi)^{0.5}$$

where V is velocity, r_c is radius of curvature of the stream channel, g is the acceleration of gravity, and $\tan \Phi = \Delta h/w$. Superelevation (elevation difference between the inside and outside bank mud lines) is Δh and w is the channel width. This approach oversimplifies a complex phenomenon and there are several uncertainties, not the least of which is the subjectivity of measuring the radius of curvature of the bend (Prochaska et al., 2008). Superelevations from two surges are recorded on the banks of the S-curve. The higher superelavation corresponds to the highest middle surge. This surge partially overtopped the first bend and ran up the outside bank of the second bend. Estimated velocity of this surge is 5.4 m/sec (~ 12 mi/hr). The third, smaller surge remained within the stream channel and its estimated velocity is 2 m/sec (~4.5 mi/hr). The middle fork channel is relatively narrow. No doubt the surges slowed when they encountered wider channels downstream and eventually flowed across the younger fan of the North Fork of Oak Creek. DeGraff (2008) estimated the velocity of the flow at Oak Creek campground to be 5.4 m/sec (12 mi/hr) based on measurements of runup on trees and estimated the thickness of the flow to be about 3.3 m (10 ft). It appears that this was

Figure 31: Site on the middle fork of Oak Creek where superelevation was measured and an estimated velocity of 5.4 m/s (~12 mi/hr) was calculated.

the second, larger surge as well. These data are consistent with velocity measurements of flows elsewhere in the southern Sierra reported by DeGraff (1994) that range from 2.4 to 7.1 m/sec (5.5 to 16 mi/hr).

At other locations in the Oak Creek drainage, velocity may have been different than this estimate on the middle fork. For example, where the viscous granular debris flow traversed the South Fork, higher viscosity may have translated to lower flow velocity. Also, where the flows came together and moved across Highway 395, the fan gradient and relative flow confinement decreased, likely resulting in lower velocity.

Movement of Large Boulders

Large boulders (≥ 1 m) were moved by flows on both the North and South forks of Oak Creek. Boulders were found perched in tree crotches as much as 3 m above the ground (Figures 23, 29). Volumes of the largest boulders on the North Fork that definitely moved during this event were about 1 to 6.5 m^3. The largest basalt boulder (1.6 x 1.17 x 0.60 m; 4.9 x 3.6 x 2 ft) observed has a volume of about 1.12 m^3 and assuming a 3.0 g/cc density for basalt, it weighs about 3,300 kg (~7200 lbs). The largest granitic boulder has a volume of about 6.3 m^3 and assuming a density for granite of 2.7 g/cc it weighs about 8,100 kg (~18,000 lbs). On the South Fork, the largest boulders that moved during this

event are all granitic; the largest, shown on Figure 7, has dimensions of 3.2 x 2.3 x 1.3 m (9.8 x 7 x 4 ft) with a volume of about 9.6 m^3. Assuming a density of 2.7 g/cc for granite, this boulder weighs ~26,000 kg (~57,000 lbs). Another large granitic boulder nearby, now resting on a terrace, could only have been moved to its present location by a debris flow. It sits on a partially burned plank and fence post with barbed wire still attached. Its dimensions are 2.7 x 1.6 x 1.5 m (8.2 x 4.9 x 4.6 ft) (~ 6.5 m^3) and its weight is ~18,000 kg (~40,000 lbs).

Deposition on Alluvial Fans

Although some sediment and debris derived from the North Fork and South Fork of Oak Creek and their tributaries was deposited along stream banks, the bulk of it was delivered to the younger fans of Oak Creek. The apex of the younger fan of the North Fork is at an elevation of about 1,450 m (4,400 ft) and the apex of the younger fan of the South Fork is at 1,500 m (4,600 ft) elevation. Above these elevations the flows were confined to the channels and their immediate banks which were incised into the older deposits, but once the flows emerged onto the fan apices they spread out and thinned (Plate 1). Sediment delivered to the younger fan of the North Fork is dominated by coarse, pebbly sand though there are boulders as well as woody debris (Figure 32). In contrast, sediment delivered to the younger fan of the South Fork is dominated by boulders, but also contains woody debris and flotsam swept from the Bright Ranch. Field observations suggest that hyperconcentrated flows moved down the North Fork, while initially, debris flows moved down the South Fork followed by more fluidized flows.

Figure 32: Sediment, trees and boulders deposited on the fan of the North Fork of Oak Creek (Photo by Jerry DeGraff).

Once the North Fork hyper-concentrated flow crossed Oak Creek Road at the camp ground (Plate 1) it spread laterally across the younger fan of the North Fork of Oak Creek. Here the North Fork turns abruptly southward, flowing southeast to the Mt. Whitney Fish Hatchery. The capacity of the channel of Oak Creek was exceeded and the flow filled abandoned channels. The flow continued across the interfluves until it came to rest, assuming the distributary pattern of the fan drainage system (Figure 3). The flow continued along the abandoned drainages for 1 to 1.5 km (0.6 to 0.9 mi) before finally stopping. Thickness of the deposit ranges from 2 cm to 40 cm (0.78 to 15.7 in). Generally it is about 5 cm (2 in) thick, but it thickens to bulbous snouts up to 40 cm (15.7 in) thick along its margins that are often lined with woody debris. This hyperconcentrated flow is analogous to the "low sediment" debris flow described by Whipple and Dunne (1992) on the fans of the great bajada south of Independence Creek.

The debris flow that emerged from the canyon of the South Fork of Oak Creek has a boulder snout, and left a boulder field up to 150 m (460 ft) wide and 1,500 m (4,600 ft) long on the South Fork fan along the new channel of the creek (Figure 12).

Sediment and debris from the North and South forks of Oak Creek merged west of the Mt. Whitney Hatchery and flowed due east (Figure 15) toward the hatchery and homes along Oak Creek. Oak Creek quickly became choked and was diverted to a new more southerly course, locally following roads, spreading sediment and debris through the Bell Access subdivision, and causing extensive damage. A resident of Ft. Independence, immediately east of Hwy 395, reported, "…It sounded like a freight train coming through, and that was when it was still on the other side of the highway. I've never heard anything like that. Big boulders, people's propane tanks were floating down the highway" (Inyo Register, July 15, 2008). The flow reached the highway between 5:30 and 6 P.M. and was diverted southward along it (Plate 1). East of Hwy 395 the flow followed stream beds out into the floodplain of the Owens River. The runout from the apex of the North Fork fan was approximately 6 km and the runout from the apex of the South Fork fan was approximately 7 km.

DAMAGE TO PRIVATE PROPERTY AND INFRASTRUCTURE

Virtually all the damage to private property and public infrastructure occurred along the active channels of Oak Creek and its tributaries (Figure 33; Table 4). Nearly all the sediment deposition occurred on the young alluvial fans (Plate 1).

On the South Fork of Oak Creek, the Bright Ranch was completely destroyed (Figures 25 and 28). On the North Fork, the culvert beneath the Oak Creek road was destroyed and has since been replaced (Figure 33, Locality 3). The North and South forks merge about 500 m (1,500 ft) west of the Mt. Whitney Fish Hatchery. Oak Creek flows due east along a topographic low (a coalescing zone) between the younger fans of North and South forks of Oak Creek and is a locus of active sedimentation. Employee residences at the hatchery were destroyed or damaged (Figure 33, Localities 5,7,8) and sediment entered the fish breeding facilities, killing all of the fish. Twenty-five homes along Oak Creek were reportedly destroyed (Inyo Register, July 15, 2008) but only 17 damaged or destroyed homes were observed during this investigation with the remainder being out buildings. They were situated very close to the creek and were battered by mud, boulders and logs (Figure 34).

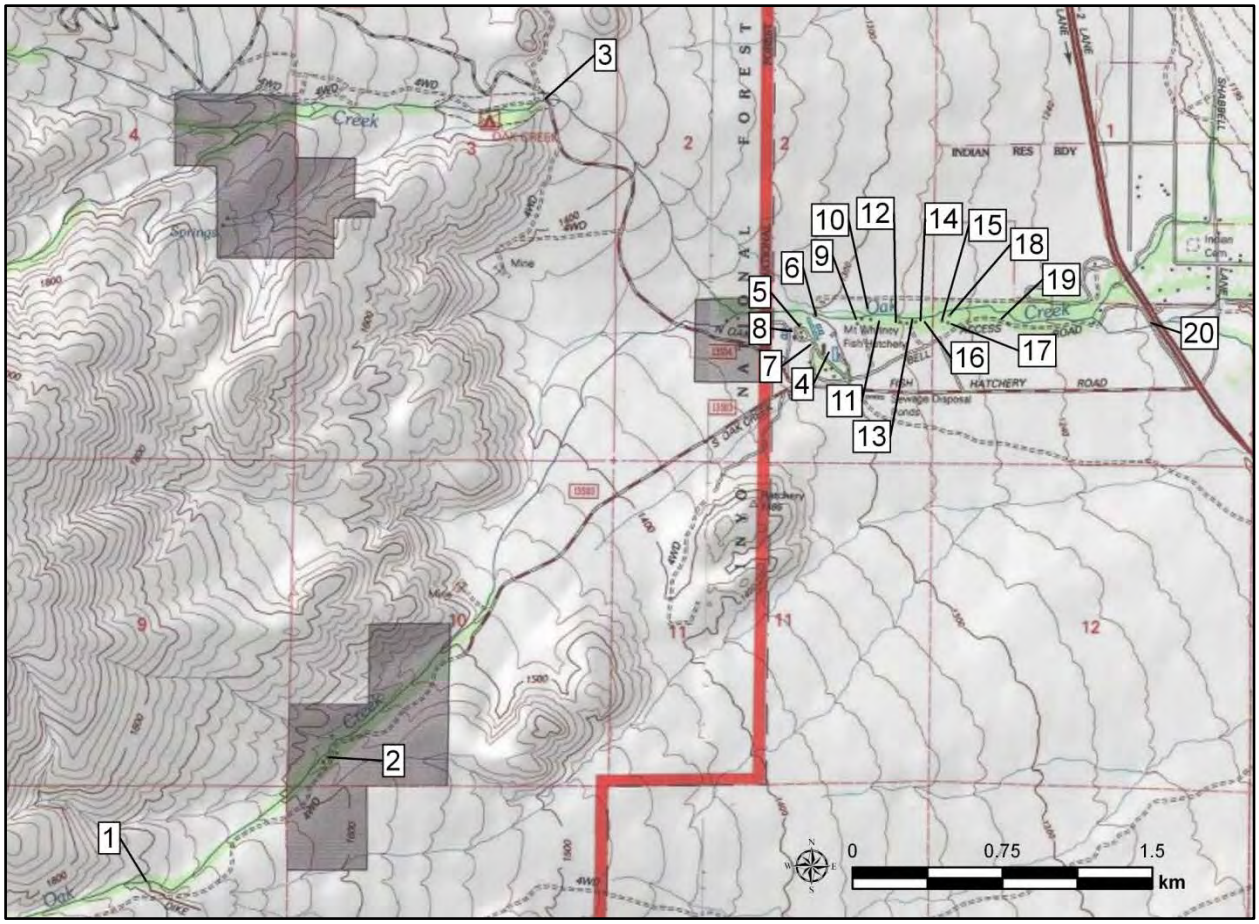

Figure 33: Map showing locations of damaged structures west of Highway 395 during the July 12, 2008 flows. See Table 4 for descriptions of the damaged structures. Observation of damaged structures on the east side of Highway 395 was not conducted as part of this investigation.

Figure 34: This home was damaged by boulders while others were damaged mostly by finer grained sediment. The water in the foreground is from Oak Creek which was forced from its channel during the storm. It was restored to its original channel (Locality 16, on Figure 33) soon after the storm, so residents could access their homes (Photo by Jim Stroh).

Most of the flow was diverted to the south by Highway 395, though some sediment crossed the highway through the Fort Independence Indian Reservation, reportedly damaging another 25 homes (Inyo Register July 15, 2008). Oak Creek was diverted back toward its original channel (Locality 6, Figure 33) by Caltrans soon after the event, allowing some downstream residents to reach their homes. Flow continued across the highway for days, requiring traffic detours or escorts to pass through the area.

TABLE 4:
Observed damage to structures west of Highway 395 during the flows of July 12, 2008.

Locality	Structure	Comments
1	Concrete intake	Massive concrete intake structure partially swept away
2	Residence	Mobile home swept off foundation and destroyed
3	Culvert	Culvert has been replaced and road repaired
4	Hatchery	Mt. Whitney Fish Hatchery breeding facilities and fish stock destroyed. Historic building lightly damaged and has been repaired.
5	Residence	Severely damaged and not habitable
6	Channel restoration	Site where Oak Creek was restored to its original channel.
7	Residence	House lightly damaged by mud
8	Residences	Two houses lightly damaged by mud
9	Residence	House destroyed; not habitable
10	Residence	Small one-room cottage destroyed; not habitable
11	Residence	Modular home severely damaged; off foundation
12	Residence	Double-wide trailer severely damaged; off foundation
13	Residence	House slightly damaged and has been repaired
14	Residence	House destroyed: not habitable
15	Residence	House destroyed; has been removed
16	Residence	House severely damaged; repairs not complete
17	Residences	Two houses slightly damaged and have been repaired
18	Residence	Slightly damaged and has been repaired
19	Residence	Mobil home severely damaged; not habitable
20	Culvert	Culvert beneath of HWY 395 replaced

RECURRENCE

We are not aware of any events comparable to the flows of July 12, 2008 in the Oak Creek drainage reported during the past 150 years, and certainly since the construction of the Mt. Whitney fish hatchery in 1916. Investigations in the Chalfant Valley suggest recurrence intervals for debris flows of similar character to the July 12, 2008 Oak Creek flows of between 300 to 320 years (Beaty, 1970; Hubert and Filipov, 1989). Two debris flows, both much smaller than the 2008 Oak Creek flow, occurred in 1983 and 1990 in Black Canyon, a few km North of Oak Creek (Whipple, 1992). A long runout debris flow, much smaller than that of the Oak Creek flow occurred in the Haiwee Creek watershed about 80 km (50 mi) south (Lancaster, 2012). This debris flow was also the result of an intense cloud burst on a recently burned watershed.

Preliminary analysis of the measured sections on the North Fork of Oak Creek (Figures 8a,b in Appendix A) suggests there was at least one or possibly two fires between 1,280 and 1,370 years ago, followed by flooding. There is also evidence of a fire at about 600 years ago that was followed by flooding and debris flows. The measured section at station 15 (Figure 8c) on the middle fork of Oak Creek, suggests there was a fire followed by a debris flow about 2,400 years ago. However, there appears to be a 1,000-year gap in the sedimentary record, so more measured sections and dating are required before a fire-flood history can be determined. Although the data are incomplete, they do seem to suggest that recurrence intervals for events similar to the July 12, 2008 event in the North Fork drainage are on the order of several hundreds of years, fairly close to what has been reported for Chalfant Valley.

DEBRIS AND HYPER-CONCENTRATED FLOW HAZARDS

Alluvial fans in the Owens Valley are primarily the result of rainfall, concentration of runoff in channels, and deposition due to flooding. These alluvial fan floods occur as debris flows and hyperconcentrated flows issue from the mountains and deposit sediment and debris on alluvial fans in response to the tectonic deepening of Owens Valley. Guidelines to assess debris flow hazards developed by the Utah Geological Survey (Giraud, 2005), and the Alluvial Fan Task Force (AFTF) Planning Manual (2010) defines a debris flow hazard area as an area where there is geomorphic or geologic evidence of debris flows during the Holocene (last 10,000 to 12,000 years). Plate 1 is a geologic map showing the Quaternary (~last 2 million years) deposits in the Oak Creek drainage. Three ages of alluvial fan deposits are shown: in stratigraphic order they are young (Holocene to late Pleistocene - Qyf), old (Pleistocene - Qof), and very old (Pleistocene to Pliocene - Qvof). There are boulder piles, levees and snouts along the active and abandoned channels on the younger fans providing geomorphic evidence of Holocene debris flows on the younger fans. Most of the features were buried or surrounded by sediment and debris from the July 2008 floods (Qdh on Plate 1). There were no significant deposits from this event on the older fans.

CONCLUSIONS

In the late afternoon of July 12, 2008 a tropical storm dropped intense rain (7.6 - 63.5 mm; 0.3 to 2.5 inches, in 39 minutes) on steep slopes of the Oak Creek drainage that had been burned in the prior year, causing widespread flooding. Conclusions from this investigation are:

- The storm cell was centered between the North and South forks of Oak Creek.
- Scour within the channels of the North and South forks of Oak Creek and their tributaries triggered debris flows and hyperconcentrated flows, with erosion extending up to 3,000 m (9,100 ft) in elevation. The flows travelled over 1,500 m (4,600 ft) of relief, and 16 km (10 mi) down into Owens Valley. The runout extended 6 km (3.8 mi) from the apex of the North Fork fan and 7 km (4.4 mi) from the apex of the South Fork fan.
- Sand-rich hyperconcentrated flows dominated the flow in the North Fork of Oak Creek and boulder-rich debris flows dominated along the South Fork.
- Although rilling was extensive on the steep slopes in the drainage, the amount of sediment derived from them is considered negligible.
- Nearly all the debris was derived from channel scour. The total debris yield for the entire drainage is estimated to be ~1½ million m^3 (~2 million yd^3), with the North Fork contributing nearly one million m^3 and the South Fork contributing over one-half million m^3.
- Three surges flowed down the North Fork. The first and third surges were about 1 m (3 ft) high, with the speed of the third surge estimated at about 2 m/sec (~4.5 mi/hr). The middle surge was as high as 3.9 m (12 ft) and is estimated to have travelled at a speed of about 5.4 m/sec (~12 mi/hr).
- Boulders ranging from less than one meter to over three meters (3 to 9 feet) across, weighing up to 26,000 kg (57,000 lbs), were moved by the flows.
- Once on the fans, the debris and hyperconcentrated flows quickly filled the active and abandoned channels and spread across the fan interfluves. The channel of the South Fork of Oak Creek was blocked by boulder debris near the apex of the fan, avulsion occurred, and the stream established a new course.
- Recurrence intervals for events of this magnitude on Oak Creek appear to be several hundred years but more research on a fire and flood history for the drainage is needed.
- Alluvial fans in the Owens Valley are the result of debris and hyperconcentrated flows issuing from the mountains in response to the tectonic deepening of Owens Valley. Older fans in the Oak Creek drainage were abandoned about 100,000 years ago and the debris flow hazard on them is low. Younger fans began forming after about 100,000 years ago and are still forming today. The relative potential for debris and hyperconcentrated flows on the younger fans is variable but should be considered high. The highest relative potential for debris and hyperconcentrated flow is along active streams.

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APPENDIX A: Measured Stratigraphic Sections

Stratigraphic Sections

Three sections of the stratified sediments were measured and described in the field on October 6, 7, and 8 in 2009 (Figure 8a,b,c: See field station location map in text, Figure 9). Two of the measured sections (field stations 62 and 63) are near the confluence of the North and middle forks of Oak Creek and the third (field station 15) is about 2.5 km (1.6 mi) upstream on the middle fork of Oak Creek. Sampling of wood, charred wood, peat, and organic sediment was conducted after stratigraphic horizons were defined, and samples were sent to Beta Analytic Laboratory in Miami, Florida on 11/5/2009 and 12/9/2009. Test results are provided in Appendix B. Sample number 71 (See location on Figure 9) is included in the Beta Analytic laboratory report dated 1/15/2010, but was sampled from a profile in the South Fork of Oak Creek, and therefore does not appear on Figures 8 a, b, and c.

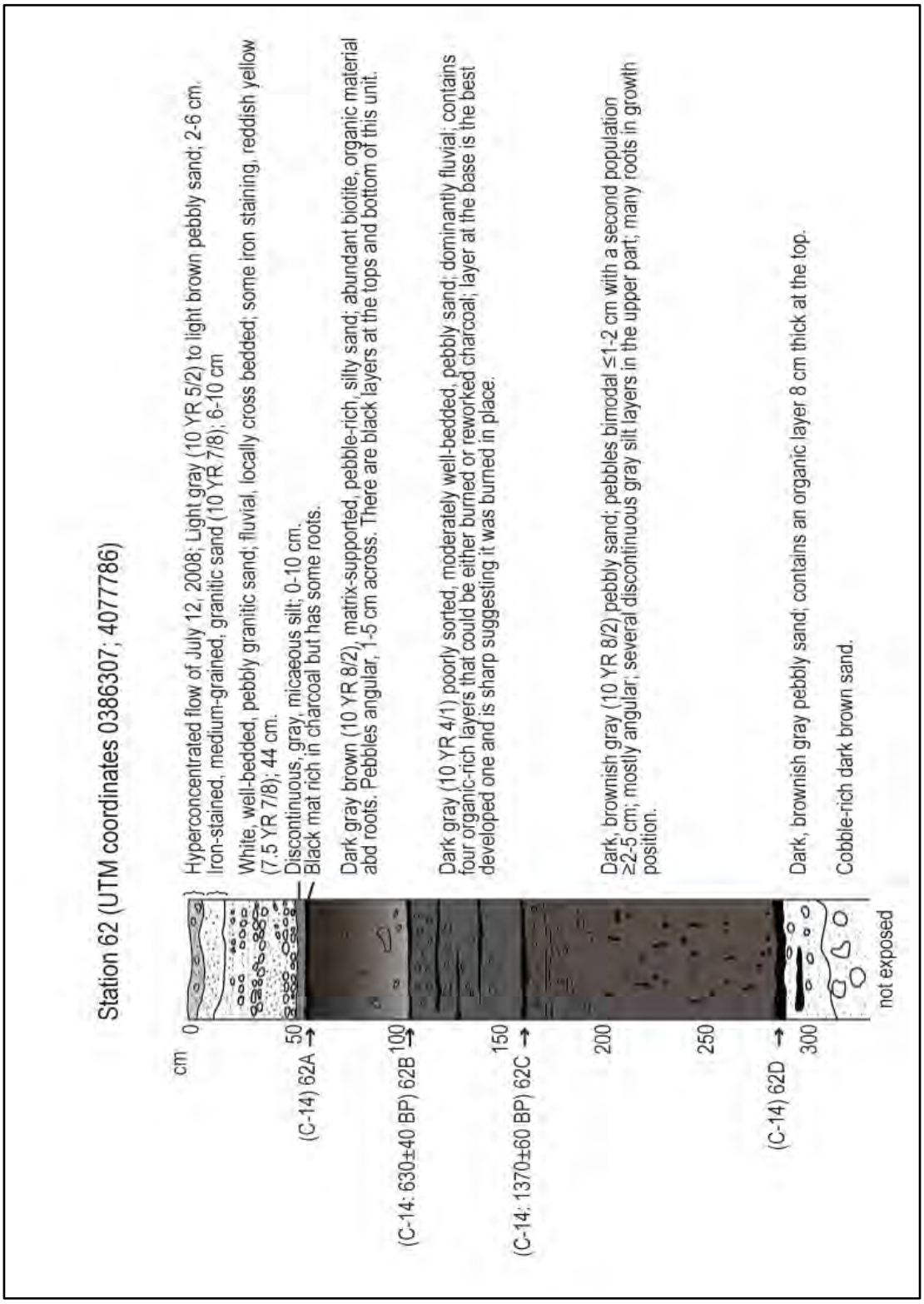

Figure 8a: Measured section at field station 62. Conventional radiocarbon ages: Sample 62A is uncertain <200 years Before Present(BP); Sample 62B, 640 ± 40 BP; Sample 62C, 1370 ±60 BP; Sample 62D, 1110 ± 40 BP. Sample 62D is interpreted as a reworked deposit in the thalweg of a scoured channel and is not part of the measured section. See Appendix 1 for analytical data.

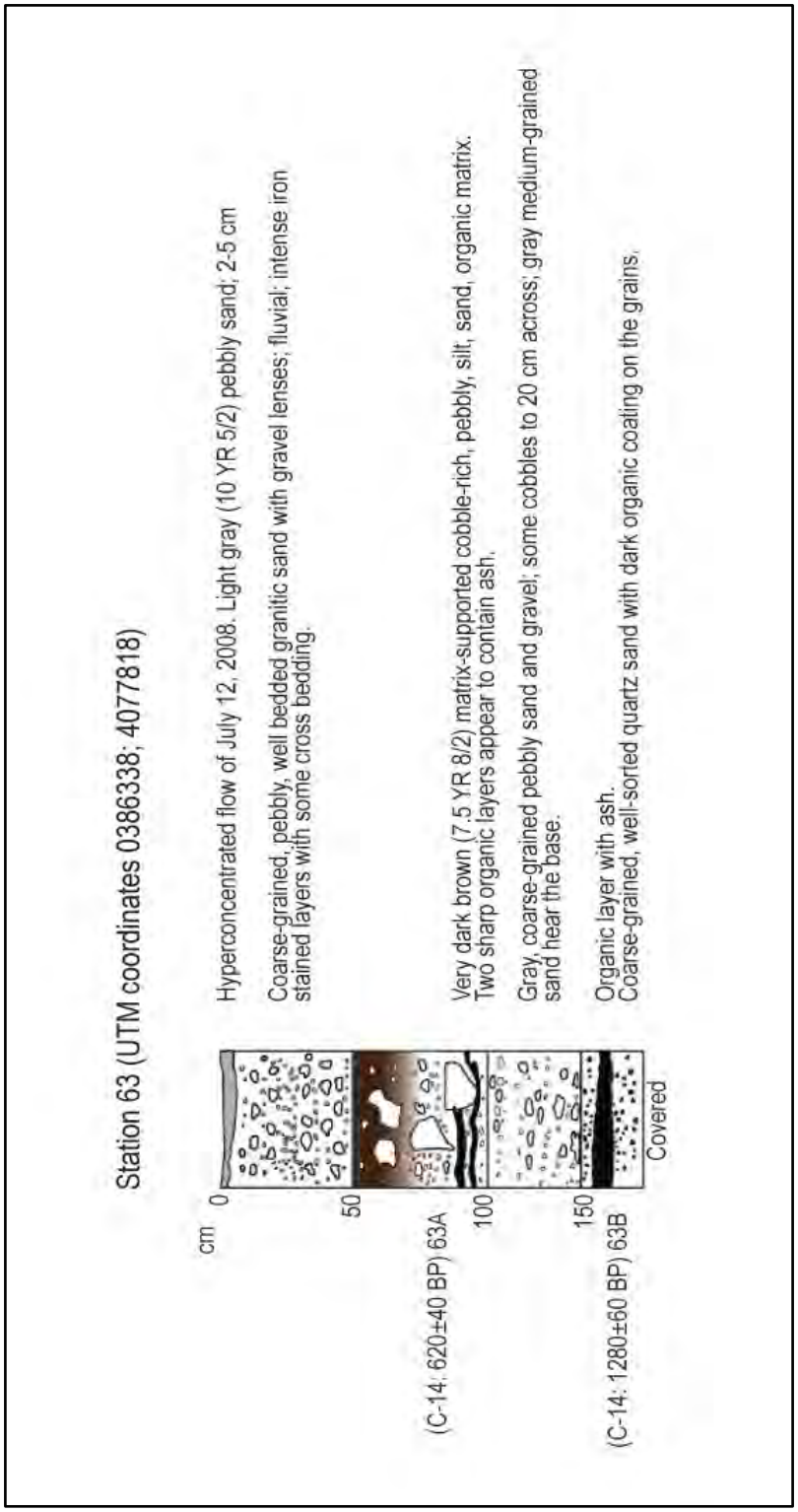

Figure 8b: Measured section at field station 63. Conventional radiocarbon ages: Sample 62A, 620 ± 40 BP; Sample 63B, 1280 ± 60 BP.

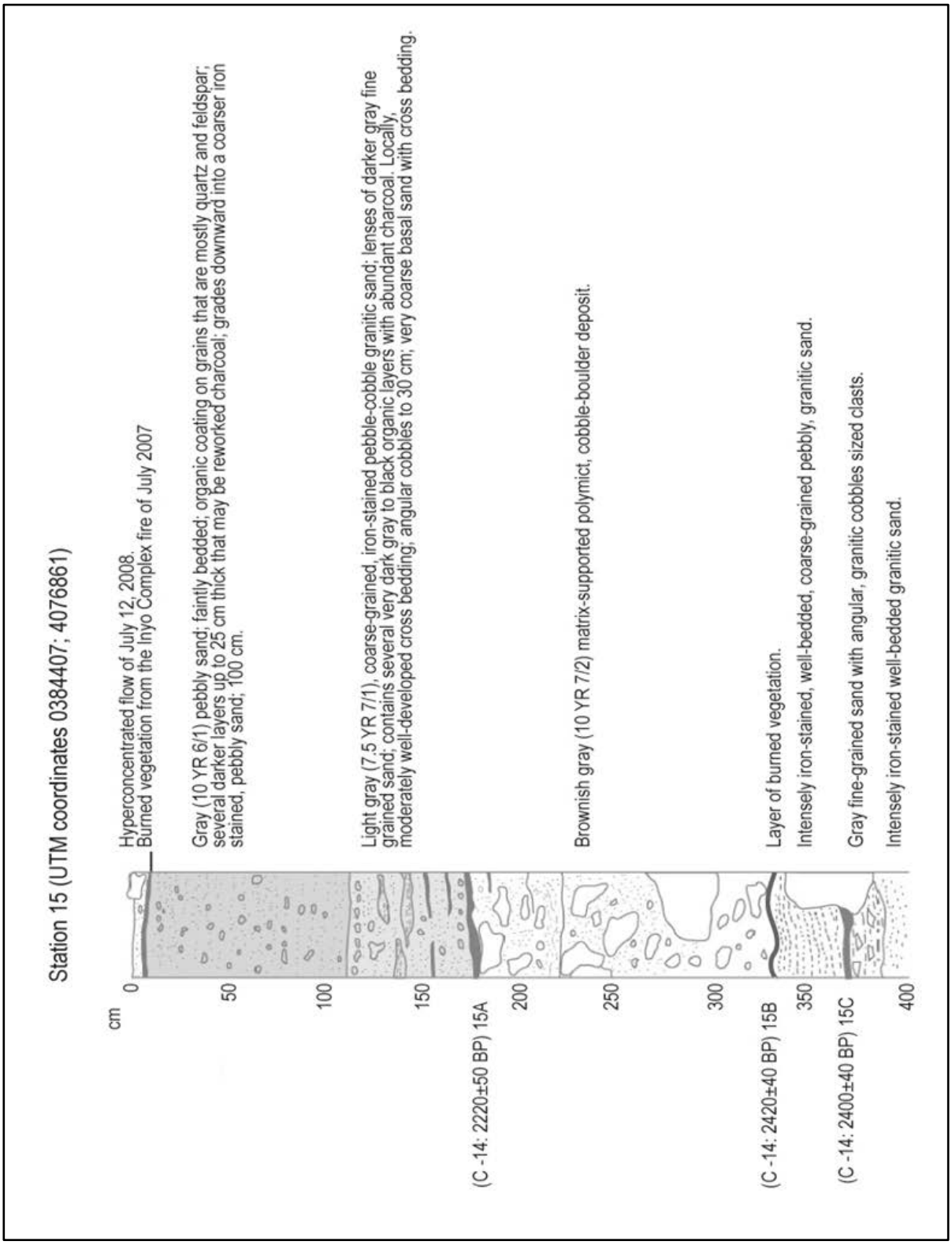

Figure 8c: Measured section at field station 15. Conventional radiocarbon ages: Sample 15A, 2220 ± 50 BP; Sample 15B, 2420 ± 40 BP; Sample 15C 2400 ± 40 BP.

APPENDIX B: Radiocarbon Dating Results

Beta Analytic Inc.
4985 SW 74 Court
Miami, Florida 33155 USA
Tel: 305 667 5167
Fax: 305 663 0964
Beta@radiocarbon.com
www.radiocarbon.com

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December 3, 2009

Mr. David Wagner
California Geological Survey
336 Rosedale Drive
Independence, CA 93526
USA

RE: Radiocarbon Dating Results For Samples DW-15A, DW-15C, DW-62A, DW-62D

Dear Mr. Wagner:

Enclosed are the radiocarbon dating results for four samples recently sent to us. They each provided plenty of carbon for accurate measurements and all the analyses proceeded normally. The report sheet contains the dating result, method used, material type, applied pretreatment and two-sigma calendar calibration result (where applicable) for each sample.

You will notice that Beta-268016 (DW-62A) is reported with the units "pMC" rather than BP. "pMC" stands for "percent modern carbon". Results are reported in the pMC format when the analyzed material had more ^{14}C than did the modern (AD 1950) reference standard. The source of this "extra" ^{14}C in the atmosphere is thermo-nuclear bomb testing which on-set in the 1950s. Its presence generally indicates the material analyzed was part of a system that was respiring carbon after the on-set of the testing (AD 1950s). On occasion, the two sigma lower limit will extend into the time region before this "bomb-carbon" onset (i.e. less than 100 pMC). In those cases, there is some probability for 18th, 19th, or 20th century antiquity.

We analyzed these samples on a sole priority basis. No students or intern researchers who would necessarily be distracted with other obligations and priorities were used in the analyses. We analyzed them with the combined attention of our entire professional staff.

Information pages are enclosed with the mailed copy of this report. They should answer most of questions you may have. If they do not, or if you have specific questions about the analyses, please do not hesitate to contact us. Someone is always available to answer your questions.

Our invoice has been sent separately. Thank you for your prior efforts in arranging payment. As always, if you have any questions or would like to discuss the results, don't hesitate to contact me.

Sincerely,

Darden Hood
Digital signature on file

BETA ANALYTIC INC.
DR. M.A. TAMERS and MR. D.G. HOOD
4985 S.W. 74 COURT
MIAMI, FLORIDA, USA 33155
PH: 305-667-5167 FAX:305-663-0964
beta@radiocarbon.com

REPORT OF RADIOCARBON DATING ANALYSES

Mr. David Wagner

Report Date: 12/3/2009

California Geological Survey

Material Received: 11/5/2009

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 268014 SAMPLE : DW-15A ANALYSIS : Radiometric-Standard delivery MATERIAL/PRETREATMENT : (wood): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 390 to 170 (Cal BP 2340 to 2120)	2250 +/- 50 BP	-27.1 o/oo	2220 +/- 50 BP
Beta - 268015 SAMPLE : DW-15C ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 740 to 690 (Cal BP 2690 to 2640) AND Cal BC 660 to 640 (Cal BP 2610 to 2590) Cal BC 550 to 390 (Cal BP 2500 to 2340)	2420 +/- 40 BP	-26.0 o/oo	2400 +/- 40 BP
Beta - 268016 SAMPLE : DW-62A ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (peat): acid/alkali/acid COMMENT: reported result indicates an age of post 0 BP and has been reported as a % of the modern reference standard, indicating the material was living within the last 50 years.	99.9 +/- 0.5 pMC	-26.4 o/oo	100.2 +/- 0.5 pMC
Beta - 268017 SAMPLE : DW-62D ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (peat): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 870 to 1010 (Cal BP 1080 to 940)	1130 +/- 40 BP	-26.0 o/oo	1110 +/- 40 BP

Dates are reported as RCYBP (radiocarbon years before present, "present" = AD 1950). By international convention, the modern reference standard was 95% the 14C activity of the National Institute of Standards and Technology (NIST) Oxalic Acid (SRM 4990C) and calculated using the Libby 14C half-life (5568 years). Quoted errors represent 1 relative standard deviation statistics (68% probability) counting errors based on the combined measurements of the sample, background, and modern reference standards. Measured 13C/12C ratios (delta 13C) were calculated relative to the PDB-1 standard.

The Conventional Radiocarbon Age represents the Measured Radiocarbon Age corrected for isotopic fractionation, calculated using the delta 13C. On rare occasion where the Conventional Radiocarbon Age was calculated using an assumed delta 13C, the ratio and the Conventional Radiocarbon Age will be followed by "*". The Conventional Radiocarbon Age is not calendar calibrated. When available, the Calendar Calibrated result is calculated from the Conventional Radiocarbon Age and is listed as the "Two Sigma Calibrated Result" for each sample.

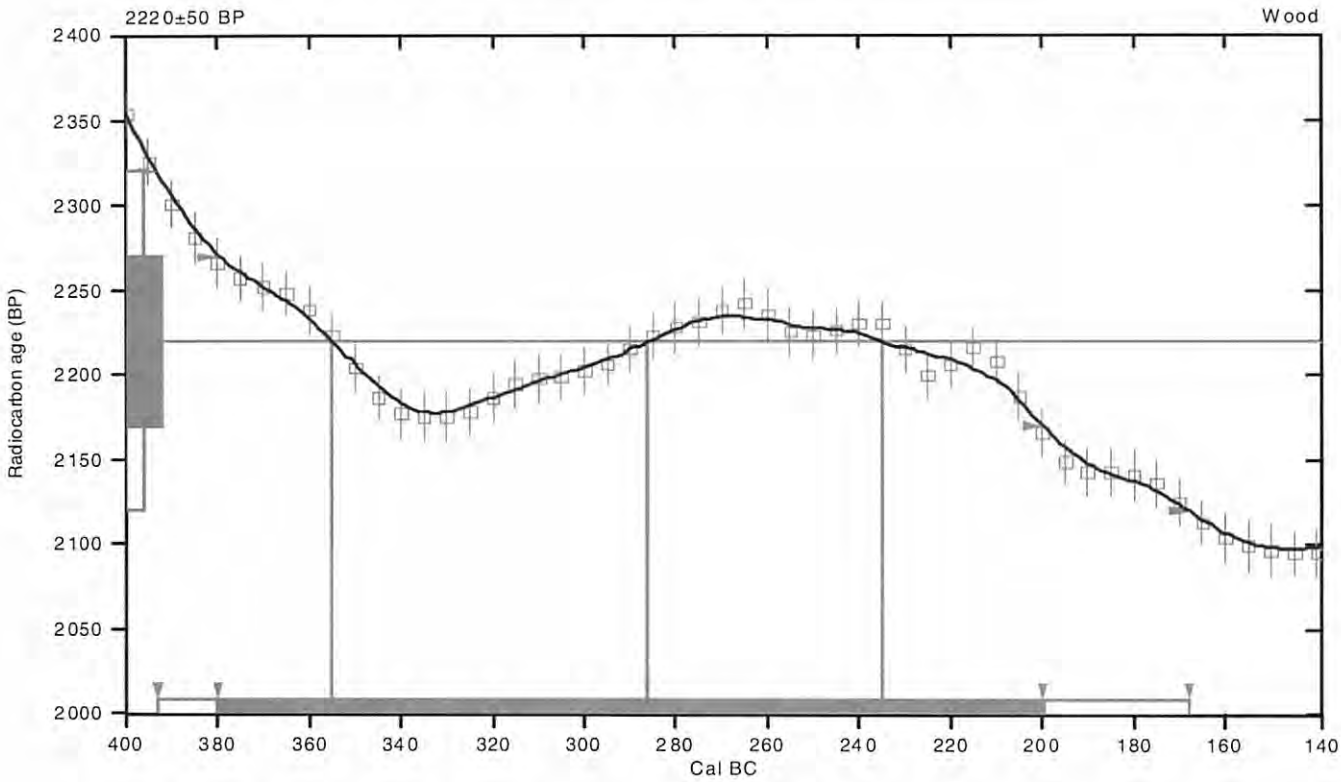
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-27.1:lab. mult=1)

Laboratory number:	**Beta-268014**
Conventional radiocarbon age:	**2220±50 BP**
2 Sigma calibrated result: (95% probability)	**Cal BC 390 to 170 (Cal BP 2340 to 2120)**

Intercept data

Intercepts of radiocarbon age with calibration curve:	Cal BC 360 (Cal BP 2300) and Cal BC 290 (Cal BP 2240) and Cal BC 240 (Cal BP 2180)
1 Sigma calibrated result: (68% probability)	Cal BC 380 to 200 (Cal BP 2330 to 2150)



References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

A Simplified Approach to Calibrating C14 Dates

Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Radiocarbon Dating Laboratory

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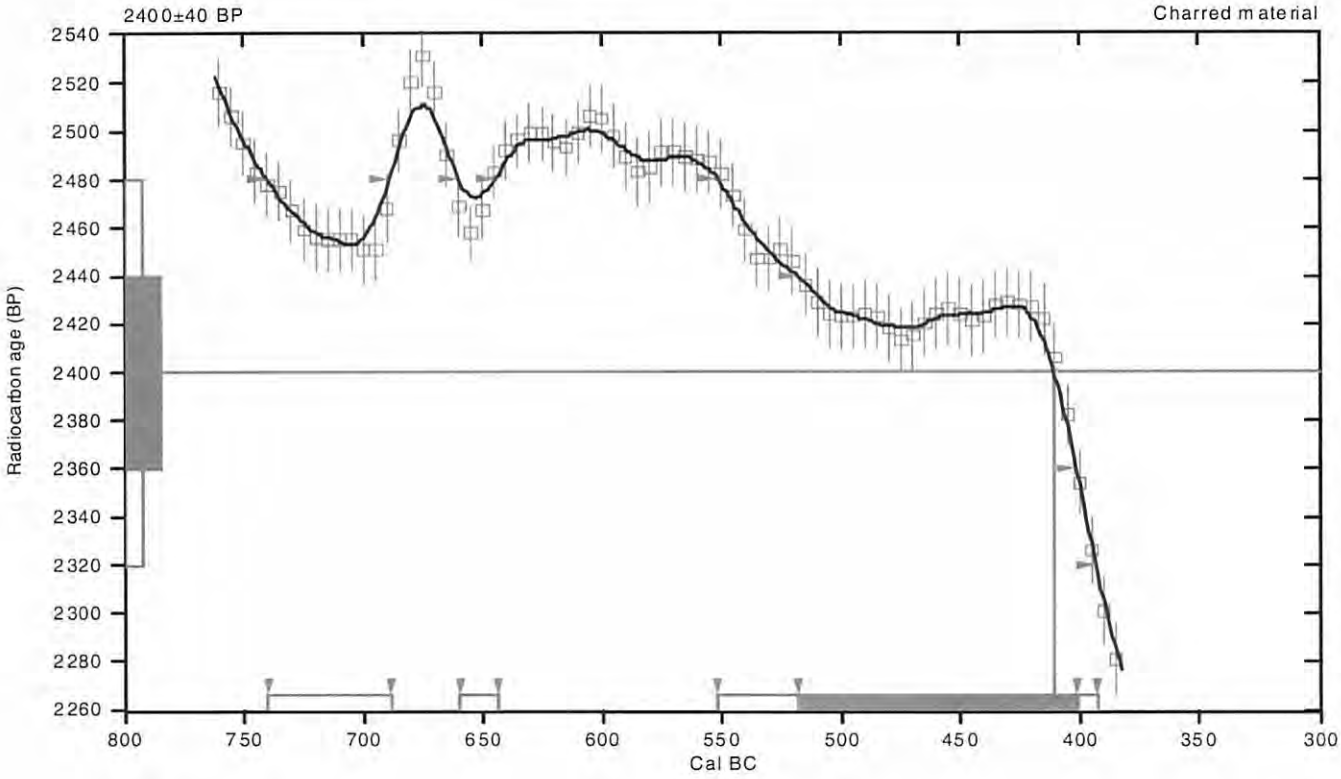
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-26:lab. mult=1)

Laboratory number:	**Beta-268015**
Conventional radiocarbon age:	**2400±40 BP**
2 Sigma calibrated results: (95% probability)	**Cal BC 740 to 690 (Cal BP 2690 to 2640) and Cal BC 660 to 640 (Cal BP 2610 to 2590) and Cal BC 550 to 390 (Cal BP 2500 to 2340)**

Intercept data

Intercept of radiocarbon age with calibration curve:	Cal BC 410 (Cal BP 2360)
1 Sigma calibrated result: (68% probability)	Cal BC 520 to 400 (Cal BP 2470 to 2350)



References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

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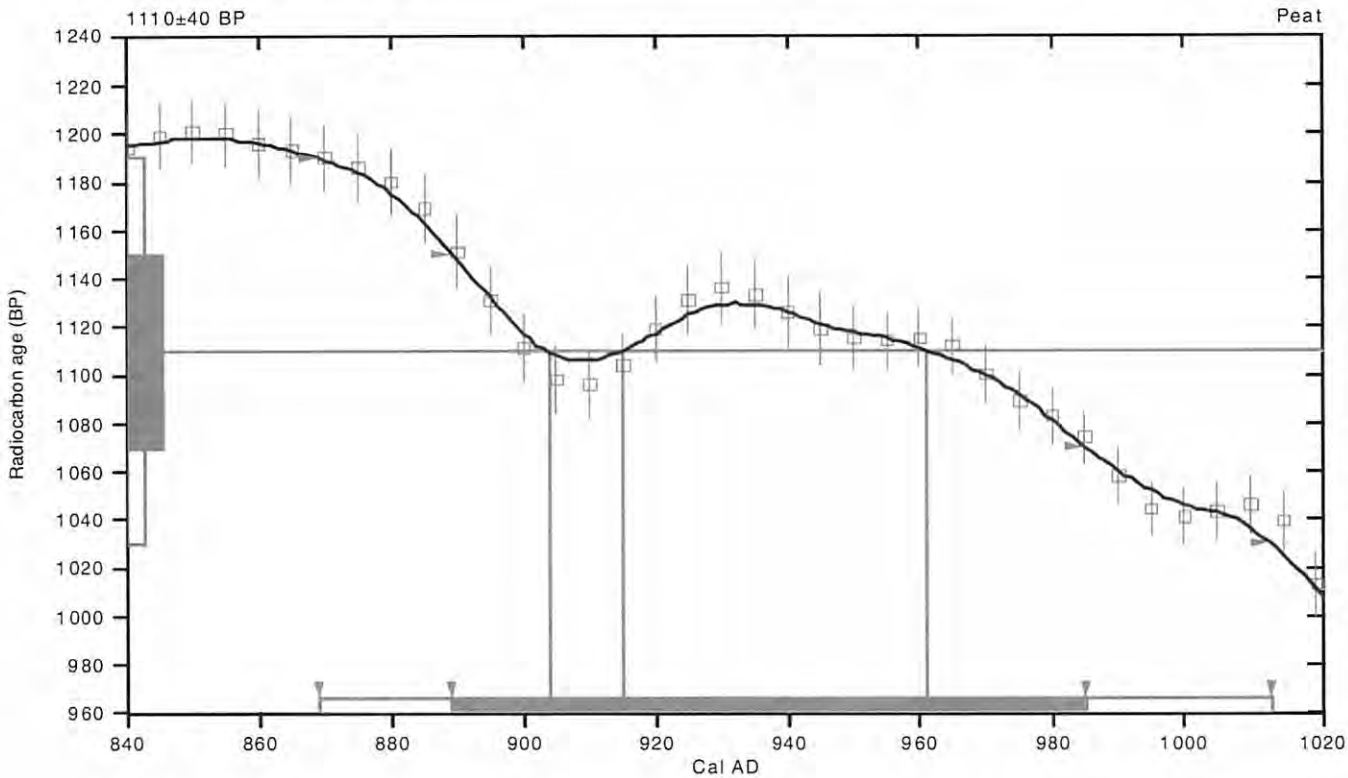
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-26:lab. mult=1)

Laboratory number:	**Beta-268017**
Conventional radiocarbon age:	**1110±40 BP**
2 Sigma calibrated result: (95% probability)	**Cal AD 870 to 1010 (Cal BP 1080 to 940)**

Intercept data

Intercepts of radiocarbon age with calibration curve:	Cal AD 900 (Cal BP 1050) and Cal AD 920 (Cal BP 1040) and Cal AD 960 (Cal BP 990)
1 Sigma calibrated result: (68% probability)	Cal AD 890 to 980 (Cal BP 1060 to 960)



References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

A Simplified Approach to Calibrating C14 Dates

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Mr. David Wagner
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Independence, CA 93526
USA

RE: Radiocarbon Dating Results For Samples DW15B, DW62B, DW62C, DW63A, DW63B, DW71

Dear Mr. Wagner:

Enclosed are the radiocarbon dating results for six samples recently sent to us. They each provided plenty of carbon for accurate measurements and all the analyses proceeded normally. As usual, the method of analysis is listed on the report with the results and calibration data is provided where applicable.

As always, no students or intern researchers who would necessarily be distracted with other obligations and priorities were used in the analyses. We analyzed them with the combined attention of our entire professional staff.

If you have specific questions about the analyses, please contact us. We are always available to answer your questions.

The cost of analysis was previously invoiced. As always, if you have any questions or would like to discuss the results, don't hesitate to contact me.

Sincerely,

Darden Hood
Digital signature on file

BETA ANALYTIC INC.
DR. M.A. TAMERS and MR. D.G. HOOD
4985 S.W. 74 COURT
MIAMI, FLORIDA, USA 33155
PH: 305-667-5167 FAX:305-663-0964
beta@radiocarbon.com

REPORT OF RADIOCARBON DATING ANALYSES

Mr. David Wagner

Report Date: 1/15/2010

California Geological Survey

Material Received: 12/9/2009

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 270397 SAMPLE : DW15B ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 750 to 680 (Cal BP 2700 to 2630) AND Cal BC 670 to 610 (Cal BP 2620 to 2560) Cal BC 600 to 400 (Cal BP 2560 to 2350)	2440 +/- 40 BP	-26.0 o/oo	2420 +/- 40 BP
Beta - 270398 SAMPLE : DW62B ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (organic sediment): acid washes 2 SIGMA CALIBRATION : Cal AD 1280 to 1410 (Cal BP 670 to 540)	650 +/- 40 BP	-26.1 o/oo	630 +/- 40 BP
Beta - 270399 SAMPLE : DW62C ANALYSIS : Radiometric-Standard delivery MATERIAL/PRETREATMENT : (organic sediment): acid washes 2 SIGMA CALIBRATION : Cal AD 580 to 770 (Cal BP 1370 to 1180)	1390 +/- 60 BP	-26.2 o/oo	1370 +/- 60 BP
Beta - 270400 SAMPLE : DW63A ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (organic sediment): acid washes 2 SIGMA CALIBRATION : Cal AD 1280 to 1410 (Cal BP 670 to 540)	630 +/- 40 BP	-25.9 o/oo	620 +/- 40 BP

Dates are reported as RCYBP (radiocarbon years before present, "present" = AD 1950). By international convention, the modern reference standard was 95% the 14C activity of the National Institute of Standards and Technology (NIST) Oxalic Acid (SRM 4990C) and calculated using the Libby 14C half-life (5568 years). Quoted errors represent 1 relative standard deviation statistics (68% probability) counting errors based on the combined measurements of the sample, background, and modern reference standards. Measured 13C/12C ratios (delta 13C) were calculated relative to the PDB-1 standard.

The Conventional Radiocarbon Age represents the Measured Radiocarbon Age corrected for isotopic fractionation, calculated using the delta 13C. On rare occasion where the Conventional Radiocarbon Age was calculated using an assumed delta 13C, the ratio and the Conventional Radiocarbon Age will be followed by "*". The Conventional Radiocarbon Age is not calendar calibrated. When available, the Calendar Calibrated result is calculated from the Conventional Radiocarbon Age and is listed as the "Two Sigma Calibrated Result" for each sample.

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REPORT OF RADIOCARBON DATING ANALYSES

Mr. David Wagner

Report Date: 1/15/2010

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 270401	1290 +/- 60 BP	-25.7 o/oo	1280 +/- 60 BP
SAMPLE : DW63B			
ANALYSIS : Radiometric-Standard delivery			
MATERIAL/PRETREATMENT : (organic sediment): acid washes			
2 SIGMA CALIBRATION : Cal AD 650 to 890 (Cal BP 1300 to 1060)			
Beta - 270402	290 +/- 60 BP	-23.3 o/oo	320 +/- 60 BP
SAMPLE : DW71			
ANALYSIS : Radiometric-Standard delivery			
MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid			
2 SIGMA CALIBRATION : Cal AD 1440 to 1670 (Cal BP 510 to 280) AND Cal AD 1780 to 1790 (Cal BP 160 to 160)			

Dates are reported as RCYBP (radiocarbon years before present, "present" = AD 1950). By international convention, the modern reference standard was 95% the 14C activity of the National Institute of Standards and Technology (NIST) Oxalic Acid (SRM 4990C) and calculated using the Libby 14C half-life (5568 years). Quoted errors represent 1 relative standard deviation statistics (68% probability) counting errors based on the combined measurements of the sample, background, and modern reference standards. Measured 13C/12C ratios (delta 13C) were calculated relative to the PDB-1 standard.

The Conventional Radiocarbon Age represents the Measured Radiocarbon Age corrected for isotopic fractionation, calculated using the delta 13C. On rare occasion where the Conventional Radiocarbon Age was calculated using an assumed delta 13C, the ratio and the Conventional Radiocarbon Age will be followed by "*". The Conventional Radiocarbon Age is not calendar calibrated. When available, the Calendar Calibrated result is calculated from the Conventional Radiocarbon Age and is listed as the "Two Sigma Calibrated Result" for each sample.

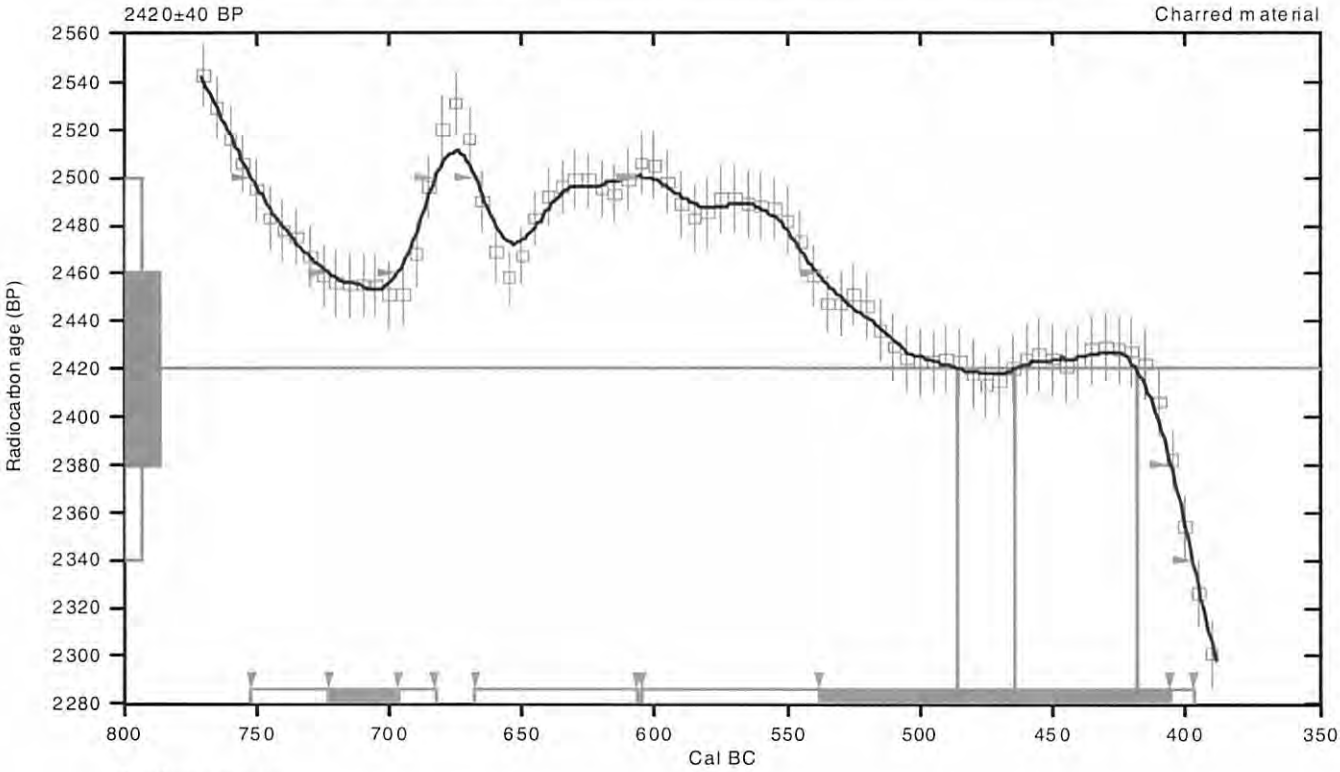
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-26:lab. mult=1)

Laboratory number:	**Beta-270397**
Conventional radiocarbon age:	**2420±40 BP**
2 Sigma calibrated results: (95% probability)	**Cal BC 750 to 680 (Cal BP 2700 to 2630) and Cal BC 670 to 610 (Cal BP 2620 to 2560) and Cal BC 600 to 400 (Cal BP 2560 to 2350)**

Intercept data

Intercepts of radiocarbon age with calibration curve:	Cal BC 490 (Cal BP 2440) and Cal BC 460 (Cal BP 2410) and Cal BC 420 (Cal BP 2370)
1 Sigma calibrated results: (68% probability)	Cal BC 720 to 700 (Cal BP 2670 to 2650) and Cal BC 540 to 410 (Cal BP 2490 to 2360)



References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

A Simplified Approach to Calibrating C14 Dates

Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Radiocarbon Dating Laboratory

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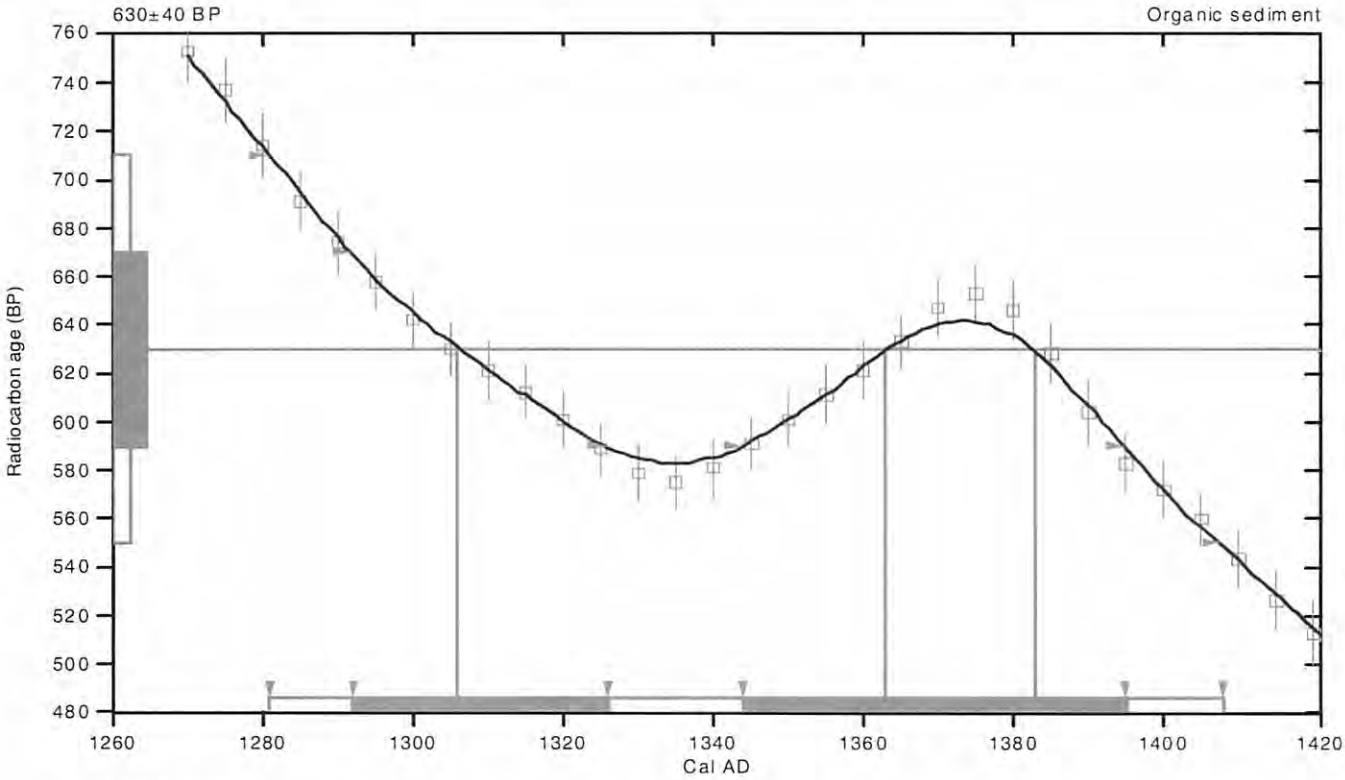
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-26.1:lab. mult=1)

Laboratory number:	**Beta-270398**
Conventional radiocarbon age:	**630±40 BP**
2 Sigma calibrated result: (95% probability)	**Cal AD 1280 to 1410 (Cal BP 670 to 540)**

Intercept data

Intercepts of radiocarbon age with calibration curve:	Cal AD 1310 (Cal BP 640) and Cal AD 1360 (Cal BP 590) and Cal AD 1380 (Cal BP 570)
1 Sigma calibrated results: (68% probability)	Cal AD 1290 to 1330 (Cal BP 660 to 620) and Cal AD 1340 to 1400 (Cal BP 610 to 560)



References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

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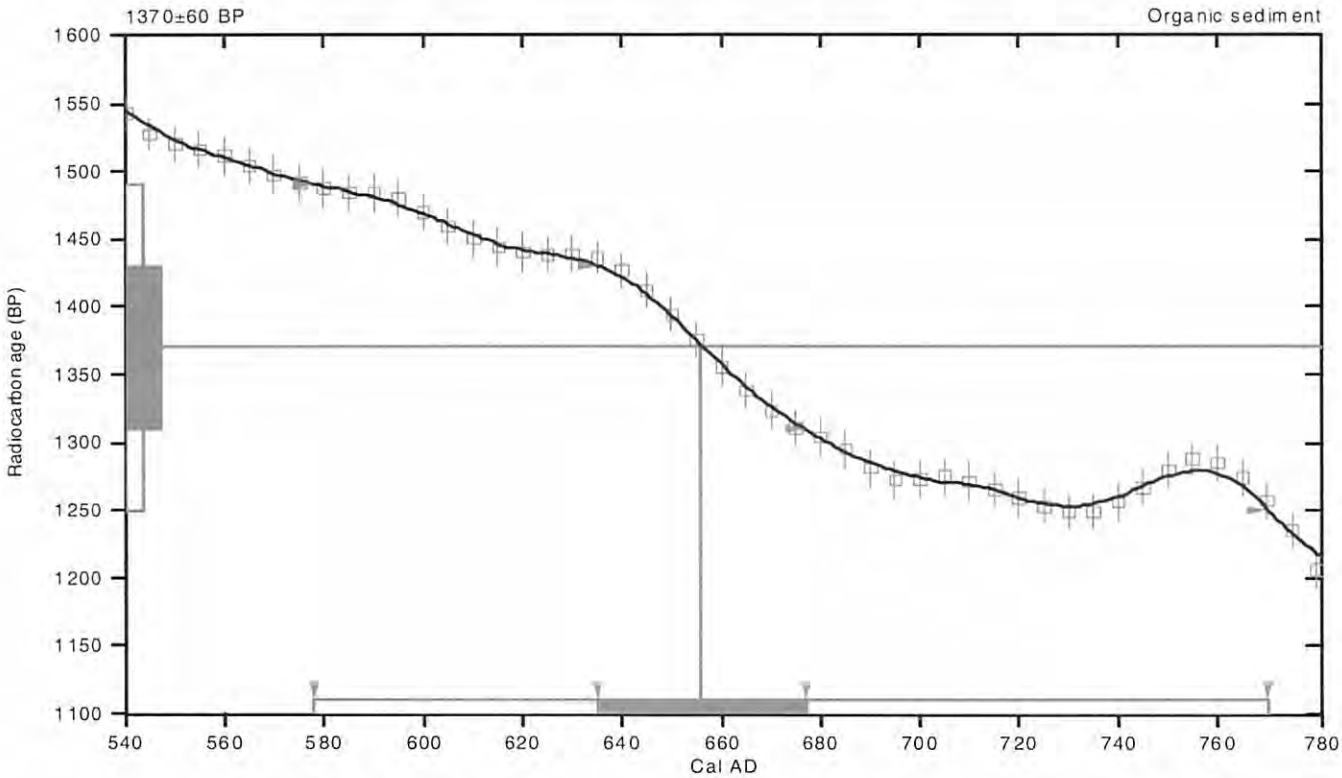
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-26.2:lab. mult=1)

Laboratory number:	**Beta-270399**
Conventional radiocarbon age:	**1370±60 BP**
2 Sigma calibrated result: (95% probability)	**Cal AD 580 to 770 (Cal BP 1370 to 1180)**

Intercept data

Intercept of radiocarbon age with calibration curve:	Cal AD 660 (Cal BP 1290)
1 Sigma calibrated result: (68% probability)	Cal AD 640 to 680 (Cal BP 1320 to 1270)



References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

A Simplified Approach to Calibrating C14 Dates

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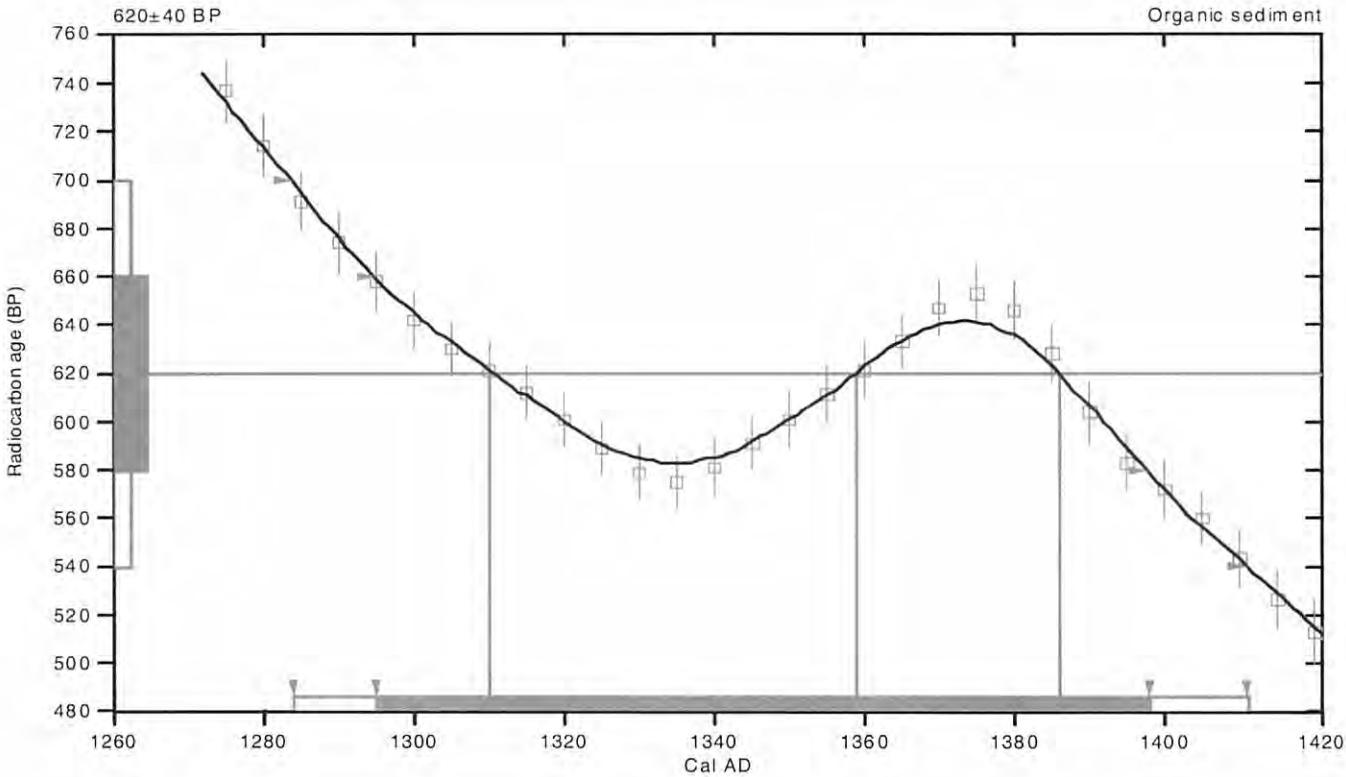
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-25.9:lab. mult=1)

Laboratory number:	**Beta-270400**
Conventional radiocarbon age:	**620±40 BP**
2 Sigma calibrated result: (95% probability)	**Cal AD 1280 to 1410 (Cal BP 670 to 540)**

Intercept data

Intercepts of radiocarbon age with calibration curve:	Cal AD 1310 (Cal BP 640) and Cal AD 1360 (Cal BP 590) and Cal AD 1390 (Cal BP 560)
1 Sigma calibrated result: (68% probability)	Cal AD 1300 to 1400 (Cal BP 660 to 550)



References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

A Simplified Approach to Calibrating C14 Dates

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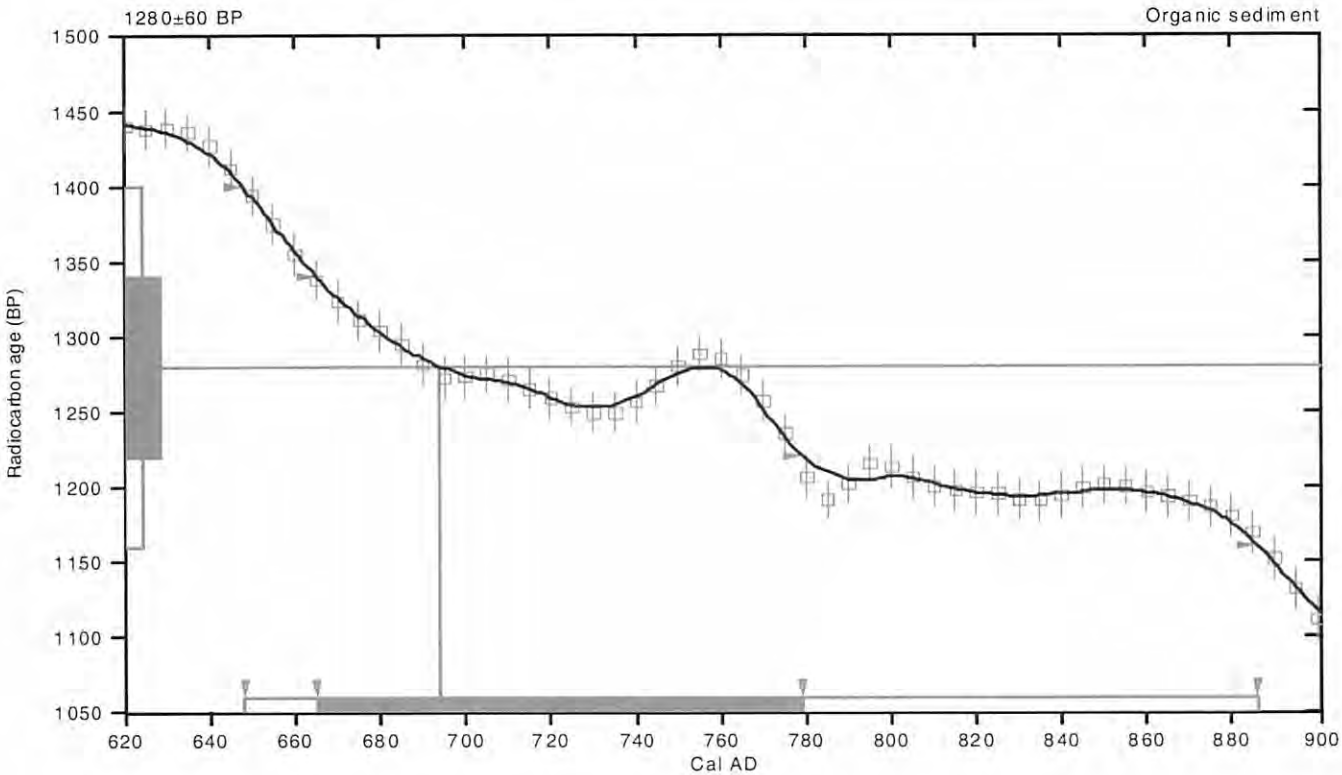
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-25.7:lab. mult=1)

Laboratory number:	**Beta-270401**
Conventional radiocarbon age:	**1280±60 BP**
2 Sigma calibrated result: (95% probability)	**Cal AD 650 to 890 (Cal BP 1300 to 1060)**

Intercept data

Intercept of radiocarbon age with calibration curve:	Cal AD 690 (Cal BP 1260)
1 Sigma calibrated result: (68% probability)	Cal AD 660 to 780 (Cal BP 1280 to 1170)



References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

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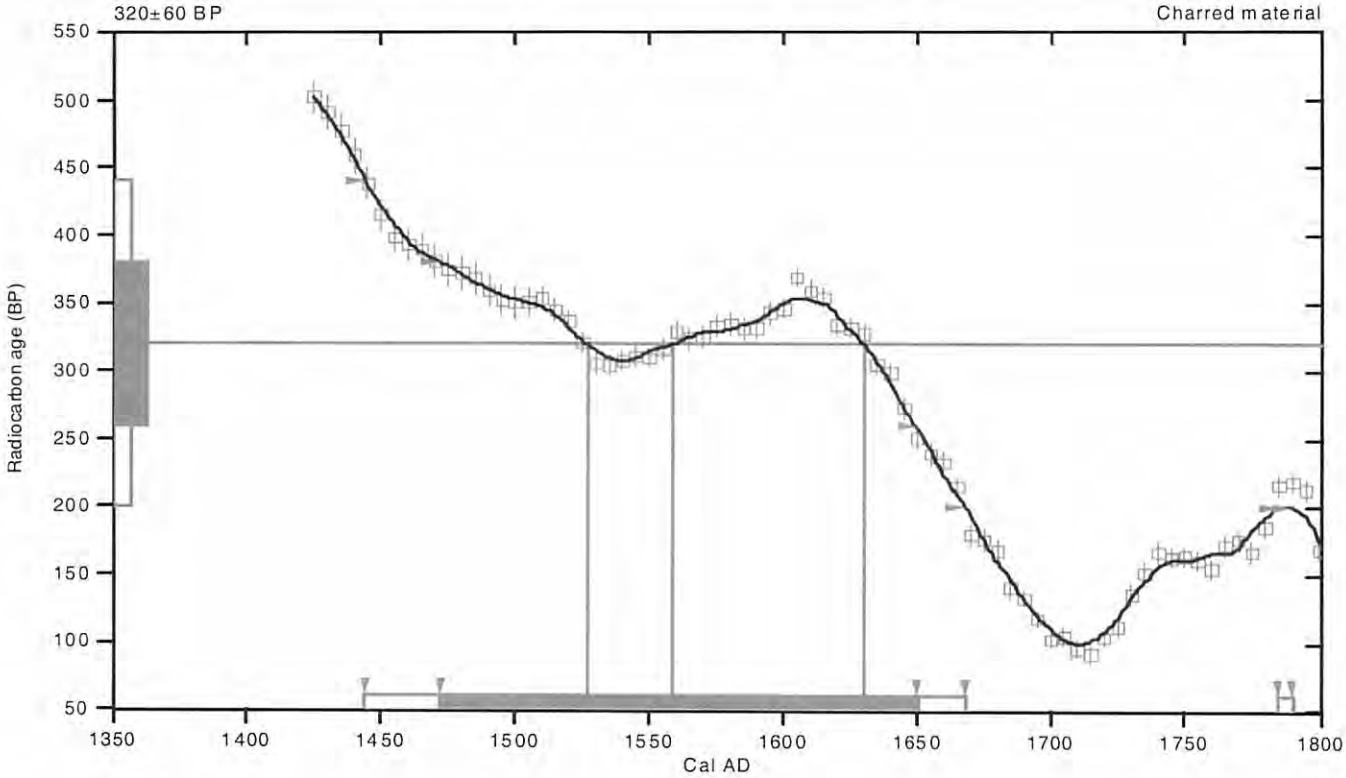
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-23.3:lab. mult=1)

Laboratory number:	**Beta-270402**
Conventional radiocarbon age:	**320±60 BP**
2 Sigma calibrated results: (95% probability)	**Cal AD 1440 to 1670 (Cal BP 510 to 280) and Cal AD 1780 to 1790 (Cal BP 160 to 160)**

Intercept data

Intercepts of radiocarbon age with calibration curve:	Cal AD 1530 (Cal BP 420) and Cal AD 1560 (Cal BP 390) and Cal AD 1630 (Cal BP 320)
1 Sigma calibrated result: (68% probability)	Cal AD 1470 to 1650 (Cal BP 480 to 300)



References:

Database used

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Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

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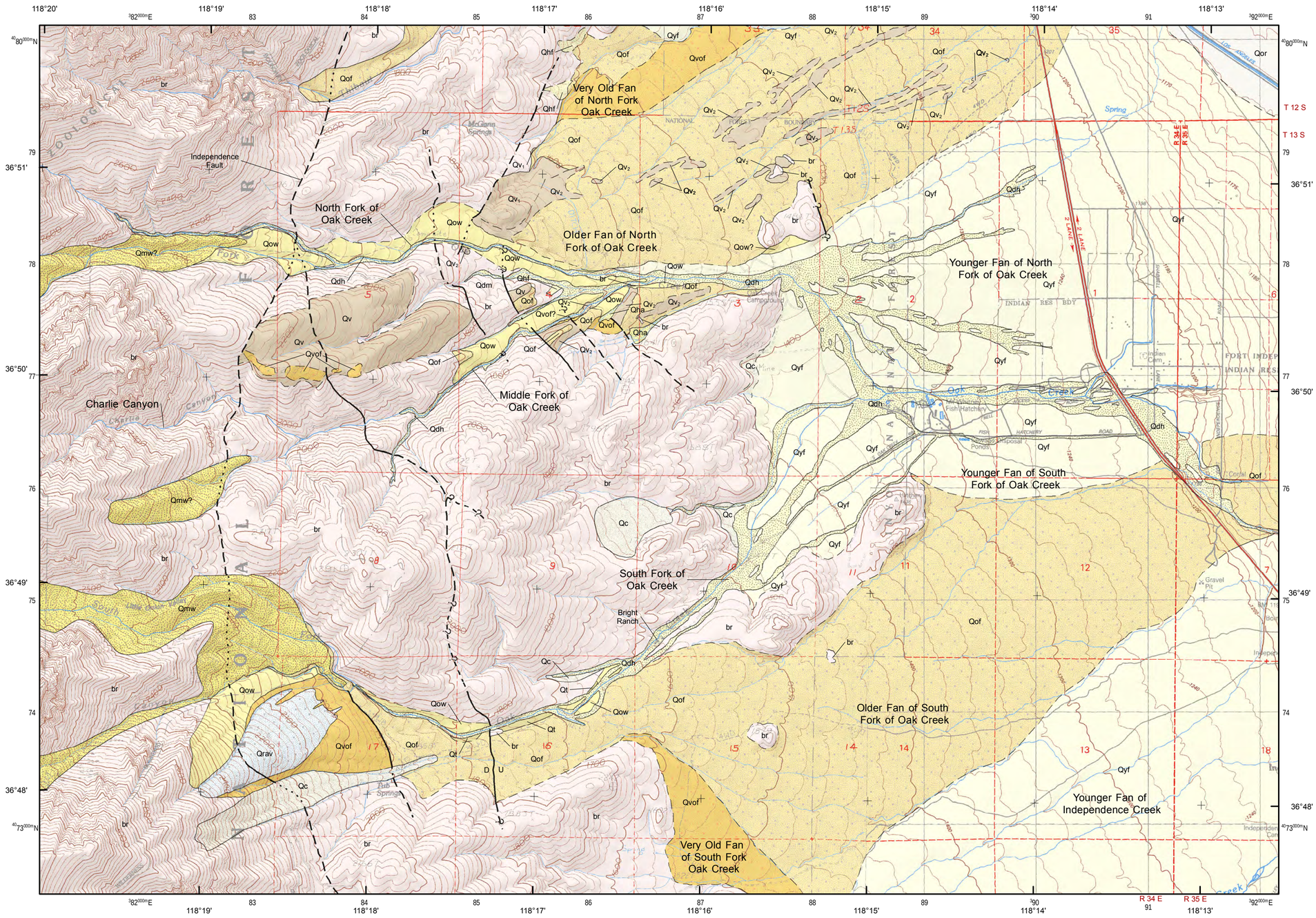
APPENDIX C: Plates 1 and 2



Projection and 1000-meter grid: Universal Transverse Mercator, Zone 11 North, North American Datum of 1927

Base map of topography, hydrography, transportation, and cultural features from USGS 7.5-minute digital raster graphics, Kearsarge Peak and Independence quadrangles. Shaded topographic base from USGS 1/3 arc-second digital elevation model.

GEOLOGIC MAP OF THE QUATERNARY DEPOSITS IN THE OAK CREEK DRAINAGE INYO COUNTY, CALIFORNIA

by
David L. Wagner, CEG

Digital preparation by
Solomon McCrea

July 2012

www.conservation.ca.gov/cgs

The Department of Conservation makes no warranties as to the suitability of this product for any particular purpose.

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Information on this map is not sufficient to serve as a substitute for the geologic and geotechnical site investigations required under Chapters 7.5 and 7.8 of Division 2 of the California Public Resources Code.

SCALE 1:24 000

1 — 0.5 — 0 — 1 MILES

1000 — 0 — 1000 — 2000 — 3000 — 4000 — 5000 — 6000 — 7000 — 8000 — 9000 — 10000 FEET

1 — 0.5 — 0 — 1 — 2 KILOMETERS

1000 — 0 — 1000 — 2000 METERS

CONTOUR INTERVAL 20 METERS
NATIONAL GEODETIC VERTICAL DATUM OF 1929

TRUE NORTH
MAGNETIC NORTH
13½°
APPROXIMATE MEAN DECLINATION, 2009

CALIF.
MAP LOCATION

MAP UNITS

Qdh Silt, sand, pebbles, boulders, and debris deposited during the debris flows and hyperconcentrated flows of July 12, 2008.

Qha Holocene alluvium along modern stream courses. Found mostly along the north and middle forks of Oak Creek but in most places masked by deposits from the July 12, 2008 mudflow.

Qhf Holocene alluvial fan deposits. Sand, silt and gravel. These deposits are found at the mouths of canyons and are likely the result of minor debris flows.

Qor Fluvial sediments of the Owens River meander belt. These deposits occur east of Hwy 395.

Qc Colluvium. A mixture of rock soil and organic material. Locally includes aeolian sand.

Qrav Rock avalanche deposit in the southwest corner of the map area. Angular blocks of granitic and metamorphic rock mostly 0.3-0.51 m across with no matrix. Le et al. (2007) reported cosmogenic abandonment age of 18.7 ka, suggesting the avalanche occurred during the Tioga glacial stage.

Qt Terrace surfaces cut into outwash deposits by the South Fork of Oak Creek.

Qyf Younger debris flow fan. Large (0.2 -1 m) to very large (>1 m) boulders, cobbles and pebbles in a coarse sandy to silty, micaeous matrix. Locally the matrix is rich in clay. Granitic boulders are fairly fresh to moderately weathered, the surface is covered with grus and is gray on air photos. There are abandoned stream channels with boulder levees, boulder debris flow snouts, as well as boulder fields on their surfaces. Younger fans occur in the eastern part of the map area and are traversed by the north and south forks of Oak Creek. The oldest, basal part of the younger fans could be as old as 200 ka (Gillespie, 1982) but are not exposed in the map area. Most of the younger fans are likely the same age as the bulk of fans forming the great bajada between Independence and the Alabama Hills near Lone Pine. Cosmogenic dating indicates that most the surfaces of these fans were abandoned about 15,000 to 35,000 years ago (Tioga and Tenaya glacial stages) but in some areas they are mantled with Holocene (<11,000 years) debris flow deposits (Dühnforth, et al., 2007; Le et al., 2007; Zehfuss, et al., 2001). The younger fan deposits along the South Fork of Oak Creek appear younger, more bouldery and generally a much thinner deposit than the larger younger fan along the North Fork of Oak Creek.

Qow Glacial outwash deposits. Angular to rounded boulders with or without a coarse sandy matrix. These deposits are the glacial equivalent to the younger debris flow fans. In the modern channel of the North Fork of Oak Creek these deposits have been reworked into sinuous boulder trains. Along the South Fork and Middle Fork of Oak Creek, the outwash deposits have flat upper surfaces with well developed soils on them. There are abandoned debris flow channels with marginal boulder levees. This outwash appears to be mid Wisconsin (Tenaya stage) in age (Gillespie, 1982).

Qmw Glacial moraines of Wisconsin age (Tioga, Tenaya, Tahoe stages). Unsorted glacial till consisting of abundant boulders in a fine, clay-rich matrix. Gillespie (1982) mapped four ages of moraines on the upper reaches of South Fork of Oak Creek that are shown as one unit on this map.

Qof Older debris flow fan. Boulders, cobbles and pebbles in a clay-rich, sand and silt matrix. Granitic boulders and cobbles are deeply weathered. The older fan has a smooth surface underlain by a well-developed, reddish soil rich in grus, making it distinct from the younger, gray fans. All but the largest granitic boulders on the fan surface have been eroded to the level of the fan or disintegrated completely leaving the most resistant rocks. The older fan north of the North Fork of Oak Creek was probably abandoned about 100 to 200 ka (Gillespie, 1982). The older fan south of the South Fork of Oak Creek is likely a similar age though it could be somewhat younger.

Qv Lava flows of the Big Pine Volcanic Field. Basalt lava with abundant granitic xenoliths and less common ultramafic xenoliths. Basaltic lava flows along the North Fork of Oak Creek and in the foothills were erupted from sources higher in the mountains. These flows are among the oldest of the Big Pine Volcanic field (Darrow, 1972; Gillespie, 1982). Gillespie (1982) divided the flows of the Big Pine field into four of subdivisions. Above the North Fork of Oak Creek the flows cap ridges and are undivided (Qv), with Isotopic dates ranging from 208 ka to approximately 1.2 Ma (Blondes, 2008; Gillespie, 1982, Gillespie et al., 1983). A second group of flows subdivided as Qv2 and Qv1 (youngest to oldest) are present in the map area and are interbedded with fanglomerate of the older fan of the North Fork of Oak Creek. Isotopic dates on these flows range from 100 ka to 420 ka (Bierman et. al., 1991; Blondes, et al., 2007).

Qvof Very old fan deposits. Old alluvium composed of boulders and cobbles of resistant metamorphic rock types in a coarse sandy matrix. Many of the clasts are stained a deep red color and granitic clasts are nearly nonexistent. Scattered exposures occur beneath the older fan deposits. The gravels are probably early Pleistocene and or Pliocene.

br Bedrock-Chiefly Mesozoic granitic and metamorphic rocks. See Moore (1963) for information on the bedrock.

SYMBOL EXPLANATION

[For geologic line symbols: lines are solid where location is accurate, long-dashed where location is approximate, short-dashed where location is inferred, dotted where location is concealed. Queries added where identity or existence may be questionable.]

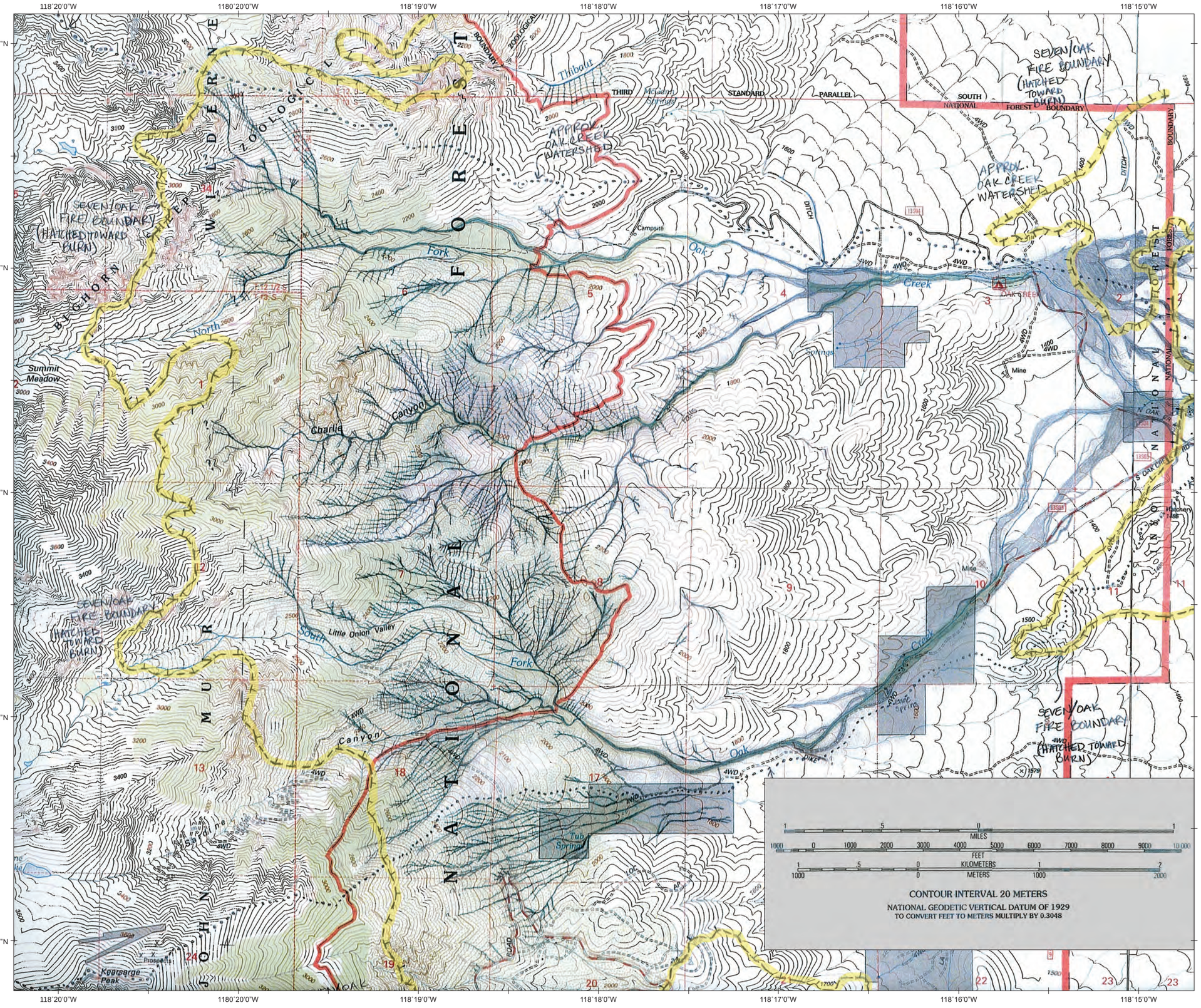
Contact

70° D U —?— —?— ·?· · ·? Fault – showing dip of fault plane angle, direction and U, upthrown block; D, downthrown block when known

MAP REFERENCES (See Reference cited in text)

Geology compiled from Gillespie (1982) and from mapping and air photo interpretation by M. DeRose (2008) and D. L. Wagner (2008-2009)

PLATE 2
FIELD MAP OF EROSION AND CONCENTRATED FLOW FEATURES
OAK CREEK DRAINAGE, INYO COUNTY, CA



APPROXIMATE MEAN DECLINATION, 2012

MAP LOCATION

MAP EXPLANATION

A portion of the field map prepared by DeRose showing rilled slopes and scoured drainages based on aerial photographs and field observations following the July 12, 2008 event. The approximate boundaries of the Oak Creek drainage are denoted by the dotted line. The approximate boundaries of the Inyo Complex fire are shown by the hachured line. Base: Topographic map of the Kearsarge Peak and the Independence 7.5 Minute Quadrangles. (Note: Map presented as drawn, with highlights placed on fire boundary.)

MAP FEATURES

Areas of concentrated flow and channel scour. Shaded area denotes privately owned land.

Areas of slope erosion by rilling and gullying

Inyo National Forest Boundary

Wilderness Boundary

Approximate watershed boundaries

Approximate Inyo Complex fire boundaries (hatchured toward burn area)