Fiscal Year 2013 Summary Report
Nuclear Regulatory Commission-Sponsored Research Project G6016

Paleoseismology of the East Tennessee Seismic Zone

Prepared for:

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INTRODUCTION

The following is the annual report for the second year of funding for the Nuclear Regulatory Commission grant (Job Number G6016) to the University of Tennessee–Knoxville from October 1, 2012, to September 30, 2013. It summarizes the activities of the PIs and our results for this time period related to the paleoseismology of the East Tennessee seismic zone (ETSZ; Fig. 1), roughly in chronological order.

SUMMARY REPORT

Presentations related to our research and potential earthquake hazard in the East Tennessee seismic zone were made in September, October, and November, 2012, to the East Tennessee Geological Society; Eastern Section of the Seismological Society of America meeting (Blacksburg, VA, graduate student presentation); and the Annual Meeting of the Geological Society of America (Charlotte, NC, graduate student presentation). All presentations were well done and well received. The abstracts are appended to this report. NRC support was acknowledged in all presentations.

We resumed work on the Douglas Lake sites in late October with lake level dropped for winter runoff. Erosion during high water had exhumed the thrust fault to the NE of the main trench at DL-6 (Wells N) site (Figs. 2 and 3), and other features here, e.g., cross-bedded sand in the footwall of the thrust (Fig. 4). Very good down-dip plunging slickensides (top-to-the-NW) were visible on the fault and the fault was traceable some 25 m up slope from the trench (Fig. 2). A second thrust fault was re-exposed at DL–6 near the low water line; this fault truncates the fissure that is truncated by the 1 m-displacement thrust in the main trench up slope (Fig. 5). The Wells S site was visited in mid-December and work continued on the relationships between Quaternary sediment-filled fissures (Fig. 6) and overlying terrace deposits (fissures do not penetrate the overlying sediments). Orientations of all structures at DL–6 and Wells S sites have been measured. Tilted beds in one of the terraces at Wells S site (DL–9) were excavated by hand and we tentatively concluded that the tilting is related to slumping, although additional study is needed. The parallel orientation of the fissure at DL–6 and the principal set of fissures at Wells S site (DL–9, N33E) were also reconfirmed.

A two-day field review of DL–6 and Wells S sites by NRC geologists Drs. Gerry Stirewalt and Alice Stieve was hosted at the end of December, 2012. This brought the NRC staff up-to-date on our activities and principal accomplishments to that point.

Our paper on the preliminary site investigation of the East Tennessee seismic zone (Hatcher et al., 2012) was also published at the end of 2012. This was the first paper published on paleoseismology in the ETSZ, although various reports had been written

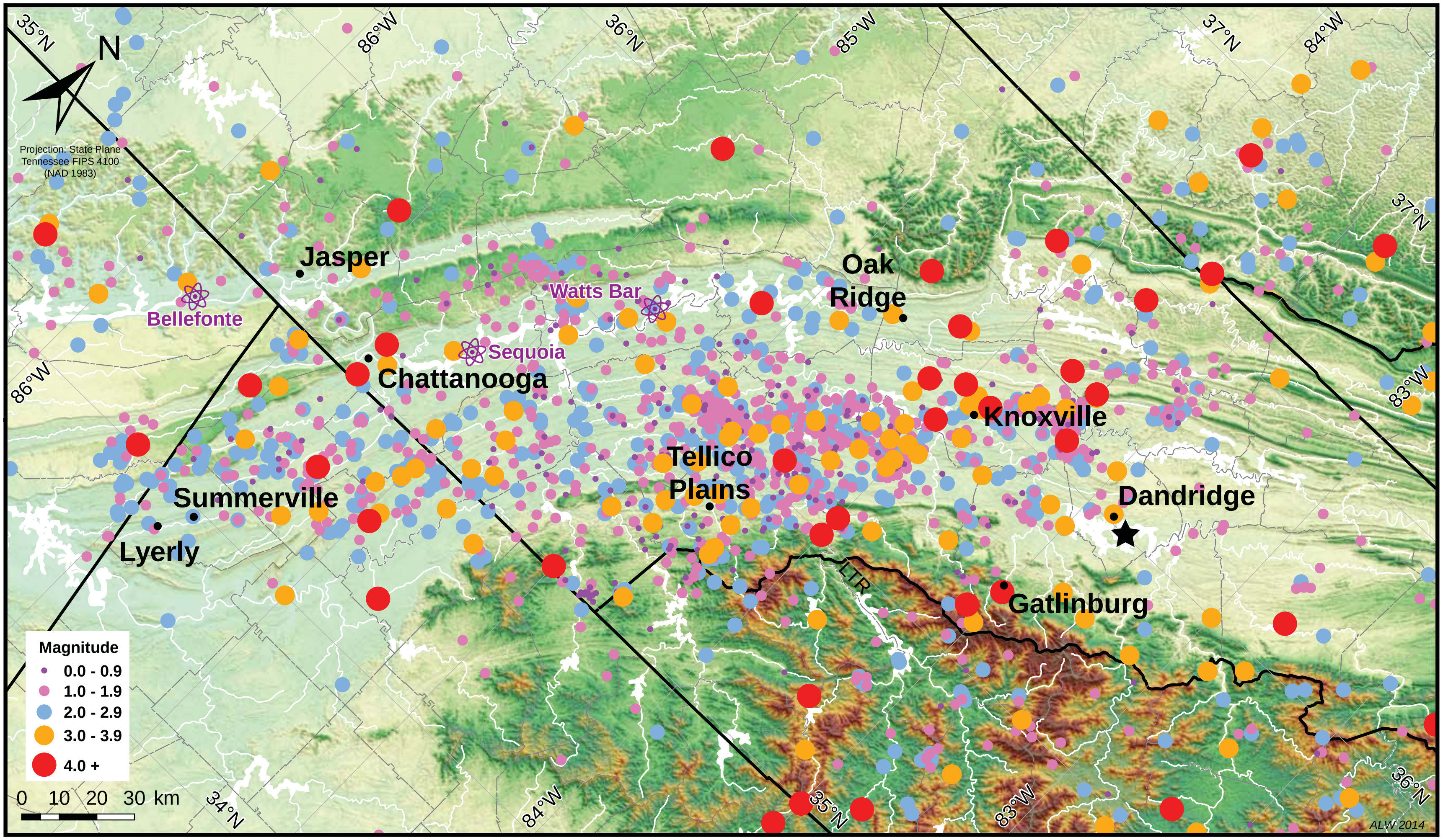
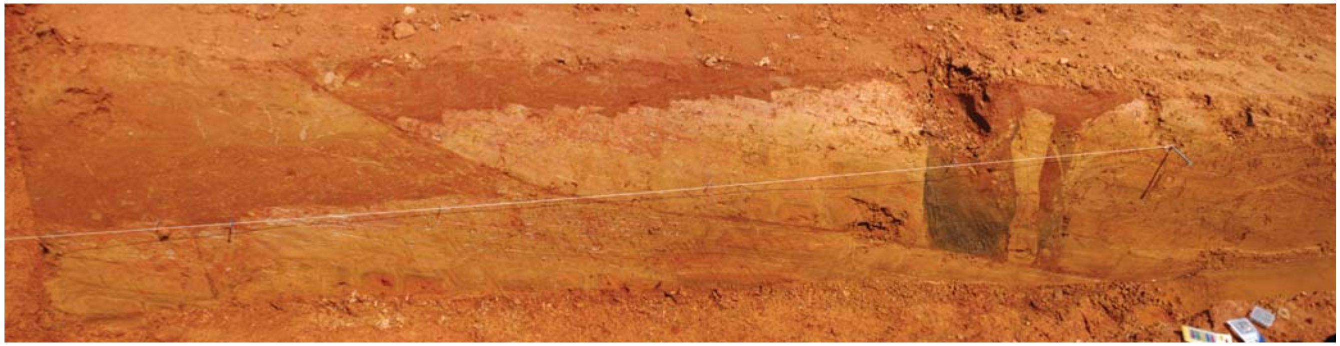


Figure 1. East Tennessee seismic zone earthquakes from 1777 to June, 2014, superposed on a digital elevation model (DEM) of the region. The black star is the area near Dandridge, TN, where most of the data confirming extensive prehistoric damage have been found to date. LTR—Little Tennessee River. DEM from NASA Shuttle Radar Topography Mission-90m resolution; Geographic features from the National Atlas; EQs from USGS/NEIC & CEUS Seismic Source Characterization for Nuclear Facilities. EPRI, Palo Alto, CA, U.S. DOE, and U.S. NRC: 2012.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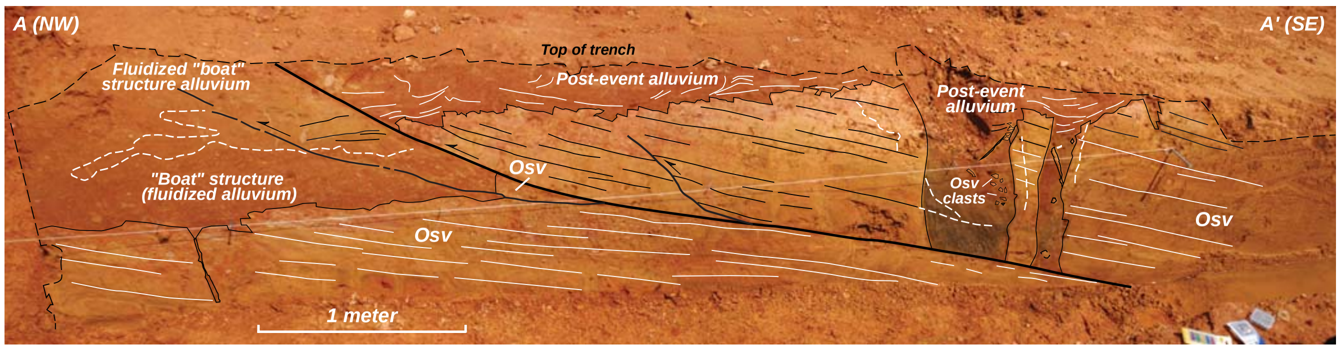

B

Figure 2. (A) Composite photo of the NE wall of trench 2 featuring the listric thrust fault, truncated fissures, "boat" structure, and strata in the E wall of trench 2 at site DL-6. The N55E thrust fault has an apparent upslope displacement of ~1 m and truncates both the fissures and "boat" structure produced by earlier event(s). This fault formed post-15 ka, based on OSL dates of material that fills the fissures. The material labeled alluvium in (B) is terrace sand in which all initial bedding has been partially to totally destroyed by fluidization triggered by forceful expulsion of groundwater along the fault. Note the reddish-brown alluvium that appears to have been dragged along the main thrust. The subhorizontal white "line" crossing the photo is a string used as a baseline for reference purposes. (B) Sketch overlay on the photo in A identifying important features. Note the clear truncation by the thrust fault of the alluvium-filled fissure toward the SE end of the photo, and also the two small-displacement splay thrusts that propagated into both the hanging wall and footwall. The splay in the hanging wall is confined to the Sevier Shale and did not cut the Sevier Shale–alluvium contact, but it is also listric and joins the main thrust downdip. Osv—Sevier Shale. Use of white and black lines has no geologic significance; the two colors were used to provide contrast with different-colored backgrounds. The dashed white lines bedding within the different units. (Photo by J.D. Vaughn. Figure 16 from Hatcher et al., 2012.)

Figure 3. Tracing the thrust fault uphill from the east boundary of the trench at DL–6. Note the slickensides (grooves) on the fault surface that plunge down the dip of the fault and in a few places indicate NW transport. The flagged stake marks the east end of the E-W arm of the trench.

Figure 4. Map view of concentric ridges representing cross-bedded sand in the footwall of the thrust along the west side of the trench at DL–6 (Wells N). The thrust is buried by recent lake sediment in the lower part of the photo.

Figure 5. Truncation of the fissure (greenish-looking material across the center of the photo that gradually disappears from right to left) by the thrust fault down slope from the trench at DL–6. Here Sevier Shale is thrust over the fissure material. The shale has a layered fractured appearance, and the fault zone is exposed in the small area to the left of the layered shale with a small isolated piece of reddish-brown soil resting on it (white arrow). Faint slickensides are visible on the fault surface (NW-directed).

Figure 6. "Map" view of branching, alluvium-filled fissures in Sevier Shale at DL-9 (Wells S) site. The faint concentric lines in the shale that parallel the fissure boundaries are Liesegang diffusion bands.

previously for contractors and government agencies, but these are not commonly available for use throughout the scientific community.

Two large rainfall events occurred during early January, 2013, and Douglas Lake filled to almost full pool elevation (302m; 990 ft), covering the sites where we had been concentrating our efforts and making them inaccessible. All activities on Douglas Lake were suspended for more than 6 weeks until the lake was again drawn down to normal wintertime levels (~291m; ~955 ft) in late February. Work on Douglas Lake was resumed in early March, permitting reconnaissance of the S side of Douglas Lake between the Wells S site (DL–9) and Douglas Dam. The banks of the French Broad River below Douglas Dam were also explored, but they yielded nothing that looked promising. The only paleoseismic feature found to date in this area is a small-displacement fault previously located in 2011 on one of the islands ~2 km NE of Douglas Dam (see Fig. 19 in Hatcher et al., 2012, GSA Special Paper 493).

Initial reconnaissance along some of the banks of Tellico Reservoir was made by foot during the winter of 2013. Some promising 2- to 3-cm-wide fractures were observed (with some rotation on at least one that strikes 030), but it quickly became clear that, because this reservoir is not lowered in fall and winter like Douglas and other upper tributary reservoirs, reconnaissance by boat is the best way to explore this reservoir. Tellico Lake is located in the area of greatest historic earthquake activity in the ETSZ, so exploration of the banks of this reservoir is very important. Plans were initiated to conduct reconnaissance by boat of the Tellico Lake shoreline during the coming months.

During March, surficial materials in a large area W of the large trench at Wells N site were cleared, exposing several small faults with slickensides exhibiting similar top-to-the-WNW (and WSW with gentle E and SE plunge) kinematic trend as the small fault that truncates the Quaternary sediment-filled fissure farther down the slope. The goal of this activity was to attempt to trace the 1-m displacement fault westward from the exposure in the trench walls. The geology and structures exposed in this area were mapped in detail on a 1-m grid (partially mapped from earlier work E of the trench), together with the area on both sides of the main DL–6 trench (Fig. 7; Warrell, 2013, Plate 1). A great deal of new information was gleaned from this exercise, which permitted us to trace the main fault to the point of truncation of the fissure southward from the trench. The detailed geologic map reveals a very complex array of fractures and faults that have small displacements. These faults may be splays of the 1-m displacement fault exposed in the trench a few m to the east.

New optically stimulated luminescence (OSL) age dates were obtained (Dr. Steven L. Forman, University of Illinois-Chicago) on quartz in Quaternary sediment filling fissures in

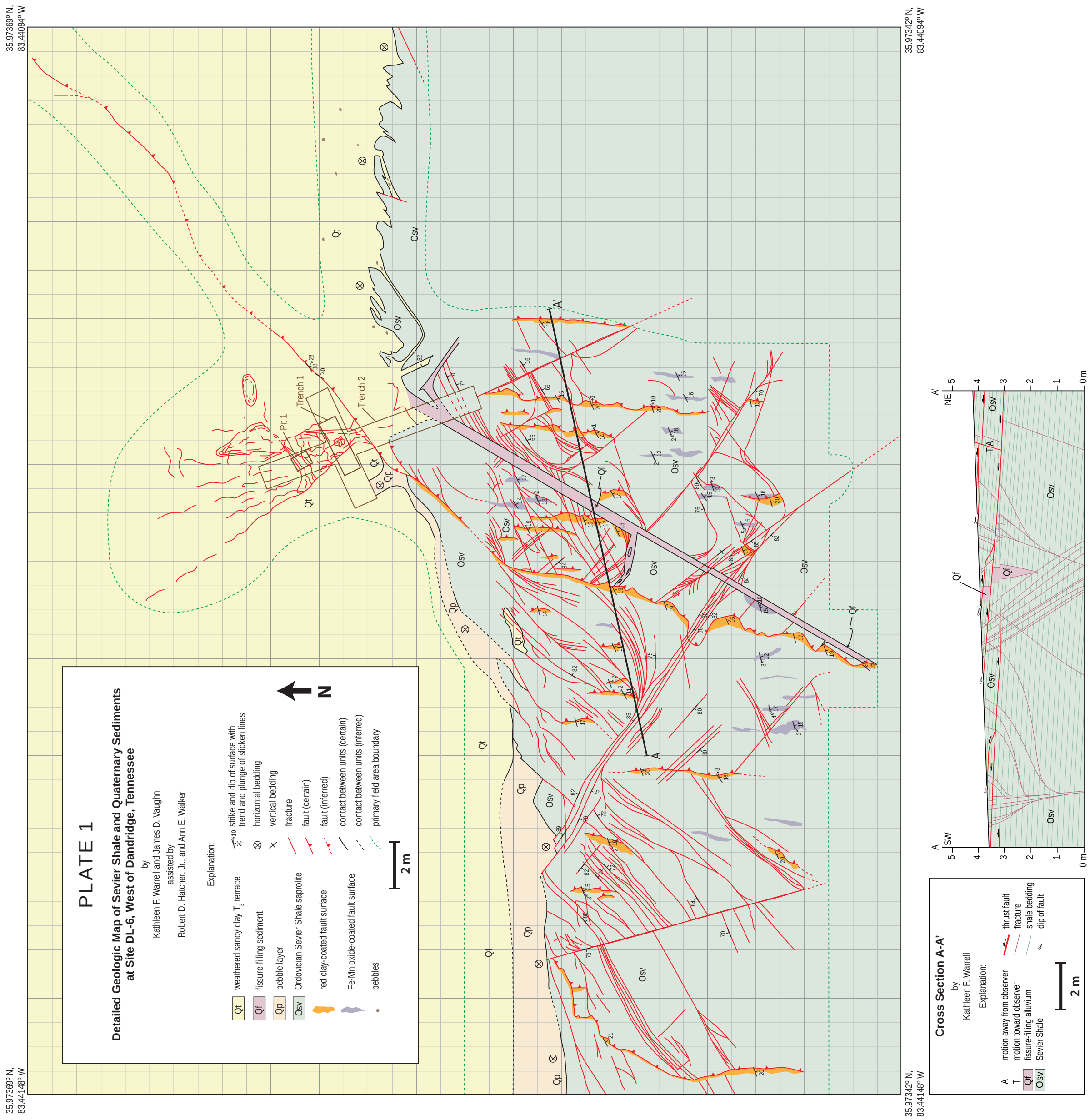

Figure 7. Detailed geologic map of the area surrounding the trench at DL–6 (Wells N) site. (Plate 1 in Warrell, 2013.)

the Wells N and S sites range from 11,880 ka (Wells S, DL–9) to 15,450 and 15,865 ka (Wells N, DL-6), providing a maximum age for faulting observed at the Wells N site. We feel that the $M_w > 6.5$ earthquakes that produced the thrust fault and other structures that truncate the fissure and produced liquefaction at this site occurred post-15 ka. An OSL age date of 21,765 ± 1445 y (also performed by Dr. Forman) was received in June from an additional sample of fissure fill material from the Wells S (DL–9) site on Douglas Lake. While this date is some 6,000 y older than the oldest age date from either the Wells S or Wells N (DL–6) sites, it is still on the same order of magnitude as three other dates (15,865 ± 1735 y also from DL–9; 11,880 ± 1420 y and 15,450 ± 1745 y from DL–6 fissure, with an additional age of 4,890 ± 700 y from the DL–6 fissure). Faulting and liquefaction that we have observed at DL–6 postdates all of these ages.

Several small sand dikes were discovered during a canoe traverse during the summer of 2012 along part of the Chattooga River near Lyerly, GA (Fig. 8). A source bed of white sand is visible in the riverbank, but more recent erosion and deposition has removed any indication of a sandblow, or other liquefaction structures. A sample of the sand in the dikes has subsequently been collected for OSL dating.

A presentation was made to NRC staff in early May. The goal of the presentation was to summarize the research presented in the December, 2012, publication of GSA Special Paper 493, principally the pilot project results, summarize additional results not presented in the paper (including a summary of M.S. thesis research by Kathleen Warrell), and then present and discuss ideas for future research in the ETSZ. We feel that this presentation and feedback received were very useful.

We have observed suspicious features in vintage aerial photos (obtained from the National Archives) of the Tennessee River floodplain that could be the products of liquefaction (Fig. 9). Examination of these features over the past several months has led to discussions about the possibility of conducting seismic reflection surveys over some of these features using shallow marine seismic acquisition equipment. Similar surveys have been made with success in the Mississippi River, and we would like to explore this possibility further to see what the mobilization and acquisition costs might be as a possible direction for one element of future research.

Graduate student Kathleen Warrell completed and successfully defended her M.S. thesis in mid-July, and subsequently moved to Rutgers University to pursue a Ph.D. degree in rock mechanics. She completed the entire M.S. program in <2 yrs, something very unusual among our M.S. students because she started with an incomplete geology background. Her research was largely supported by this grant, and she has written a

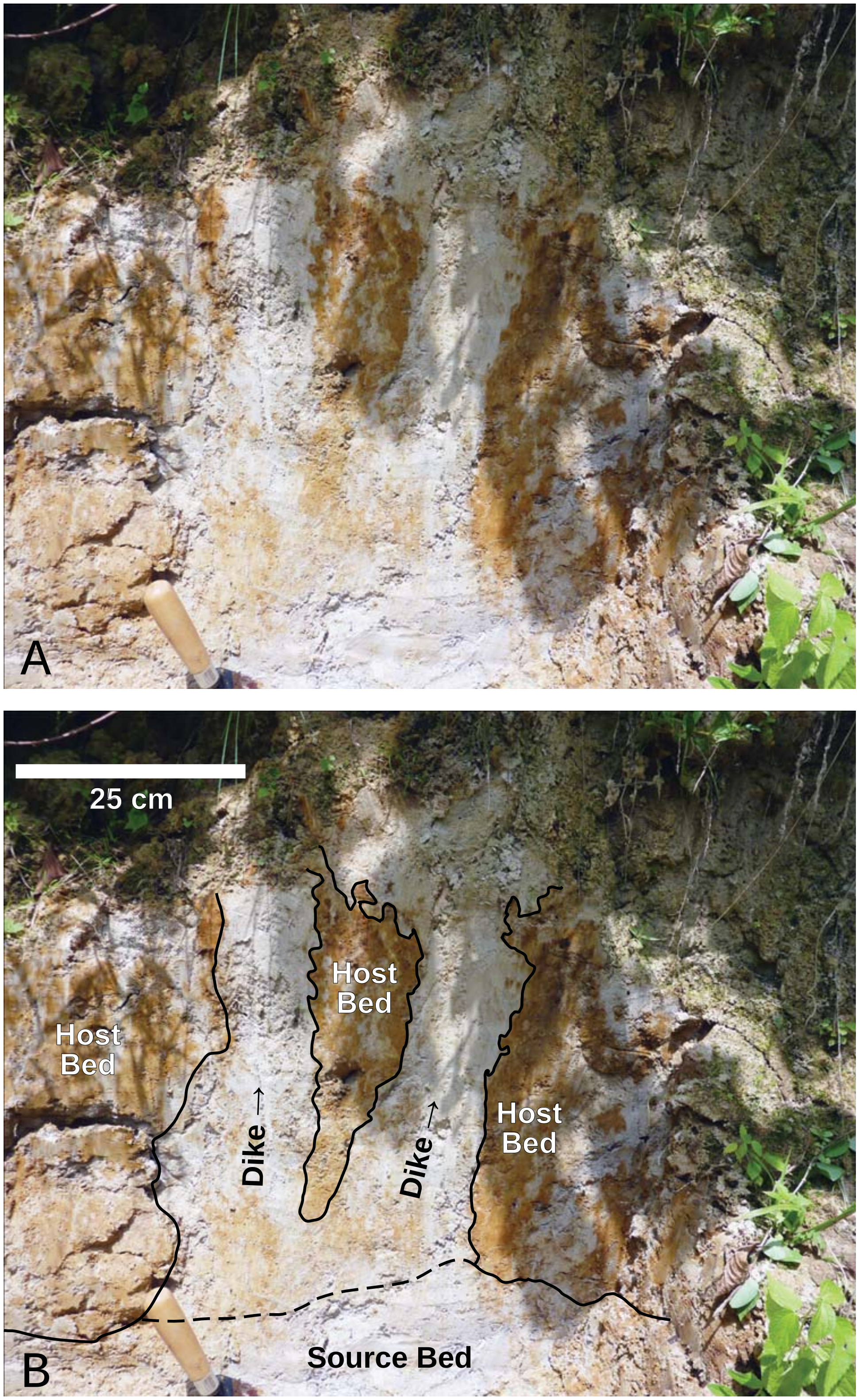

Figure 8. (A) Sand dikes exposed in a cut bank along the Chattooga River, south of Lyerly, GA. The white sand dikes extend from a source bed of similar white sediment, cutting through the mottled red and gray alluvium; (B) interpretation; dashed line indicates approximate boundary between source bed and sand dikes. (Figure 3–6 in Warrell, 2013.)

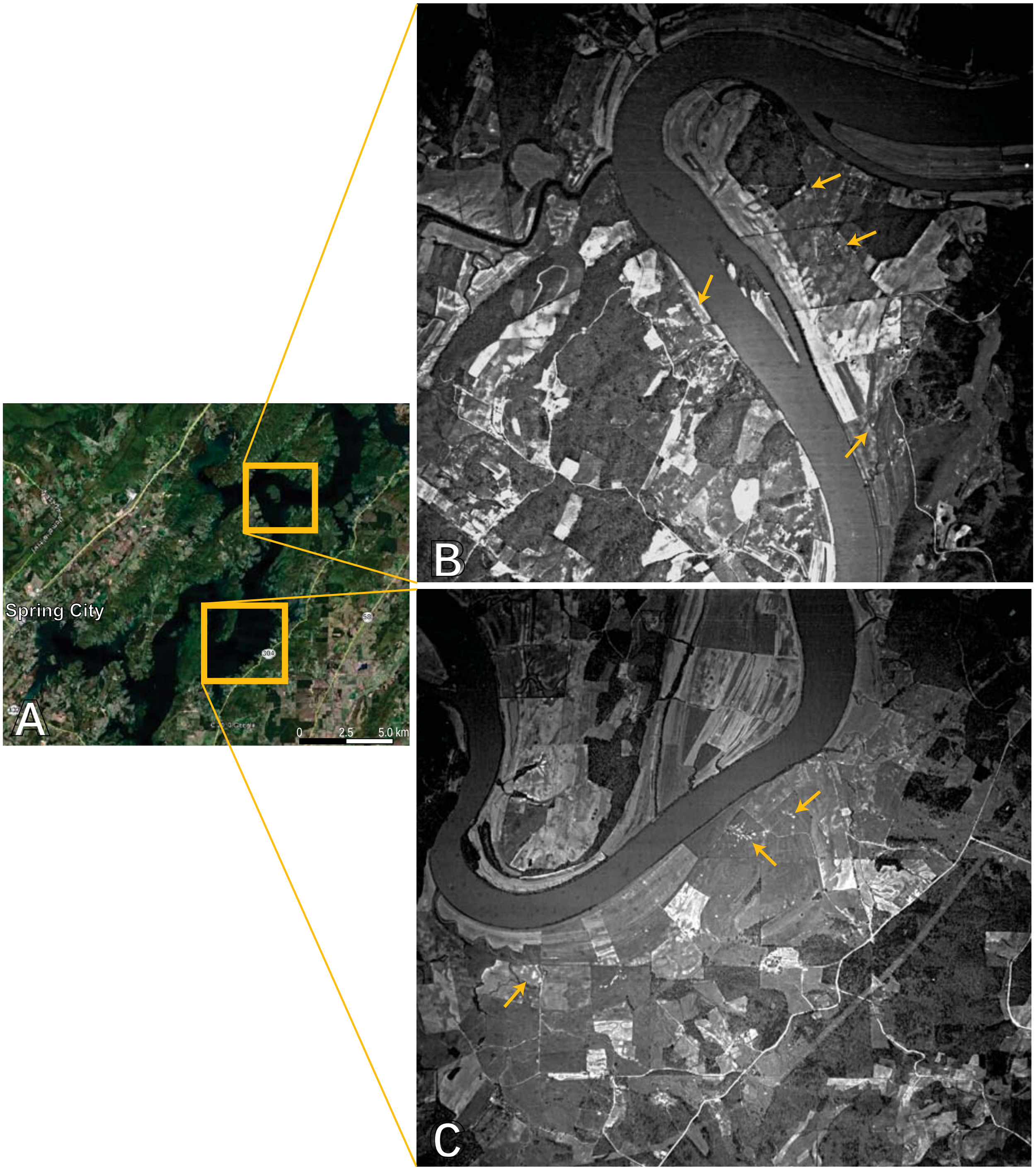

Figure 9. (A) Present-day Watts Bar Reservoir near Spring City, TN, 80 km southwest of Knoxville, TN. Image from Google Earth. (B) Pre-impoundment 1938 TVA aerial photograph of a meander along the Tennessee River with arrows pointing to areas containing tonal anomalies along the floodplain. (C) 1938 TVA aerial photograph of another meander along the Tennessee River south of that in B with arrows pointing to some areas on the floodplain containing tonal anomalies. Note that the areas of tonal anomalies in A are all currently inundated by Watts Bar Reservoir. (Figure 4-6 in Warrell, 2013.)

paper based on the thesis, which is currently in review with the *Bulletin of the Seismological Society of America*.

Additional reconnaissance was made of part of the shore of Tellico Lake that revealed fractures in the T7 terrace a short distance NW of Vonore, TN. The water level in the lake was very high because of excessive rainfall earlier in 2013, so a plan was formulated to return to this site by boat later in the year when the lake level may be naturally lower and TVA lowers the reservoir by ~2 m. This should provide a more complete exposure of the terrace deposit, fractures, and possibly the underlying shale bedrock. This exposure and others nearby have subsequently provided important and useful new insight into the paleoseismic history of the ETSZ (Fig. 10).

A paper was presented at the Eastern Section of the Seismological Society of America meeting in Charlevoix, Québec, later in the fall of 2013. The presentation discussed the relationships between Quaternary sediment-filled fissures on the north and south sides of Douglas Lake for which we have several optically stimulated luminescence age dates. The abstract is appended with the other presentations made during 2012-13 summarizing the results of this project.

CONCLUSIONS

We feel that this research project has to date been very productive, and has increased the knowledge about the paleoseismic history of the ETSZ by several orders of magnitude. When we began our pilot study in 2008, there was virtually nothing known about the record of prehistoric seismicity in the ETSZ. In contrast with the other major seismic zones in the eastern U.S. where significant amounts of research on paleoseismology has been conducted during several decades, all assessments of seismic hazard (Petersen et al., 2008) were based largely on the distribution and frequency of present-day seismicity, and have consistently underestimated the seismic capability of the ETSZ in light of our findings to date.

The area of greatest present-day seismic activity is located from near Maryville, TN, to south of Tellico Plains, TN (Fig. 1). To date, most field activities have been concentrated in the area around Douglas Lake where the lake level is lowered some 15 m in late fall, exposing a large area of Quaternary sediment that rests on shale bedrock. Even though this area is on the northeastern margin of the ETSZ, the amount of exposure and opportunities to locate paleoseismic features is greater than any other. While the most seismically active area in the ETSZ is located beneath Tellico Lake, the level of this reservoir is maintained at near full-pool elevation throughout the year, with maximum fluctuation of the lake levels on the order of 2 m. Despite this, we have been able to

Figure 10. Normal fault exposed along Tellico Lake ~2 km northwest of Vonore, TN. River terrace material is faulted against Upper Cambrian Nolichucky Shale. We interpret the inclined bedding in the gravel to be related to drag on the fault.

discover some significant paleoseismic features and expect to find more during the remainder of the funding period.

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Hatcher, R. D., Jr., Vaughn, J. D., and Obermeier, S. F., 2012, Large earthquake paleoseismology in the East Tennessee seismic zone: Results of an 18-month pilot study, *in* Cox, R. T., Boyd, O. L., and Locat, J., eds., Recent Advances in North American Paleoseismology and Neotectonics East of the Rockies: Boulder, Colorado, Geological Society of America Special Paper 493, p. 111-142.

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S., Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J., and Rukstales, Kenneth S., 2008, Documentation for the 2008 Update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008–1128, 61 p., <http://pubs.usgs.gov/of/2008/1128/>http://pubs.usgs.gov/of/2008/1128/.

Technical Report: Central and Eastern United States Seismic Source Characterization for Nuclear Facilities. EPRI, Palo Alto, CA, U.S. DOE, and U.S. NRC: 2012.

Warrell, Kathleen F., 2013, Detailed geologic studies of paleoseismic features exposed at sites in the East Tennessee seismic zone: Evidence for large, prehistoric earthquakes [M.S. thesis]: Knoxville, University of Tennessee, 129 p.

ABSTRACTS OF PAPERS PRESENTED AT PROFESSIONAL MEETINGS

PRESENTED AT 2012 EASTERN SECTION OF SSA (Blacksburg, VA) AND 2013 GSA ANNUAL MEETING (Charlotte, NC)

New Paleoseismic Data Providing Additional Evidence for Large, Prehistoric Earthquakes in the East Tennessee Seismic Zone

Warrell, Cox, Hatcher, Counts, Vaughn, Obermeier

The East Tennessee seismic zone (ETSZ) is the second most active in the central and eastern U.S., but has no recorded history of M > 4.8 earthquakes. The source of these earthquakes is in the basement at 5-25 km depth, and has to date revealed no surface connection. Paleoseismic features, however, have been observed at multiple sites in the ETSZ. Other sites of possible paleoseismic features, some of which reside beneath reservoirs today, have been identified in 1930s- to 1950s-vintage aerial photographs. We have found evidence of several large earthquakes in the French Broad River Valley ~50

km E of Knoxville. Several thrust and strike-slip faults cut Quaternary alluvium with 25 cm to ~1 m of displacement along Douglas Lake near Dandridge, TN. A 30 cm-wide Quaternary sediment-filled fissure in Ordovician Sevier Shale on the N side of Douglas Lake is aligned with a similar sediment-filled fissure ~2 km away on the S side of the lake. The N-side fissure is truncated by a thrust fault with ~1 m displacement, thrusting Ordovician shale over Quaternary sediments. Shale chips are also present in river terrace sediment, and may have been liquefied and boiled up from underlying weathered Ordovician Sevier Shale during paleoseismic events. X-ray diffraction (XRD) analyses matched the mineralogy of the shale chips and underlying shale. Vintage aerial photos of flood plains along the Tennessee River in E TN and NE AL, and the Chattooga River in NW GA, reveal circular to elliptical features in river terrace sediment that may be related to liquefaction. Reconnaissance along the Chattooga River has discovered possible paleoseismic sand dikes. Grain-size analyses of dikes and likely source bed (same mineralogy), and host bed (more clay-rich) sediments confirm that the sediments are liquefiable, and that the host is finer grained than the dikes or likely source. Together, these data support the capability of the ETSZ to produce M > 6.5 earthquakes.

PRESENTED AT 2013 EASTERN SECTION OF SSA (Charlevoix, Québec)

MORE PALEOSEISMIC EVIDENCE FROM THE EAST TENNESSEE SEISMIC ZONE

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The East Tennessee seismic zone is one of the most seismically active areas of intraplate North America. A lakeshore site near Dandridge, TN, exposes Paleozoic shale broken by

linear, NE-striking fissures containing late Pleistocene alluvium from a terrace above the shale (optically stimulated luminescence ages of 15.9±1.7 ka and 21.8± 1.4 ka). Average fissure width = 30 cm (max 60 cm), tapering to 0 cm <5 m below the terrace. Secondary fissures ~5 cm wide exploit Paleozoic joints. Hillside aspect turns 90° from E/NE to NNE at this site, but the fissures do not deviate from a linear NE trend, suggesting they pre-date river incision below the terrace level. Fissures do not extend above a 25 cm-thick basal cobble layer in the alluvium, but above the fissuring the alluvium contains E/NE-striking systematic joints (parallel to modern S_{Hmax}) and the basal meter of the alluvium appears gently folded into a NE-striking anticline.

A walking survey of the lake shore showed that the fissures are narrowly restricted to a 25 m-wide zone colinear with previously reported NE-striking alluvium-filled fissuring that is displaced by a parallel late Quaternary SE-dipping thrust fault exposed 1.25 km to the NE across the French Broad River valley. Thus, a narrow corridor of fissuring at least 1.25 km long is associated with contractional faulting and probably strong late Quaternary seismicity. We suggest that the fissures developed parallel to the crest of a thrust fault-propagation fold during a paleo-earthquake, allowing cobbles to fall in from the alluvium. A later earthquake accompanied thrust propagation through the fissures on the north shore, but not along strike on the south shore. These earthquakes were coeval with deposition of the terrace alluvium because: 1) fissures and folding only disturb the basal alluvium; 2) the strike of fissures is not influenced by post-terrace topography; and 3) the north-shore thrust does not cut the upper alluvium.

EXPENDITURES SUMMARY—OCTOBER 1, 2012 THROUGH SEPTEMBER 30, 2013

Beginning Balance	$391,763.50
Salaries	$46,015.37
Travel	$11,339.92
Supplies, age dates, site excavation, other	$12,258.30
Overhead	$17,969.32
TOTAL FY 2013 EXPENDITURES	**$87,582.91**
Ending balance	$304,180.59