

Integration of the NEES T-Rex Vibrator and PASSCAL Texan Recorders for Seismic Profiling of Shallow and Deep Crustal Targets

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INTRODUCTION

In September 2004, Stanford University and the University of Texas (UT) at Austin collected crustal reflection and refraction data with the Network for Earthquake Engineering Simulation (NEES) tri-axial (T-Rex) vibrator in two separate surveys: (1) a 40-km “crustal-scale” profile in the Black Rock Desert and Black Rock Range, NV; and (2) a 16-km “high-resolution” basin imaging profile in Surprise Valley, CA (figure 1). Both experiments were completed at the northwestern margin of the Basin and Range Province, embedded in a larger, 300-km wide-angle refraction line recorded by an Incorporated Research Institutions for Seismology (IRIS) PASSCAL transportable array (Lerch *et al.* 2007). Our broad goals were to test the feasibility of the T-Rex in crustal-scale applications with existing IRIS-PASSCAL equipment and to augment our refraction data with structural information. T-Rex (figure 1, inset A), acquired by NEES-UT Austin in 2002, is a 29,000-kg buggy-mounted vibrator with a tri-axial mass, capable of generating *P*, *SV*, and *SH* waves (for details on T-Rex, see Stokoe *et al.* 2004). Given its relatively large mass, and hence its high peak force output of 267 kN for frequencies between 12 and 180 Hz, T-Rex is a potentially viable source for single-vibrator crustal profiling compared to COCORP (Consortium for Continental Reflection Profiling) profiling with five vibrators, each producing ≤ 120 kN (Allmendinger *et al.* 1987). Additionally, T-Rex’s ability to produce shear waves may open the door to a variety of exciting research avenues, from *V_s* velocity modeling of basin sediments for earthquake hazard analysis to the ability to record mid- and lower-crustal shear-wave anisotropy resulting from regional tectonic deformation. The integration of T-Rex into our crustal-scale and high-res profiles revealed its strengths and limitations as well as the logistic and quality-control problems associated with recording continuous vibrator data with PASSCAL’s transportable instrumentation. Our attempts to record lower-crustal reflectivity and mid-to-lower-

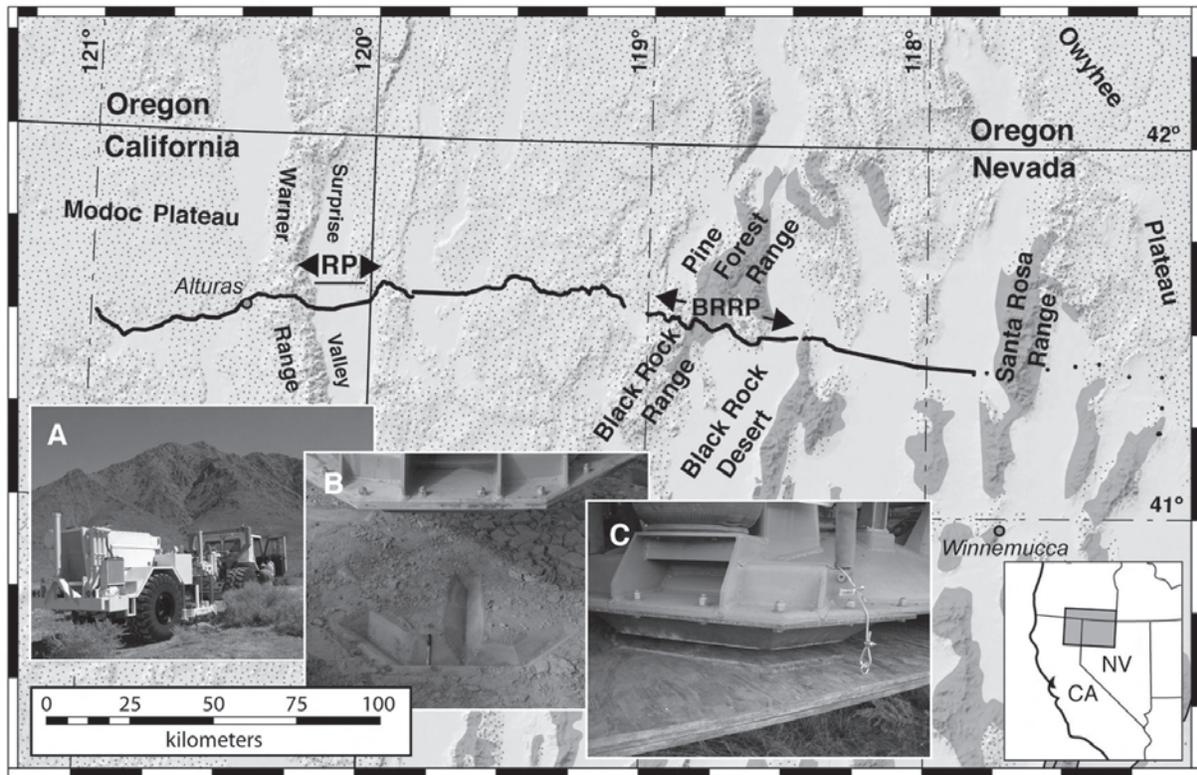
crustal anisotropy and to produce a basin *V_s* model fell short, due to mechanical limitations described in greater detail below. Despite some of our experimental shortcomings, T-Rex consistently produced refracted energy to offsets ≥ 10 km (figure 2) and coherent reflected energy to 1–2 sec two-way time travel (twtt), shown in figure 3. These propagation distances allowed construction of an upper-crustal velocity model of the Black Rock Desert and Black Rock Range (Lerch *et al.* 2007; Lerch, Miller *et al.* forthcoming) and a viable reflection image of the Surprise Valley basin as shown in figure 4, illustrating the value of this new addition to the crustal-seismology community. In the petroleum exploration industry, current practice is to rely almost exclusively on vertical vibrators, including for *P*-to-*SV* converted-mode seismology, which is the dominant mode of *S*-wave exploration (R. Hardage, personal communication 2007). Thus most three-component seismology in industry relies on *P*-to-*SV* mode conversions at nonvertical angles of incidence at subsurface interfaces, rather than propagating directly from true *S*-wave sources as in nine-component data acquisition (*e.g.*, Hardage *et al.* 2003). Although horizontal vibrators are the only practical sources for generating pure *SH*-data, their application is limited by the lower ground force and lower frequencies available from existing technology. The industry has not adopted three-axis vibrators, such as those tested here, due to their generally lower reliability (R. Hardage, personal communication 2007); indeed, our testing of the horizontal signal generation by the T-Rex was limited by mechanical problems, and few case studies are available (*e.g.*, Simmons *et al.* 1999; Macrides and Kelamis 2000). Thus T-Rex in principle offers the academic seismological community the opportunity to address research questions of interest to, but not yet routinely tackled by, the petroleum exploration community.

EXPERIMENT DESIGN AND DATA ACQUISITION

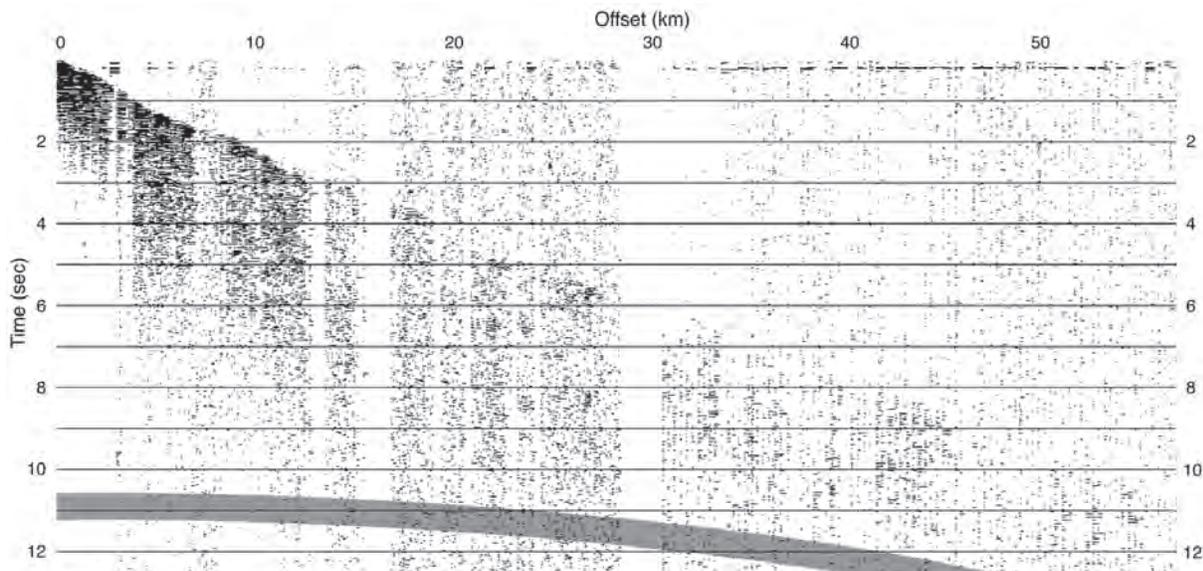
Crustal Design and Acquisition

In our 40-km crustal-scale profile, we had multiple goals whose success likelihoods ranged from probable to tenuous: from obtaining upper-crustal structural information to recording mid-to-lower-crustal *V_s* anisotropy. In order to balance desired upper-crustal resolution with an attempt to record mid-crustal

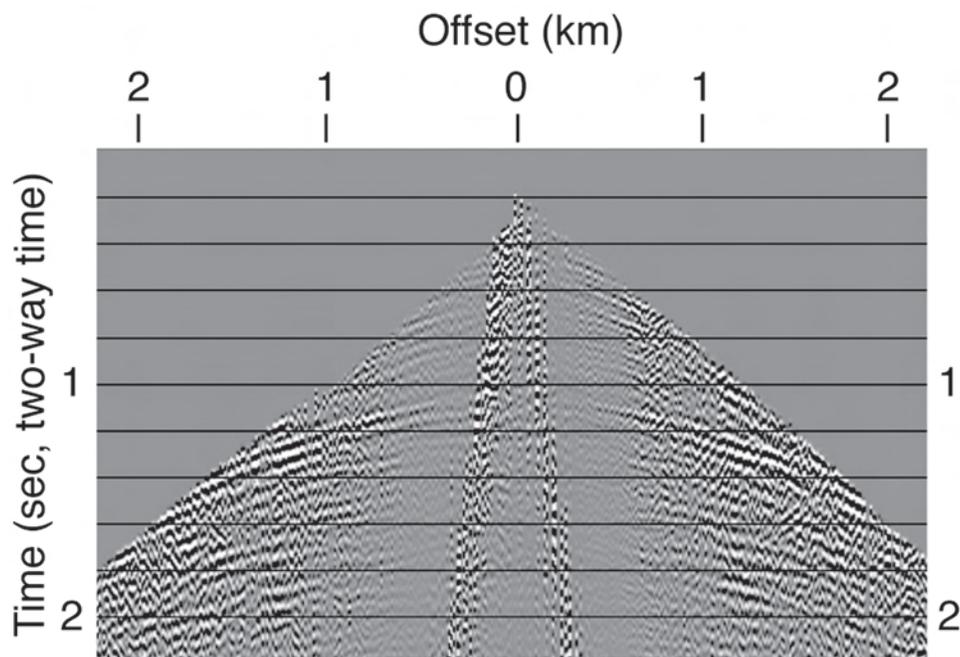
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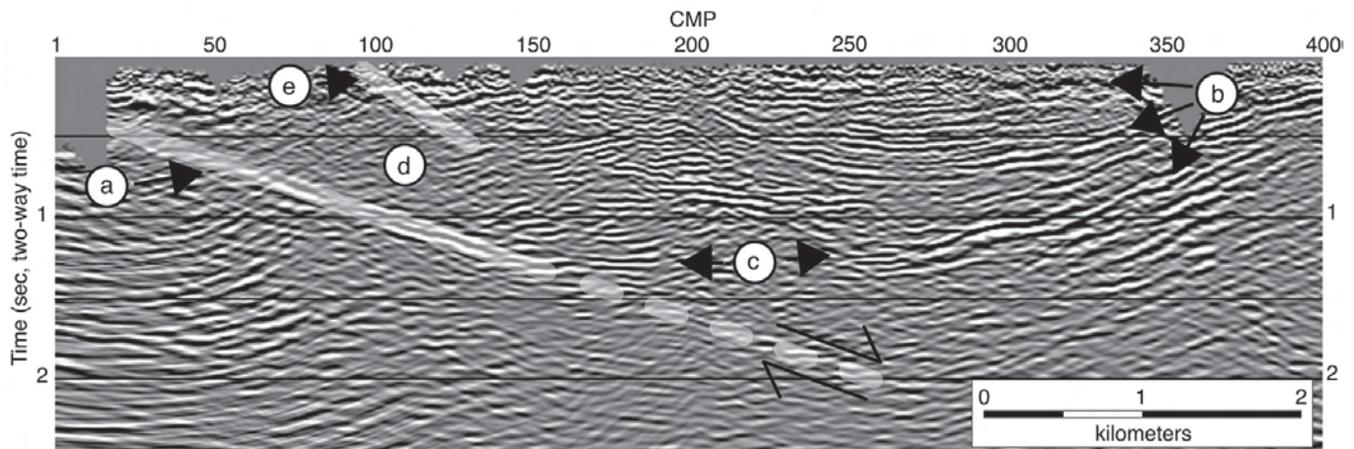
▲ **Figure 1.** Shaded relief map of the northwesternmost Basin and Range and its transition to the high volcanic plateaus of northeastern California and southern Oregon. Light gray: Quaternary deposits. Stippled area: Tertiary volcanic and sedimentary units. Dark gray: Paleozoic and Mesozoic igneous and metamorphic units. Black circles: 2004 Stanford seismic refraction geophone locations (appears as a solid line west of the Santa Rosa Range due to dense instrument spacing). Thin line labeled RP in Surprise Valley corresponds to the basin imaging reflection profile. Arrows surrounding BRRP correspond to the extent of our crustal-scale reflection profile across the Black Rock Desert and Black Rock Range. Inset photos: (A) T-Rex in the Black Rock Range; (B) indentation in road surface from pad cones (pen for scale); (C) plywood pad added to baseplate to protect paved road surfaces. Geology simplified from Jennings *et al.* 1977; Stewart and Carlson 1978; and Walker and MacLeod 1991.



▲ **Figure 2.** Best source gather from crustal profile. Coherent arrivals visible to offsets of ~ 20 km, with discontinuous energy visible to ~50 km. Wide gray line represents Moho travel time calculated from the Lerch *et al.* (2007) wide-angle velocity model. Gather produced by stacking ten coincident sweeps, applying a bandpass filter (4-6-36-42 Hz), and performing a predictive deconvolution.



▲ **Figure 3.** One of the better source gathers from the Surprise Valley hi-res profile. Gather produced by stacking four adjacent sweeps to create a single, 40-m source array. Refracted first-breaks have been muted, and a broad bandpass filter has been applied.



▲ **Figure 4.** Seismic cross-section of Surprise Valley. The Surprise Valley fault (a) appears as a continuous, moderate amplitude east-dipping reflector that bounds the western side of the basin. Prominent west-dipping reflectors (b) on the eastern edge of Surprise Valley correspond to variably dipping (10–15°) late Miocene to Pliocene (8–4 Ma) volcanic strata. The deepest basalt reflection shallows as it approaches the Surprise Valley fault (c). We interpret the reflection-free region (d) immediately above the SVF to be alluvium deposited along the range-front during footwall exhumation. West-dipping reflectors near CMP 100 appear to be truncated by a fault splay (e) of the Surprise Valley fault. Seismic data processed as described in text. Figure displayed with no vertical exaggeration based on basin-fill $V_p < 2$ km/s.

reflectivity and shear-wave data during the crustal-scale profiling, T-Rex swept every 300 m to produce reflection data and at 3-km intervals (every 10th source point) to provide wide-angle refraction data for velocity modeling (see table 1 for details). Because long propagation distances for velocity profiling or deep reflections were of greatest value during this phase of the experiment, we used sweeps spanning relatively low frequencies from 5 to 40 Hz (3 octaves), comparable to previous vibrator-source experiments that successfully recorded refracted phases to offsets ≥ 70 km (e.g., Damotte *et al.* 1987; Wenzel 1988). This source con-

figuration afforded ~ 40 km of source coverage in a modest amount of field time (48 vibrator-hours, or six eight-hour days), while our stacks of 10 vertical one-minute sweeps recorded at 3-km intervals provided greater nominal source effort than individual vibration points from the 1983 COCORP 40°N Nevada deep reflection profile, which recorded strong Moho reflections approximately 150 km south of our profile (e.g., Klemperer *et al.* 1986). The COCORP survey used 32 s/sweep with eight sweeps/SP and three vibrators at 120 kN each plus two vibrators at 94 kN each for a total of 1.4×10^5 kN s. In contrast, our

TABLE 1
Source and Receiver Specifications for Crustal and Basin Imaging Portions of Experiment

Experiment Phase	Source Spacing	Source Effort and Type	Sweep Frequencies	Receiver Spacing
Crustal reflection	300 m	1 min. <i>P</i>	5–40 Hz	100 m
		2 × 1 min. <i>SV</i> 2 × 1 min. <i>SH</i>		
Crustal refraction	3 km	10 × 1 min. <i>P</i>	5–40 Hz	100 m
		20 × 1 min. <i>SV</i> 20 × 1 min. <i>SH</i>		
Basin imaging	10 m	1 min. <i>P</i>	5–80 Hz	40 m
'hi-res' reflection	40 m	1 min. <i>P</i>	5–40 Hz	40 m

NEES T-Rex survey used a 60 s/sweep with 10 sweeps/SP and one vibrator at 267 kN for a total of 1.6×10^5 kN s. Crustal data were continuously recorded in four-hour windows at 125 sps (8 ms sample rate) by a combination of vertical (RefTek RT125 A, “Texans”) and three-component (RefTek RT130) instruments forming a 40-km recording array spaced at 100 m, embedded within the larger wide-angle profile. Although the self-contained Texan instruments are popular because they can be deployed quickly, they were originally designed for shot-source refraction data (with short recording windows), causing their limited disk space of 32 MB to be rapidly taxed by the continuous vibrator recording (12 continuous hours at 250 sps, 24 continuous hours at 125 sps). This memory limitation necessitated an active and complex deployment scheme for our experiment in which individual digitizers recorded until their disk space was filled, requiring a greater number of deployment teams than would normally be required by an experiment of this size to constantly retrieve and redeploy instruments. Recording through individual digitizers obviated any real field-based quality control, forcing us to generate “best-guess” sweeps that were then viewed at the end of the recording windows on a trace-by-trace basis. Because T-Rex was a late addition to our larger wide-angle experiment, we didn’t have the opportunity to do any preliminary testing of sweep length and frequencies, meaning that the entirety of our profiling was a “test.” In addition to recording issues, T-Rex provided another challenge to us as crustal seismologists. This vibrator, acquired for use primarily through the NEES consortium, was designed to be used in soil and structural engineering studies, and as a result lacked three fundamental recording capabilities for seismic profiling: baseplate location (x , y , and z), absolute sweep timing, and reference sweep. Our solutions to these problems were fairly straightforward, but did require forethought and the installation of recording and timing equipment from PASSCAL in the vibrator cab.

Basin Imaging Design and Acquisition

Our hi-res survey imaged the tectonically active Surprise Valley basin to constrain basin depth, fault geometry, and basin-fill *P*- and *S*-wave velocities. Our source effort per line kilometer from single one-minute sweeps spaced every 10 m exceeded

prior successful efforts to image upper-crustal structures (*e.g.*, Belcher *et al.* 1986). Belcher *et al.* (1986) used 25 s/sweep at 222 sweeps/km with one vibrator at 120 kN for a total of 6.7×10^5 (kN s)/km.

In contrast, our NEES survey used 60 s/sweep at 100 sweeps/km with one vibrator at 267 kN for a total of 1.6×10^6 (kN s)/km. In Surprise Valley, T-Rex was able to maintain a rapid sweep schedule during continuous recording windows as our one-minute sweeps were followed by a 15-s listening/move-up window, which was just enough time to raise the pad, move forward 10 m, and have the pad back in position for the next sweep (see table 1 for details). The Surprise Valley profile represented ideal vibrator conditions—a straight, unpaved surface upon which we could vibrate directly—and allowed us to produce approximately 1,600 source gathers (16 km at 10 m spacing) in four days (eight four-hour windows) of field time. Because the T-Rex vibrator has the ability to vibrate in shear mode, its baseplate has 15-cm-tall teeth (cones) that provide lateral coupling with the ground (figure 1, inset B). These teeth, combined with the 30,000-kg mass of T-Rex, leave deep scars in all but the most competent surfaces, thus limiting site selection (if only *P*-wave profiling is planned, the teeth can in principle be removed, although this is not easily accomplished in the field). We were fortunate to work with a local road department that was accommodating and allowed us to vibrate directly on the road surface; we would have had considerably more difficulty conducting the same experiment on state-owned roads. In a test at the end of the experiment, we attached a one-inch plywood pad (two half-inch sheets glued and screwed together) to the baseplate and conducted limited *P*- and *S*-wave sweeps directly on asphalt surfaces without incurring any visible damage to either the plywood pad or asphalt (figure 1, inset C).

Although it was our intention to produce a high-resolution *V_s* model of the Surprise Valley basin, problems with the *S*-wave bearing mechanism on T-Rex near the end of the crustal phase prevented us from conducting *S*-wave sweeps during our basin-imaging phase. All Surprise Valley data were recorded by RefTek Texan seismographs at 250 sps (4 ms sample rate), spaced 40 m apart. As in our crustal survey, we lacked any in-field quality control. Additionally, because of our long record-

ing windows and relatively high sample rate, three times each day we had four two-person teams replace full Texans with fresh Texans at 15 sites in one-hour periods.

DATA QUALITY

Crustal Data

Although our source effort at pad locations spaced every 3 km during the crustal phase (see table 1 for details) was greater than the individual source points from the COCORP 40°N survey where five vibrators provided source points every 100 m, we were unable to detect any sufficiently repeatable lower-crustal or Moho reflections (crustal thickness ~ 32 km, Lerch *et al.* 2007) to create a stacked section. T-Rex may not be an effective source for lower-crustal targets in future experiments without significantly larger source effort.

Despite our failure to produce a reflection image from our crustal data, we were able to model 118 upper-crustal velocities using coherent refracted arrivals from T-Rex (Lerch, Miller *et al.* forthcoming). By stacking 10 one-minute sweeps in the Black Rock profile (BRRP in figure 1), we consistently recorded upper-crustal phases to offsets of 25 km (figure 2), with discontinuous energy reaching distances of up to 60 km. Velocity modeling with these phases yielded turning rays that regularly sampled depths to ~ 5 km, illustrating T-Rex's usefulness in velocity-structure investigations. In our particular experiment, the failed detonation of the closest shotpoint of our wide angle refraction line to our crustal reflection profile caused an undesirable gap in raypath coverage. Here, we were able to use the source gathers from T-Rex to provide local raypath coverage and improve the robustness of our velocity model (Lerch *et al.* 2007). In addition to the 10 minutes of *P*-wave source effort at 3-k intervals, T-Rex also provided 40 minutes of *S*-wave effort (twenty one-minute *SV* and *SH* sweeps) in an effort to penetrate the mid-to-lower crust with *S*-waves. Here, our goal was to observe lower-crustal *V_s* anisotropy resulting from regional deformation, as had previously been accomplished elsewhere in the Basin and Range (*e.g.*, McNamara and Owens 1993). This portion of our experiment further established the limitations of T-Rex: observable energy from stacked *SV* and *SH* sweeps simply did not propagate far or deep enough to provide useful mid-to-lower-crustal information. Based on the visual inspection of *S*-wave sweeps we collected over the Black Rock Desert, coherent refracted energy from single one-minute sweeps was frequently visible to offsets of ~ 5 km (compared to offsets of ~ 10 km from single one-minute *P*-wave sweeps), suggesting that near-surface *V_s* modeling is a realistic goal with the T-Rex vibrator.

Basin Imaging Data

Despite the extreme attenuation associated with basin-fill (*e.g.*, Schlotterbeck and Abers 2001; Li *et al.* 2006), we successfully imaged several prominent reflections in the unconsolidated Surprise Valley basin ($V_p \leq 2$ km/s) that correspond with the locations of subsurface normal faults and volcanic strata predicted by the local geologic cross-section. Our 10-m source

spacing and 40-m receiver spacing yielded source gathers that contained intrabasin and basin-basement interface reflections as deep as 1–2 s (twtt, see figure 3) and provided the basis for a reflection image of the basin (figure 4). Our reflection image was produced by summing four adjacent source gathers to effectively produce 40-m source arrays that when coupled with the 40-m receiver spacing yielded 20-m CMP bins. These 20-m CMP data were then processed using ProMAX seismic software, sequentially consisting of amplitude-balancing (500 ms AGC), frequency filtering (10-14-36-42 Hz band-pass), velocity analysis, predictive deconvolution (160-ms operator length, 10-ms prediction distance, 0.1% prewhitening), CMP stacking, and poststack time migration (figure 4).

DISCUSSION

The 16-km Surprise Valley profile demonstrates the utility of the NEES T-Rex vibrator, in conjunction with seismic instrumentation operated by IRIS-PASSCAL, for shallow-to-upper-crustal reflection imaging, with possible applications ranging from earthquake hazard assessment to upper-crustal tectonic studies. As the instrument pool at the PASSCAL Instrument Center continues to be updated with next-generation Texans, similar vibrator profiles may be collected with considerably less deployment effort due to greater disk space (≥ 128 MB vs. 32 MB) and extended battery life. This pairing between the NEES and PASSCAL facilities provides a cost-effective manner by which to collect upper-crustal land-based reflection data. Beyond traditional reflection profiling, high-quality upper-crustal velocity modeling is also achievable with the T-Rex vibrator. In both profiles, we were able to use coherent refracted arrivals from T-Rex to model the upper-crustal velocity structure (Lerch, Miller *et al.* forthcoming), illustrating T-Rex's usefulness in velocity structure investigations. Our greatest disappointment with T-Rex was its inability to produce recognizable reflections from the middle to lower crust like those that were so well-documented in the COCORP surveys across the northern Basin and Range. Possible explanations for this shortcoming include: 1) the crust we imaged was inherently poorly reflective (unlikely due to the presence of visible mid-crustal and Moho reflections in the shot-source data, Lerch *et al.* 2007); 2) our use of point receivers instead of the receiver arrays used in the COCORP lines did not sufficiently attenuate random noise, which overwhelmed the vertically incident reflections; and 3) our extended sweep period, necessitated by using only one vibrator, cannot be compared directly to greater force output arrays like those used in the COCORP surveys because our weaker signal-per-unit time was not sufficient to overcome intrinsic background noise. If we were to design another experiment with T-Rex, we would undoubtedly do more testing in the field. The use of individual digitizers (*e.g.*, Texans) makes this difficult, but certainly not impossible. It would be possible to devise a scenario in which the first day of T-Rex work would be followed by the retrieval of select instruments to allow an overnight download and data assessment to better select sweep parameters for production. Since our experiment, NEES-UT Austin has acquired real-time, cabled sensors

(16 1-Hz vertical, 12 1-Hz three-component) that can extend as far as 150 m away from the truck, providing a much needed near-offset look at production parameters. It is worth noting that because we sought to test a wide variety of possible options on behalf of the wider seismological community, ~ 50% of our source effort did not contribute to our scientific results. Thus we tested sweeps to 80 Hz in our basin imaging, but only utilized energy to 40 Hz, thereby discarding half of our sweep effort. For our crustal survey, we discarded all of our *S*-wave sweeps (80% of our source effort) and only used the refraction sources every 3 km for velocity modeling, ignoring the 60-s sweeps every 300 m. All vibrator data were preprocessed by PASSCAL and are available at the IRIS Data Management Center. This process proved to be far from trivial. Because of the lack of precedent of recording continuous vibrator data on individual Texan seismographs, a significant amount of time was spent on automating the system to cut the records into correctly timed shot gathers (see Acknowledgments below).

CONCLUSIONS

The NEES T-Rex vibrator appears to be a promising addition to the seismological community, offering a viable source for upper-crustal imaging and velocity modeling. Our profiling, however, indicates that mid-to-lower-crustal targets may be out of reach for T-Rex in single-vibrator work without stacking prohibitive numbers of sweeps. In addition to standard *P*-wave velocity modeling, the *S*-wave capability of the T-Rex vibrator will likely attract the interest of many members of the seismological community, particularly those interested in shallow targets such as constraining the *V_s* structure of basins for earthquake hazard assessment. ☒

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