DEVELOPMENT OF SCENARIO GROUND SHAKING MAPS AND EVALUATIONS OF THE IMPACTS OF GROUND SHAKING ON LOCAL BUILDINGS, AVALANCHES, AND THE LAVA RIVER CAVE

NEWBERRY VOLCANO EGS DEMONSTRATION

Prepared for

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INTRODUCTION

On 24 November 2010, URS Corporation submitted to AltaRock Energy Inc. the report "Evaluations of Induced Seismicity/Seismic Hazards and Risk for the Newberry Volcano Enhanced Geothermal System (EGS) Demonstration" (Wong *et al*., 2010). We refer the reader to that report for background information on the following analyses. As a follow-on to that study and at the request of AltaRock, the following describes: (1) the development of preliminary ground shaking maps for a postulated upper-range EGS-induced seismic event of moment magnitude (**M**) 3.5 at the injection well (NWG 55-29); and (2) evaluations of the ground shaking effects on buildings located in the vicinity of the injection well and the Lava River Cave, and the potential for triggering avalanches.

DEVELOPMENT OF GROUND SHAKING MAPS

In order to provide stakeholders and the general public with estimates of what level of ground shaking might occur as a result of a potential induced seismic event from EGS, deterministic scenario maps were developed. For the Newberry Volcano EGS Demonstration, the selected area was approximately 65 km by 70 km centered roughly around the injection well NWG 55-29 (Figures 1 and 2). The area was chosen to include the nearby communities of La Pine, Sunriver and Bend.

The **M** 3.5 scenario event was selected to represent an upper-range seismic event for the Newberry EGS Demonstration. The maximum EGS event estimated for the Newberry Volcano EGS Demonstration is **M** 3.5 to 4.0 based on other similar EGS project worldwide (Wong *et al*., 2010). We regard the ground shaking that might be experienced in this postulated scenario event to have a small probability of occurrence (see following discussion). The EGS seismic event was assumed to occur at a depth of 1 km at the well NWG 55-29 although depth does not significantly impact the ground motions. The seismic event was modeled as a point source (rather than with finite dimensions) because of its small size.

To estimate the scenario event ground shaking, we require ground motion prediction models and a characterization of the near-surface geology at each site (Wong *et al*., 2010). The ground motions are calculated at equally-spaced sites over the mapped area. Each site will have a defined site condition based on the local geology. The calculated ground motion at the sites can then be contoured and a scenario ground shaking map produced.

The near-surface site geology will dictate whether the ground shaking will be modified by site effects. The site geology of the mapped area was based on the distribution and thickness of Quaternary units as defined by Lite and Gannett (2002) and Walker and MacLeod (1991) (Figure 3). V_S30, the average shear-wave velocity in the top 30 m (100 ft), was estimated for each Quaternary unit(Table 1), based on measured shear-wave velocities in similar geologic units (Wills and Clahan, 2006; McDonald and Ashland, 2008). The alluvium and glacial outwash deposits were divided into "thick" and "thin" units, based on the thickness of sediment from well data (Lite and Gannett, 2002). Generally, the thick unit is defined as a sediment thickness greater than 30 m (100 ft), and the thin unit has a sediment thickness less than 30 m. Most of the map area is covered by Quaternary volcanic and Tertiary deposits, which can be considered to be rock with its high V_S30 (Figure 3; Table 1). A V_S30 was assigned to each site based on its location within a specified Quaternary unit.

Table 1. Quaternary Units and Associated V_S30

Geologic Unit	**V_S30 (m/sec)**
Alluvium (Qal)	340
Glacial deposits (Qg)	450
Landslide deposits (QTls)	400
Quaternary volcanic and Tertiary deposits	1,350
Alluvium and glacial outwash deposits (Qs) (thick)	370
Alluvium and glacial outwash deposits (Qs) (thin)	400

To estimate ground motions, we have chosen the recently published ground motion prediction model of Chiou *et al.* (2010), which was developed for small-to-moderate shallow crustal earthquakes in California (**M** 3.0 to 5.5) (Wong *et al*., 2010). In addition we have utilized two unpublished ground motion prediction models developed by URS for The Geysers region of northern California and small geothermal-induced seismic events (**M** ≤ 4.5).

Until results from the planned AltaRock strong motion instruments become available, we do not know how ground motions from future EGS events at Newberry Volcano will compare with events from The Geysers or typical small northern California earthquakes or how the ground motions will decay with distance. Hence, the use of these California models is warranted (Wong *et al*., 2010).

For the Chiou *et al*. (2010) ground motion prediction model, the V_S30 is used as an input parameter. The Geysers ground motion models are only appropriate for soil. However, given the unavailability of any other ground motion model for EGS induced seismic events, The Geysers models were also used for the Quaternary volcanic and Tertiary deposits (rock). Hence, the ground motions for rock on the ground shaking maps are conservative. The Chiou *et al*. (2010) and The Geysers models were equally weighted in the ground motion calculations.

To ensure a smooth grid, the site spacing for the ground shaking maps was 500 m; thus the grid included 18,576 sites. Having defined the scenario EGS event, the site conditions, and appropriate ground motion prediction models, we calculated the median (50th percentile) peak horizontal ground accelerations (PGA) for each of the 18,576 sites. The ground motions are then contoured and mapped to produce the median PGA scenario map shown on Figure 1.

A second map was produced to show ground shaking as characterized by the Modified Mercalli (MM) intensity scale. The MM intensity scale is used to quantify the effects of an earthquake on the impacted population, and the built and natural environment (Table 2). The PGA ground motions were converted to MM intensities based on the relationship of Wald *et al*. (1999) (see below). As discussed in Wong *et al*. (2010), that relationship may not be appropriate for EGS seismic events but it is the only relationship available to date.

PGA (g)	Perceived Shaking	MM Intensity
< 0.002	Not felt	I
0.002 – 0.014	Weak	II – III
0.014 – 0.039	Light	IV
0.039 – 0.092	Moderate	V
0.092 – 0.18	Strong	VI

Table 2
Abridged Modified Mercalli Intensity Scale

I	Not felt except by a few under especially favorable circumstances (RF* I)
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (RF I to II)
III	Felt quite noticeably indoors, especially on upper floor of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of truck. Duration estimated. (RF III)
IV	Felt indoors by many, outdoors by few during the day. Some awakened at night. Dishes, windows, door disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably. (RF IV to V).
V	Felt by nearly everyone, many awakened. Some dishes, windows, and other fragile objects broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (RF V to VI)
VI	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight. (RF VI to VII)
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars. (RF VIII)
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel wall thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water levels. Persons driving cars disturbed. (RF VIII + to IX)
IX	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings; with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (RF IX +)
X	Some well built structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed, slopped over banks. (RF X)
XI	Few, if any, [masonry] structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown into the air.

* Equivalent Rossi-Forel (RF) intensities.
Source: Bolt, 1978

Given the uncertainties in the ground motion prediction models and their appropriateness to the Newberry Volcano area, the PGA values portrayed on Figure 1 may be uncertain by a factor of at least two. The highest estimated median PGA is 0.25 g at the injection well (Figure 1). Although the PGA is relatively high, the ground shaking is expected to be predominantly high-frequency in content, of short duration, and hence unlikely to be damaging. Based on the probabilistic seismic hazard analysis performed earlier (Wong *et al*., 2010), the annual probability of NWG 55-29 site being subjected to a PGA of 0.25 g is about 1 in 900. This level of ground shaking is localized just around the well. PGA values in excess of 0.20 g have been recorded in The Geysers in the community of Anderson Springs with no reported structural damage. Ground shaking characterized by a PGA of 0.06 g and greater (moderate and stronger shaking) is confined to an area out to 5 km from the injection well (Figure 2). PGA of 0.01 g and greater (light and stronger shaking) is felt out to distances of 12 km. Weak shaking may be felt by some residents west of Highway 97 between La Pine and Sunriver in a **M** 3.5 seismic event (Figure 2).

If the postulated scenario EGS event was smaller in magnitude, the PGA values would obviously be smaller. For example, in a **M** 3.0 scenario seismic event, the median PGA at the injection well would only be 0.15 g.

EVALUATION OF THE IMPACT ON LOCAL BUILDINGS

It has been shown in numerous large earthquakes that wood-frame buildings perform quite well (e.g., Rainer and Karacabeyli, 2000) in strong ground shaking. There are several factors that explain these observations including (Canadian Wood Council, 2003): (1) ductility, (2) strength and stiffness, (3) weight, and (4) redundancy. Wood-frame structures with nailed joints are inherently more ductile than those with rigid connections. This makes them more flexible and allows them to dissipate energy when subjected to seismic loading. Floors and roofs made of plywood are very effective in providing strength and stiffness to wood-frame structures. Wood is lighter than most materials and since the forces in an earthquake are proportional to the weight of a structure, light-weight wood-frame buildings will fare better than buildings constructed with other materials. Finally, wood-frame construction can provide numerous load paths through the walls and diaphragms (roofs and floors). This means that overloading can be transferred to alternate load paths.

Rainer and Karacabeyli (2000) observe that the life-safety objective of building codes and various degrees of damage control have been met for single-story wood-frame construction for PGAs of 0.6 g and sometimes higher.

There are only few buildings located near the injection well (≤ 5 km) where moderate ground shaking of MM V and greater could possibly occur and where there may be occupants in these buildings for an extended period of time (more than an hour)(Figures 2 and 4). Those buildings are the Paulina Lake Lodge and associated cabins, and the Paulina Lake Guard Station.

The Paulina Lake Lodge is a single-level rustic wood-frame building built in 1929 (Figure 5). A total of 14 wood cabins are located adjacent to the lodge. The date of construction of the cabins is probably similar to the Lodge. All buildings would have then been built prior to adoption of seismic design provisions in the State building code and may not have been built to code at all. The Paulina Lake Guard Station is a single-level building of light wood construction. It was built in 1934. All buildings appear to have wooden roofs with no heavy roofing materials. The Paulina Lake buildings are located in the zone where PGAs are expected to be in the range of 0.06 to 0.10 g if the **M** 3.5 scenario event were to occur (Figure 2). Thus, it is expected that if these buildings were to be shaken in a **M** 3.5 induced seismic event with its short duration, structural damage is not expected to occur assuming that these buildings are in reasonably good structural condition. This conclusion is consistent with observations of structural response at The Geysers. It is possible that some minor nonstructural damage might be incurred.

EVALUATION OF IMPACT ON LAVA RIVER CAVE

Located well outside the area of light ground shaking and PGA values less than 0.01 g (Figure 1), visitors to the Lava River Cave will probably not detect any ground shaking in the occurrence of a **M** 3.5 seismic event. It is very unlikely that the cave itself will suffer even minor damage such as small roof falls even if weak ground shaking were to occur. Observations by Bart Wills (personal communication, U.S. Forest Service, 26 January 2011) indicate that even when the cave underwent shaking from construction activities including compaction equipment during the expansion of Highway 97 which crossed over the cave, no damage was observed either during his inspection or that of the U.S. Forest Service Park attendant who inspects the cave on a daily basis.

EVALUATION OF THE POTENTIAL TO TRIGGER AVALANCHES

Ground shaking from earthquakes can trigger all forms of slope failure including landslides, rockfalls, debris slides, and avalanches. In most large earthquakes worldwide that occur in areas of moderate to steep topography, landslides have been observed to be a common hazard. Avalanche-prone areas have been defined by Glazovskaya *et al*. (1992) as areas where the snow cover exceeds 30 to 50 cm in depth, and slope steepness is greater than or equal to 17 degrees with a relative slope height of 20 to 30 m. Slopes flatter than 25 degrees and steeper than 60 degrees tend to have lower incidences of avalanches. Likewise, slopes with windward and sunny exposure have a lower rate of avalanches.

Podolskiy *et al*. (2010) evaluated 22 cases of seismically-induced avalanches worldwide from 1899 to 2010 resulting from both earthquakes and “artificial” seismicity in the range of **M** 1.9 to 9.2 at source-to-site distances of 0.2 to 640 km. The “artificial” events were explosions set off at quarries and underground mines. Based on their analyses, Podolskiy *et al*. (2010) suggest that a lower-bound for earthquake-induced snow avalanches is a **M** 1.9 event at zero distance, with a PGA of about 0.03 g.

Based on the study above and the nature of avalanche triggers, snow avalanches can occur at low levels of ground shaking. In the area of the injection well, the topography appears to be mildly sloped and so the avalanche potential is low (Figure 7). Steep areas on the flanks of Newberry Volcano may be avalanche-prone (Figure 7) and thus ground shaking from an EGS seismic event could possibly trigger avalanches if the right conditions existed (e.g., slope angle, depth of snow cover, etc.). Although no ‘downhill’ skiing facility exists around the volcano, the area is used for snowmobiling and cross-country skiing. Based on the ground shaking map (Figure 7), the steep slopes on all sides of Newberry Volcano need to be considered as potential areas where a postulated upper-range seismic event could trigger avalanches. Those areas should be identified by visual inspection by the U.S. Forest Service if they have not already been recognized. The nearest downhill ski resort to the injection well is Mt. Bachelor, well beyond the area of impact of EGS seismicity (Figure 1).

Given the observation that snow avalanches could be triggered in low levels of ground shaking, it is recommended that that mitigation measures be taken to safeguard the public in the areas on the flanks of Newberry Volcano prone to avalanches if the EGS seismicity reaches magnitudes of **M** 2.0 and larger, or if PGA values exceed 0.01 g at the injection well.

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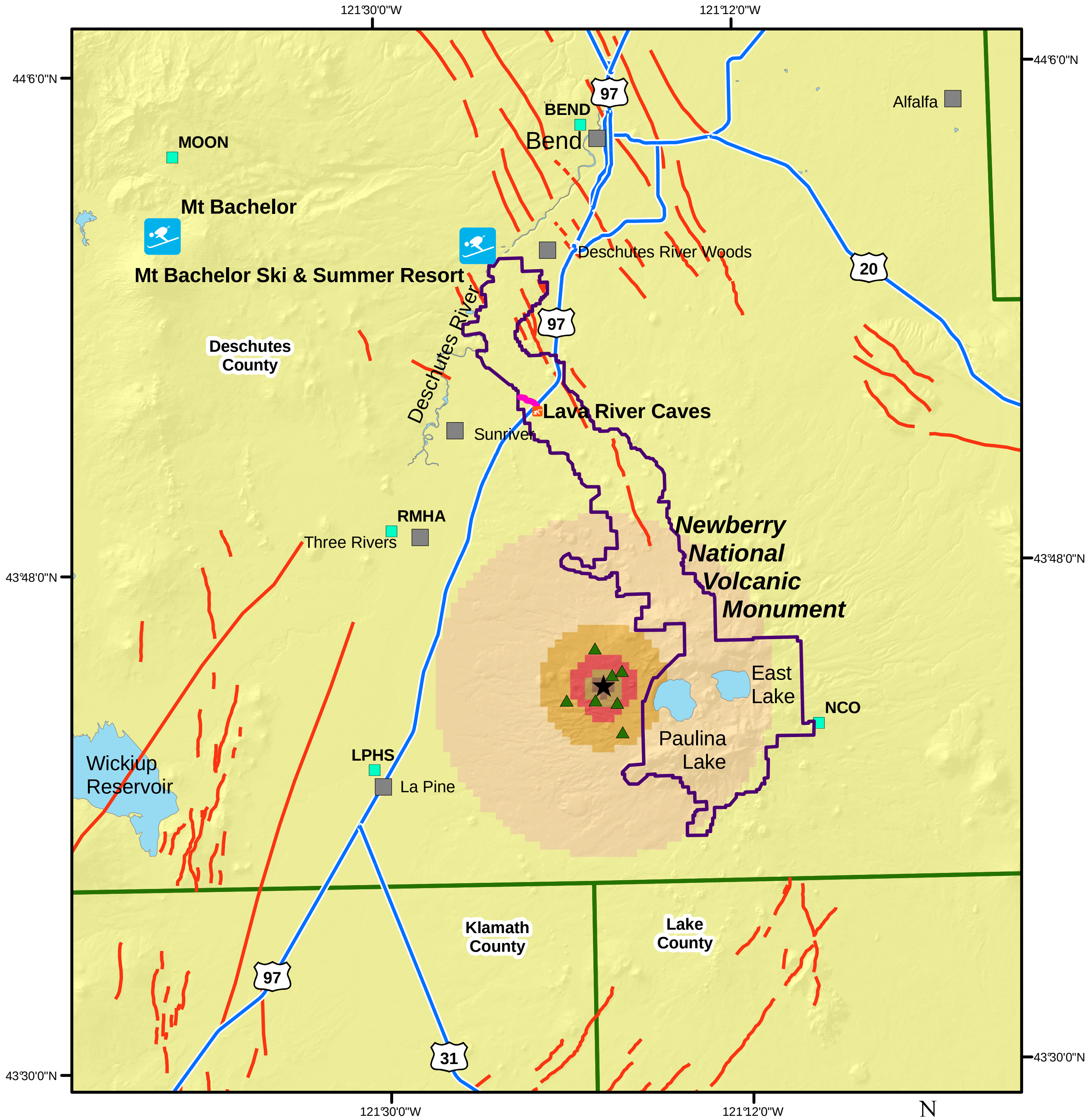


Peak Horizontal Ground Acceleration

PGA (g's)

- < 0.01
- 0.01 - 0.05
- 0.06 - 0.10
- 0.11 - 0.15
- 0.16 - 0.20
- 0.21 - 0.25

- Injection Well (NWG 55-29)
- Quaternary Faults (Source: USGS Quaternary Fault Database)
- Towns
- Highways
- Regional Seismic Stations
- Local Seismic Stations
- Ski Areas
- Lava River Cave Trail

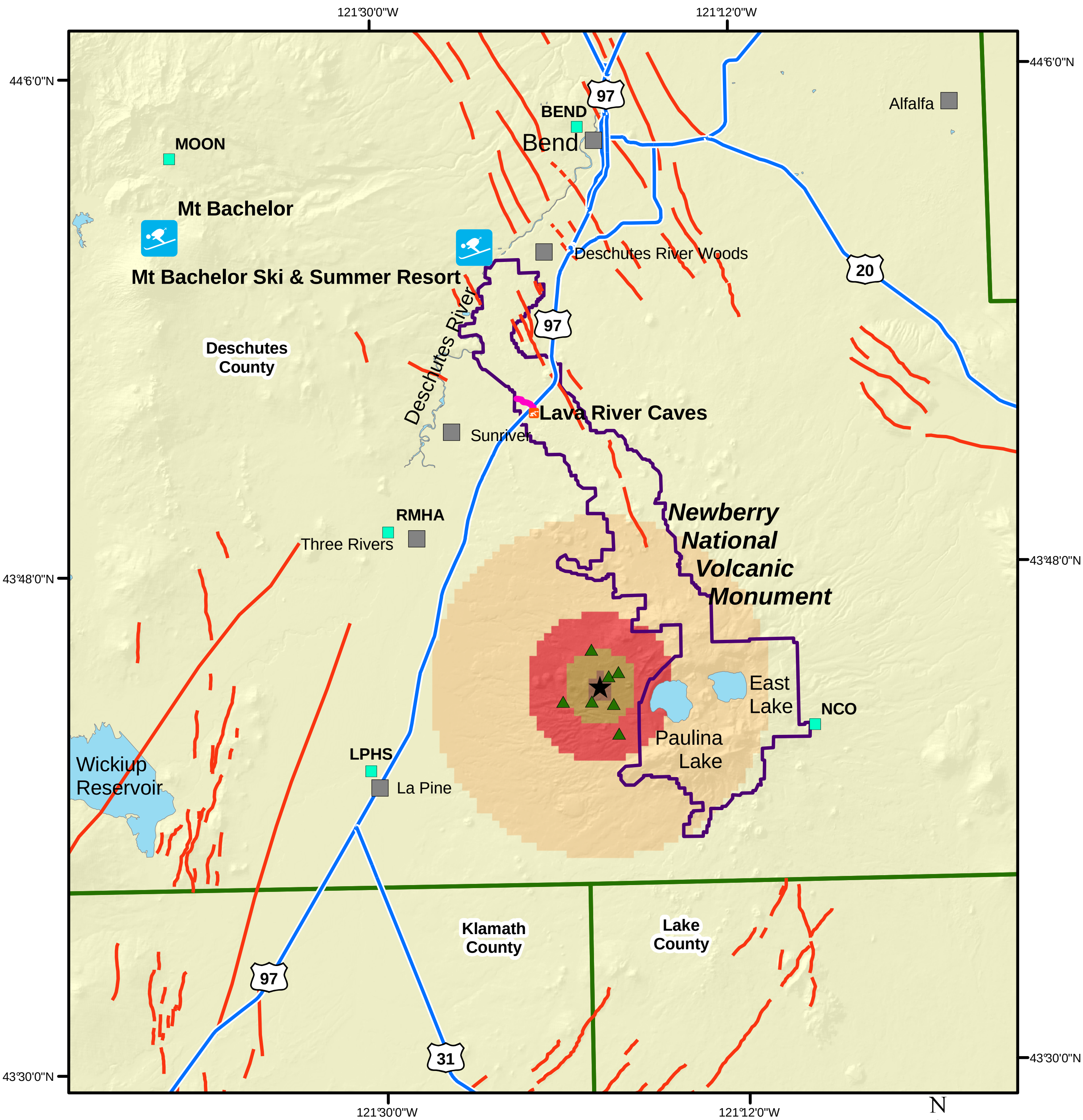
N

Kilometers
0 2.5 5 10 15

Miles
0 2.5 5 10

Date: 31 January 2011

URS	Project No. 26817879 Newberry Volcano Oregon	PREDICTED PGA GROUND SHAKING MAP FOR A POSTULATED M 3.5 INDUCED SEISMIC EVENT	Figure 1



Intensity (MMI)

- I - III (Not Felt to Weak)
- IV (Light)
- V (Moderate)
- VI (Strong)
- VII (Very Strong)

(shaking levels in parenthesis)

- Injection Well (NWG 55-29)
- Quaternary Faults (Source: USGS Quaternary Fault Database)
- Towns
- Highways
- Regional Seismic Stations
- Local Seismic Stations
- Ski Areas
- Lava River Cave Trail

Date: 31 January 2011

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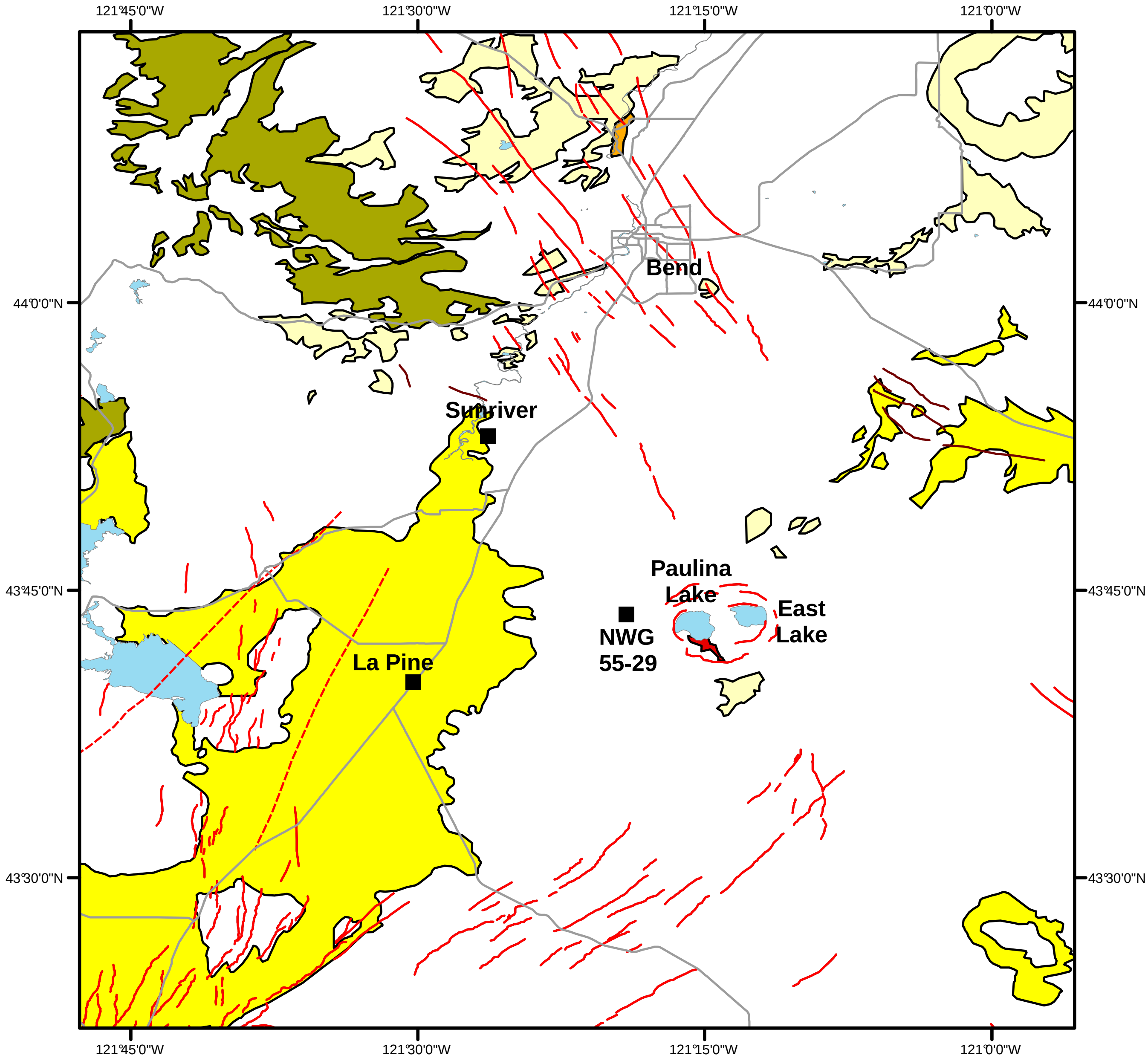
Project No. 26817879

Newberry Volcano
Oregon

PREDICTED GROUND SHAKING MAP IN INTENSITY FOR A POSTULATED M 3.5 INDUCED SEISMIC EVENT

Figure 2



Geology

- Alluvium (Qal)
- Glacial deposits (Qg)
- Landslide deposits (QTls)
- Quaternary Volcanic and Tertiary deposits
- Alluvium and glacial outwash deposits/thick (Qs)
- Alluvium and glacial outwash deposits/thin (Qs)

0 2.5 5 10 15 20 Miles

0 2.5 5 10 15 20 Kilometers

N

Date: 31 January 2011

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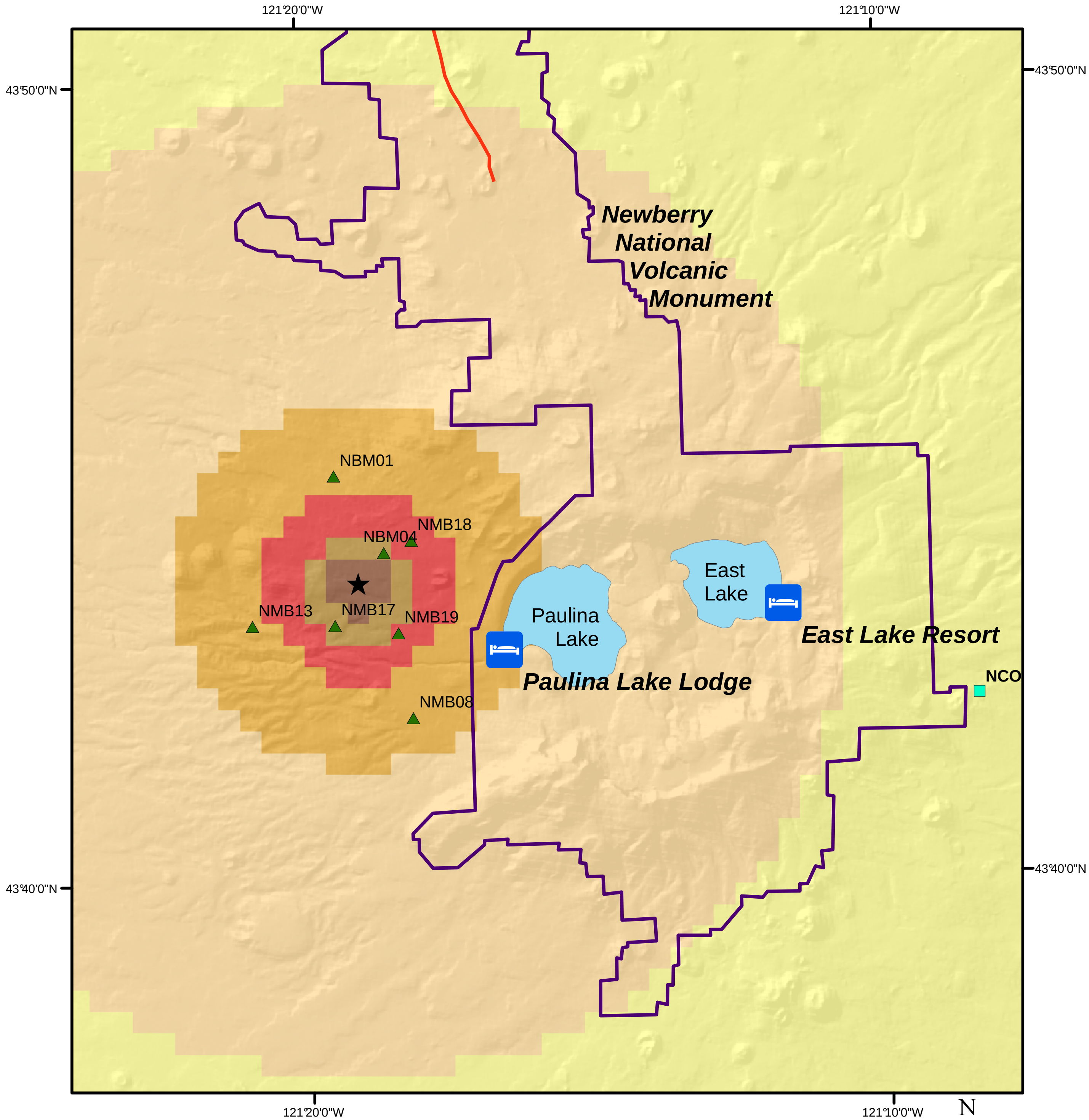
Project No. 26817879

Newberry Volcano
Oregon

SURFICIAL GEOLOGIC MAP

Figure 3



Peak Horizontal Ground Acceleration

PGA (g's)

- < 0.01
- 0.01 - 0.05
- 0.06 - 0.10
- 0.11 - 0.15
- 0.16 - 0.20
- 0.21 - 0.25

- ★ Injection Well (NWG 55-29)
- Quaternary Faults (Source: USGS Quaternary Fault Database)
- Regional Seismic Stations
- Local Seismic Stations

N

Kilometers: 0 — 2.5 — 5

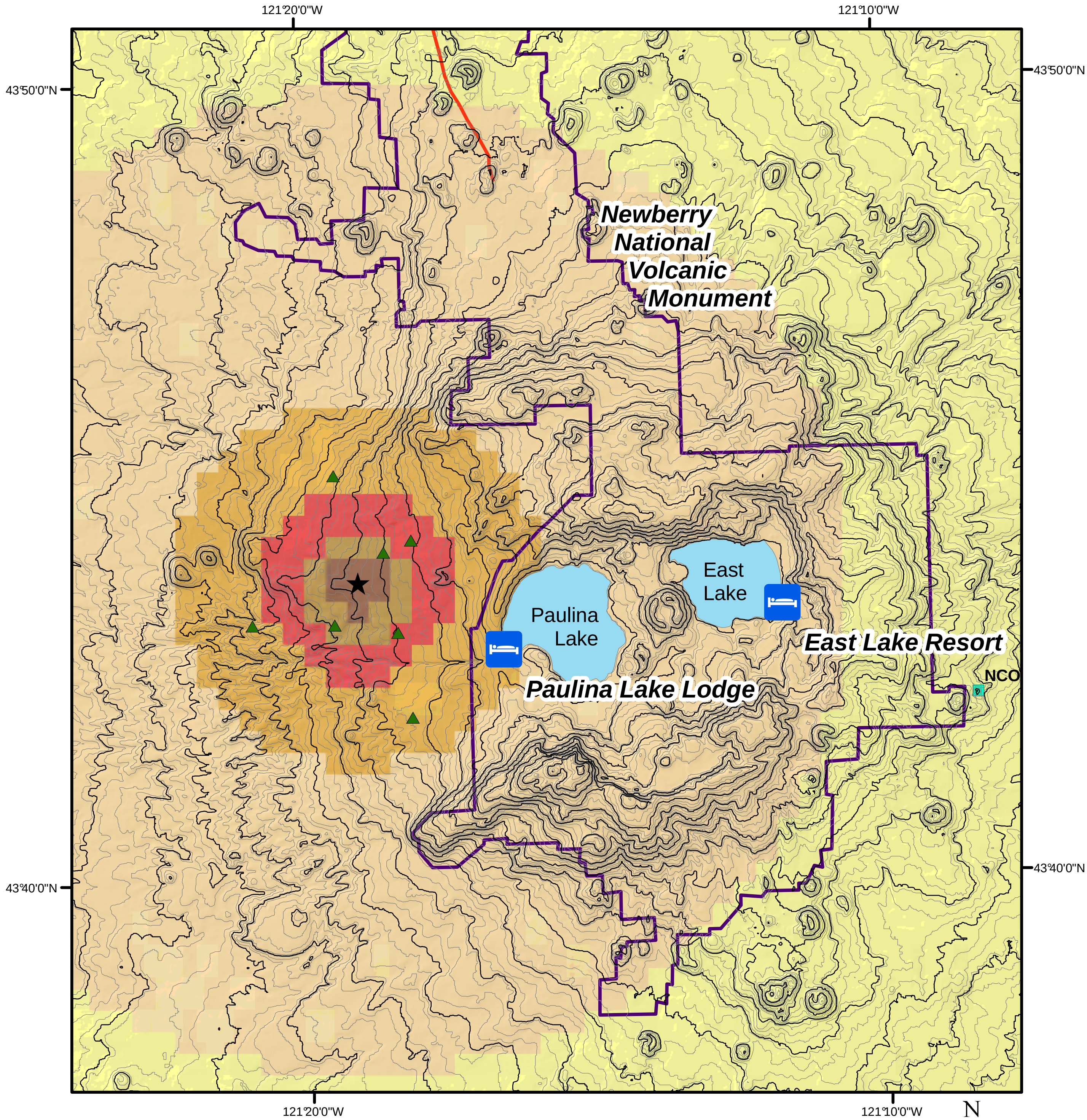
Miles: 0 — 2.5 — 5

Date: 31 January 2011

URS	Project No. 26817879	PREDICTED PGA GROUND SHAKING MAP FOR THE SITE VICINITY FOR A POSTULATED M 3.5 INDUCED SEISMIC EVENT	Figure
	Newberry Volcano Oregon		4

URS	Project No. 26817879 Newberry Volcano Oregon	PAULINA LAKE LODGE	Figure 5

URS	Project No. 26817879 Newberry Volcano, Oregon	PAULINA LAKE GUARD STATION	Figure 6



Peak Horizontal Ground Acceleration

PGA (g's)

- < 0.01
- 0.01 - 0.05
- 0.06 - 0.10
- 0.11 - 0.15
- 0.16 - 0.20
- 0.21 - 0.25

- ★ Injection Well (NWG 55-29)
- Quaternary Faults (Source: USGS Quaternary Fault Database)
- Regional Seismic Stations
- Local Seismic Stations
- Contours (15 meters)
- Contours (50 meters)

N

Kilometers: 0, 2.5, 5

Miles: 0, 2.5, 5

Date: 31 January 2011

URS	Project No. 26817879 Newberry Volcano Oregon	PREDICTED PGA GROUND SHAKING MAP FOR M 3.5 INDUCED SEISMIC EVENT - NEWBERRY VOLCANO EGS DEMONSTRATION PROJECT	Figure 7