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ABSTRACT

As part of a U.S. Navy Geothermal Program Office research project at the Hawthorne Army Weapons Depot (HAWD), we investigated the occurrence, distribution, and age of late Quaternary faults in order to better understand the structural relations that may control geothermal potential in the southern Walker basin near Hawthorne, Nevada. We utilized specialized 1:12,000- and 1:18,000-scale low-sun-angle aerial photography together with existing 2.4-m-resolution LiDAR to detect and map late Quaternary fault scarps.

Although the location and Holocene age of the Wassuk range-front fault system was previously known, we have now also identified a new zone of Holocene faulting that splays north-eastward from the Wassuk range front, extending through the HAWD and the town of Hawthorne. Near Cottonwood Canyon at the southwestern edge of the HAWD, late Holocene fault scarps comprise the range-front fault system which here has probable dextral slip occurring on northwest-striking faults. These faults extend northwest to Lucky Boy Pass where slip is apparently transferred to a series of north-northeast-striking, normal-slip faults that comprise the principal range-front faults of the Wassuk Range. The largest normal scarps along the Wassuk Range occur at the structural range-front bend at Cat Canyon where Holocene scarps as large as 10 m occur. These scarps continue to the north where exploratory trenching of the range-front fault at Rose Creek indicates that at least two Holocene faulting events have occurred.

The newly recognized Holocene faults splay from the Wassuk range front at a point mid-way between Lucky Boy Pass and Cat Canyon as a series of northeast-trending scarps cutting post-Lahontan lake and alluvial-fan deposits. Multiple sets of down-to-the-east and -west scarps form a nested graben as much as 20 km in width. Field investigations show that these scarps are of mid-Holocene age. A comparison of the mapped faults with detailed gravity data indicates that the graben overlies a structural trough in the basement. The structure may continue to the north-northeast and connect with the west-dipping Holocene range-front fault of the Gillis Range. These newly recognized fault traces demonstrate which fault orientations are active in the present stress field, and strain modeling can show which of the faults have dilational or shear tendencies.

Introduction

Our previous studies (Bell and Ramelli, 2007, 2009) have suggested that there is a spatial correlation between the presence of seismically active faults (Holocene age, <10,000 years old) and the occurrence of high-temperature geothermal sites in the western Nevada region. A comparison of the location of known high-temperature (>100°C) geothermal sites with active fault locations showed that of a total of 37 high-temperature sites, 31 sites occur directly on, or in close proximity to Holocene faults. These studies also demonstrated that many geothermal resource areas have unrecognized active fault traces that contribute to the structural controls on thermal fluid migration at the sites.

In this study, we applied these previous findings to an analysis of the structural controls that may influence the potential for geothermal resources at the Hawthorne Army Weapons Depot (HAWD) in central Nevada (Figure 1). The study was undertaken to provide one of the geothermal resource components to be integrated into the broader evaluation of resource potential being investigated at HAWD by the Department of Navy Geothermal Program Office. The HAWD is located around the town of Hawthorne at the southern end of Walker Lake basin. The previously known Quaternary faults are located along the Wassuk range front which lies in the western portion of HAWD. Limited previous active fault studies have established that the most recent activity along the Wassuk range-front fault system is latest Quaternary age and thus the range front is considered seismically active (Adams and Sawyer, 1999).

In order to better document the nature and extent of Holocene faulting along the Wassuk range front and to search for additional evidence of unrecognized Holocene faulting that may contribute to
geothermal potential within the HAWD, we conducted a detailed active fault study using specialized aerial photography and LiDAR together with field reconnaissance in order to produce a new active fault map for the Hawthorne area. In this paper, we present the results of this analysis which demonstrates that the extent of seismically active faulting is more extensive than previously known; in particular, a new fault zone is recognized through the HAWD which may play an important role in controlling resource potential.

![Figure 1](image1.png)

**Figure 1.** Location of Hawthorne Army Weapons Depot (dashed boundary) in southern Walker basin. Previously known Quaternary faults shown in white (U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006).

**Methodology**

Through sun shadowing and sun illumination, LSA aerial photography provides the ability to detect and map subtle fault features not otherwise visible on conventional mapping photography. New LSA aerial photography was acquired at a scale of 1:18,000 over the greater HAWD region in February, 2009. These acquisitions were supplemented by more limited 1:12,000-scale LSA photographic coverage previously acquired along the Wassuk range front in 1997 by Steve Wesnousky, Center for Neotectonic Studies, University of Nevada, Reno. The LSA photographic data set was complemented by a 2.5-m-resolution LiDAR data set acquired by the U.S. Geological Survey for the Walker Lake region in 2005 (Lopes and Smith, 2007). This LiDAR data set is available at [http://water.usgs.gov/GIS/metadata/usgswrd/XML/sir2007-5012_bathymetry.xml](http://water.usgs.gov/GIS/metadata/usgswrd/XML/sir2007-5012_bathymetry.xml).

Our remote sensing analysis indicated that because of the small-scale nature of many of the fault traces within HAWD, and because cultural features, such as off-road tracks, may appear to be fault traces on LiDAR imagery, it was necessary to utilize both the conventional photography and the LiDAR data set in order to confidently differentiate active fault scarps on the basin floor. A comparison of the LSA photography with LiDAR imagery (Figure 2) illustrates a trace of a northeast-striking fault scarp highlighted on both the LSA and LiDAR imagery. This east-facing fault scarp is 1-2 m in height and is the largest of the fault scarps cutting the basin floor; it is illuminated on the LSA imagery which was acquired under early morning sun conditions, and it is shadowed artificially by late afternoon sun conditions on the LiDAR imagery.

![Figure 2](image2.png)

**Figure 2.** Comparison of LSA photograph (top) with LiDAR imagery of same area (bottom). Both images highlight the east-facing Airport fault scarp (indicated by arrowheads) which extends just to the south of HAWD main base compound. On the LSA image, the scarp is highlighted by early morning sun and on the LiDAR image it is highlighted by artificial late afternoon shadowing. Linear features which show as possible fault traces on the LiDAR imagery are seen on the LSA imagery to be cultural features (roads and tracks). Note prominent Lake Lahontan shorelines cut by the scarp on the LiDAR imagery.
The age of the surface faulting can be constrained using well-established Quaternary chronologies for the western and central Nevada region. In particular, the lacustrine record provided by late Pleistocene Lake Lahontan (Morrison, 1964) provides a key stratigraphic datum in many basins including the Walker Lake basin (cf., Benson et al., 1990; Morrison, 1991). Lake Lahontan reached a maxima at ~13 ka (Adams and Wesnousky, 1998; 1999) producing a series of prominent shorelines at 1332 m elevation and below. This high ~13 ka shoreline extends through the HAWD and provides an important datum for establishing a Holocene age for the fault scarps which cross-cut the shorelines. Above the elevation of the high Lahontan shorelines, ages of faulting can be constrained by correlation of pre- and post-Lahontan alluvial fan sequences and by examination of soil chronosequences developed in the faulted deposits. Locally late Holocene (0.5-2 ka) volcanic tephra beds are exposed in alluvial fan deposits of the Wassuk Range (Bell and House, 2007) which can be used to additionally constrain age of faulting.

Results

The late Quaternary-age Wassuk range-front fault system displays evidence of segmentation, i.e., separation of the range-front fault into discrete fault segments that exhibit different slip displacements, orientations, and slip histories. These segments are from south to north (Fig. 3): Cottonwood Creek to Lucky Boy Pass; Lucky Boy Pass to Corey Canyon; Cat Canyon to Rose Creek; Rose Creek to town of Walker Lake. Between Corey Canyon and Cat Canyon, there is a gap in the range-front fault system with the active faulting splaying to the northeast through the HAWD and the town of Hawthorne. This zone of faulting is termed the Hawthorne fault zone segment.

The Cottonwood Creek-Lucky Boy Pass segment appears to be dominated by two parallel, northwest-striking, dextral faults, one lying along the range front and the other lying along the unnamed hills to the east of the range front, together forming a singular graben. At the mouth of Cottonwood Creek, an east-dipping 2-3 m high fault scarp cuts Holocene-age alluvial fan deposits. Road cuts expose probable Mono Crater tephra beds in the alluvial fan deposits suggesting that the faulting is less than 0.5-2 ka in age. The low hills to the east of the range front are bounded on the west by a series of west- and east-facing scarps 0.5-1 m in height which cut late Holocene debris flows. Although no surficial evidence of strike-slip motion, such as lateral offsets, was evident along these traces, the reversal of along-strike fault dip (scissoring) suggests the occurrence of strike-slip displacement.

From Lucky Boy Pass to Corey Canyon, faulting is characterized by a curvilinear zone of graben and nested graben lying along the range front. These extensional structures here and in the segments to the north suggest that the dextral shear to the south has been transferred to predominantly normal faulting. At Lucky Boy Pass, northeast-striking fault scarps 1-2 m in height cut Holocene-age alluvial fan deposits. Between Squaw Creek and Powell Creek these faults curve to the northwest. At Corey Creek a series of north-striking fault scarps as much as 3 m in height cut Holocene-age alluvial fan deposits originating from Corey Canyon. To the north of Corey Canyon Road, the Holocene faulting is inferred to trend up a small wash to the northeast for several hundred meters, but no other Holocene faults are evident along the range front between this point and Cat Canyon 3.2 km to the north.

This several-kilometer-long gap in north-striking Holocene faulting is replaced by a zone of northeast-striking faults which splays from the range front. This set of northeast-striking faults is here termed the Hawthorne fault zone (HFZ), a previously unrecognized zone of Holocene faulting extending through the HAWD and the town of Hawthorne. It is characterized by a set of nested graben that extend to the northeast beginning several kilometers east of the Wassuk range front. The zone of faulting is 9-11 km in width and 13-14 km in length, and it is inferred to be structurally connected with the Gillis range-front faults north of the Thorne railroad crossing. The axis of the graben system lies...
in the central and northern magazine areas about 1 km (1/2 mi) east of Hawthorne.

The faults within the nested graben are characterized by 0.5-1 m-high scarps that cut the 13 ka and younger shorelines and associated lacustrine and alluvial-fan deposits. The largest of the scarps (2 m) extends from the north side of the Hawthorne airport south through the abandoned site of Babbitt on the HAWD. Based on the degree of fault scarps degradation and the distribution of late Holocene surficial deposits which largely post-date the faulting, these faults are interpreted to be of mid-Holocene age. One set of queried fault scarps at the northern extent of the graben system occur in historical Walker Lake deposits and may reflect some late Holocene activity.

Several linear tufa mounds (Qt) are inferred to be structurally controlled based on their northeast orientation and the scarp-like morphology which abruptly bounds the tufa colonies. Such large tufa colonies are commonly associated with thermal water discharge areas along faults.

The Cat Canyon to Rose Creek segment begins near the mouth of Cat Canyon where a series of north-northwest-striking fault scarps cut a sequence of late Holocene alluvial fan deposits. These scarps comprise some of the largest Holocene offsets along the Wassuk range front with offsets of 6-10 m. The Pleistocene scarps reach heights of 15-20 m in older alluvial-fan deposits bounding the west side of the HAWD Cat Canyon reservoir.

Cat Canyon is situated in a structural right-stepping bend of the Wassuk Range; the Holocene fault scarps follow the curvilinear range front to the northeast from Cat Canyon and then north-northwest to Rose Creek. The fault scarp is discontinuously preserved along the steep range front; at House Canyon preserved scarps are 2-3 m in height and 5-6 m in height at Rose Creek.

The Walker segment extends from Rose Creek to the town of Walker and displays discontinuous 2-3 m-high Holocene scarps along the toe of the range front. Holocene range-front faulting continues to the north of Walker but was not mapped as part of this study. Two trenches excavated across the fault scarp at Rose Creek exposed structural-stratigraphic evidence for two Holocene faulting events (Bormann et al., 2010). Both events appear to pre-date 0.5-2 ka Mono Craters tephra exposed in the trenches indicating that the faulting is of mid- to late Holocene age.

**Implications for Geothermal Resource Potential**

The evaluation of Holocene faulting has contributed to understanding the structural controls of geothermal systems at HAWD in two key ways. First, the distribution of Holocene faults mapped in this study illustrates which fault structures are active in the present tectonic stress regime and thus validates stress field determination from measured fault surfaces (Moeck et al., this volume). Second, the previously unrecognized Hawthorne fault zone provides important new data for integrating geologic and geophysical data in developing a robust structural and stratigraphic model for evaluating the geothermal resource potential at HAWD. As discussed in more detail in Hinz et al. (this volume) and Moeck et al. (this volume), this northeast-trending set of young faults is favorably oriented in the present stress field, undergoing both shear slip and dilation, and thus fits with optimal structural model conditions for opening geothermal fluid pathways. One of three recognized geothermal anomalies coincides with several NNE-striking strands of the Hawthorne fault zone (Hinz et al., 2010; Kratt et al, 2010; Penfield et al., 2010).

**Acknowledgments**

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