Nevada Bureau of Mines and Geology Special Publication 36

# The Regional Structural Setting of the 2008 Wells Earthquake and Town Creek Flat Basin — Implications for the Wells Earthquake Fault and Adjacent Structures

*by*

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2011

## ABSTRACT

The 2008 Wells earthquake occurred on a northeast-striking, southeast-dipping fault that is clearly delineated by the aftershock swarm to a depth of 10-12 km below sea level. However, Cenozoic rocks and structures around Wells primarily record east-west extension along north- to north-northeast-striking, *west-dipping* normal faults that formed during the middle Miocene. These faults are responsible for the strong eastward tilt of most basins and ranges in the area, including the Town Creek Flat basin (the location of the earthquake) and the adjacent Snake Mountains and western Windermere Hills. These older west-dipping faults are locally overprinted by a younger generation of east-dipping, high-angle normal faults that formed as early as the late Miocene and have remained active into the Quaternary. The most prominent of these east-dipping faults is the set of en-échelon, north-striking faults that bounds the east sides of the Ruby Mountains, East Humboldt Range, and Clover Hill (about 5 km southwest of Wells). The northeastern-most of these faults, the Clover Hill fault, projects northward along strike toward the Snake Mountains and the approximately located surface projection of the Wells earthquake fault as defined by aftershock locations. The Clover Hill fault also projects toward a previously unrecognized, east-facing Quaternary fault scarp and line of springs that appear to mark a significant east-dipping normal fault along the western edge of Town Creek Flat. Both western and eastern projections may be northern continuations of the Clover Hill fault. The Wells earthquake occurred along this east-dipping fault system.

Two possible alternatives to rupture of a northern continuation of the Clover Hill fault are that the earthquake fault (1) is antithetic to an active west-dipping fault or (2) reactivated a Mesozoic thrust fault that dips east as a result of tilting by the west-dipping faults along the west side of the Snake Mountains. Both alternatives are precluded by the depths of the earthquake and aftershocks, about 8 km and as deep as 12 km, respectively. These depths are below where an antithetic fault would intersect any main fault, and a tilted, formerly shallow and sub-horizontal thrust fault would not extend to depths of more than about 5–6 km.

The east-dipping, high-angle, earthquake fault cuts older west-dipping faults rather than reactivating them, highlighting a change in the structural style of Basin and Range extension in this region from closely-spaced, west-dipping faults that rotated significantly during slip and accommodated large-magnitude extension, to widely-spaced, high-angle faults that accommodate much less total strain over a long time span.

## INTRODUCTION

The 2008 Wells earthquake occurred in northeastern Nevada in the northern Basin and Range Province. The rugged, north- to north-northeast-striking ranges characteristic of this region (figure 1) generally are bound on one side (locally both) by major normal faults that downdrop the adjacent basins (e.g., Effimoff and Pinezich, 1981). Most of these range-bounding faults have been active in the Quaternary, and several faults in western Nevada produced major surface-breaking earthquakes in the last century (Dohrenwend and others, 1996; Wesnousky and Willoughby, 2003; Wesnousky and others, 2005; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006; dePolo, 2008). The Wells earthquake, however, took place on an unmapped fault with no previously recognized displacement.

The area around Wells is dominated by west-dipping normal faults and correspondingly east-tilted ranges (figure 1). Many of these faults have Quaternary offset and are thus obvious candidates for potential earthquakes. Town Creek Flat—directly above the earthquake hypocenter—is an east-tilted basin with several west-facing Quaternary scarps along its east side (plate 1, in appendix A of this volume). However, aftershock data demonstrate unequivocally that the Wells earthquake occurred on a fault that strikes N40° E and dips about 55° to the southeast (Smith and others, this volume). Field reconnaissance following the earthquake found no surface rupture (DuRoss and others, 2008; Ramelli and dePolo, this volume; our observations), although we did find a faint, east-dipping scarp on the west side of the basin (about 3 km east of the surface projection of the fault defined by aftershocks).

These observations raise several questions, both for the Wells earthquake and for the seismic hazard potential of other faults in the Basin and Range. How does the fault that slipped in the earthquake relate to the regional fault pattern? Conversely, what does the earthquake fault say about the regional fault pattern and interpreted history and geometry of faulting? How large an earthquake could such a fault generate? How do we recognize and evaluate potential earthquake hazards in an area where the fault that generated a major earthquake had been unknown? To address some of these questions, this report documents the history and geometry of normal faulting around Wells (including the structure of Town Creek Flat), shows how the Wells earthquake fault relates to that pattern, and discusses what we can learn about regional fault structure from the Wells earthquake fault.

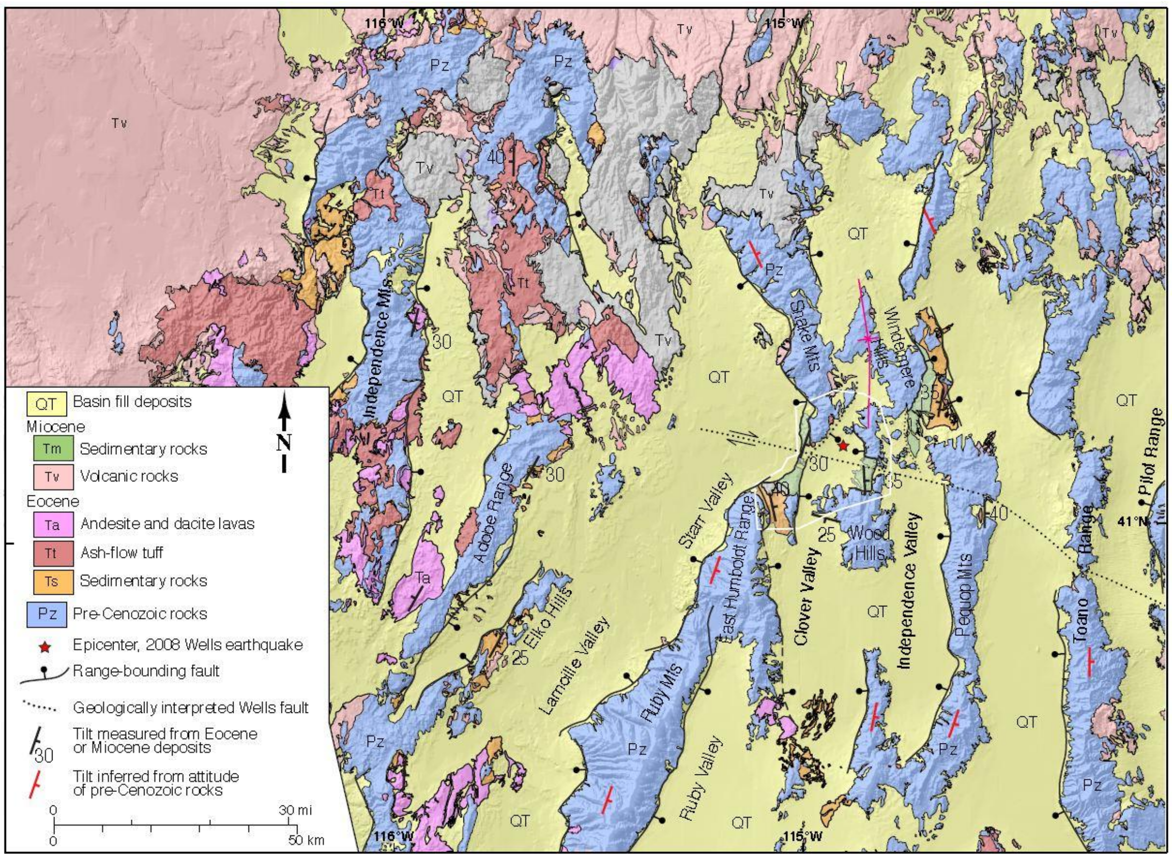


**Figure 1.** Simplified geologic map of the region around Wells, Nevada (from Coats, 1987), showing the epicenter of the Wells earthquake, major range-front faults, and tilts of ranges. The white outline shows the area of the detailed geologic map (plate 1, in appendix A of this volume). Black strike-and-dip-symbols with dip values were determined from tilts of Eocene or Miocene volcanic and sedimentary rocks. Red strike-and-dip-symbols without dip values indicate direction of tilt based on attitudes of pre-Cenozoic sedimentary rocks. Ranges near Wells are dominantly tilted eastward and have major, west-dipping normal faults along their western sides. However, major east-dipping faults are also present near Wells. The eastern side of the Windermere Hills is bordered by an east-dipping normal fault having late Quaternary displacement (U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006). A similar fault separates pre-Cenozoic rocks from west-tilted Miocene and Eocene rocks within the range (Thorman and others, 1991; Mueller, 1992, 1993; Henry, 2008). An accommodation syncline (Faulds and Varga, 1998) may lie between these west-dipping rocks and east-dipping rocks in the Snake Mountains to the west, but the location and even existence of this syncline in the folded pre-Cenozoic rocks of the western Windermere Hills are uncertain. An en-échelon set of major east-dipping normal faults having late Quaternary displacement (Sharp, 1939; Snelson, 1957; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006) bounds the eastern side of the Ruby Mountains, East Humboldt Range, and Clover Hill just southwest of Wells.

### Geophysical Characterization of the Earthquake Fault

The nature of the Wells earthquake and the geometry of the earthquake fault as indicated by geophysical data are described in detail elsewhere in this volume (Smith and others, this volume). Here, we briefly summarize relevant facts about the earthquake fault itself. The main earthquake nucleated at an estimated depth of 8 km below sea level (Smith and others, this volume). The fault defined by hypocenters of aftershocks is planar, strikes about N 40°E, and dips 55° to the southeast. Most aftershock depths were from about 2 to 10 km. Some aftershock hypocenters scatter as much as 2 km east and 4 km west of the main planar array of aftershocks, which probably indicates slip on surfaces outside the main fault plane (Smith and others, this volume). Although the earthquake fault did not break the surface, it projects to the surface in the middle of the Snake Range. The surface projection has a lateral uncertainty, perpendicular to the fault, of several kilometers, largely related to uncertainty in aftershock depths (Ken Smith, personal commun., 2011). Relocations of the aftershocks, which are underway, would most likely shift the aftershocks to greater depths, which would shift the surface projection to the west.

## GEOLOGIC SETTING OF THE WELLS REGION

Rocks and structures exposed in the ranges around Wells range from Precambrian to Miocene and record a rich history of Paleozoic and Mesozoic contraction overprinted by Cenozoic extension and magmatism (e.g., Dickinson, 2006). Precambrian, possibly Archean, rocks crop out in the northern East Humboldt Range (Lush and others, 1988). Paleozoic and Mesozoic sedimentary rocks were folded and thrust eastward to southeastward in a series of orogenic events that began with the Antler orogeny in the Late Devonian and culminated with the Sevier orogeny in the Late Cretaceous to early Cenozoic (e.g., Roberts and others, 1958; Armstrong, 1968; Thorman and others, 1991; Camilleri and others, 1997; Dickinson, 2006; Thorman and Brooks, this volume). The most deeply buried Paleozoic rocks were metamorphosed to upper amphibolite facies in the Ruby Mountains and East Humboldt Range, to lower amphibolite facies in the Wood Hills, and to greenschist facies in the western Windermere Hills (Thorman, 1970; Mueller, 1993; McGrew and Snee, 1994; Camilleri and others, 1997; Snoke and others, 1997; McGrew and others, 2000; Howard, 2003). Cenozoic magmatism around Wells took place primarily during two pulses, a major one in the Eocene and a lesser, middle Miocene pulse (Thorman and others, 1991; Brooks and others, 1995; Snoke and others, 1997; Mueller and others, 1999; Thorman and others, 2003; Ressel and Henry, 2006). Cenozoic extension probably began in some form no later than Eocene—possibly earlier—and has continued episodically to the present day, although some aspects of the timing and structural style of faulting remain controversial. The present day topography around Wells is primarily the product of middle Miocene and younger normal faulting. The Wells earthquake is the most recent manifestation (Dokka and others, 1986; Thorman and others, 1991; Hodges and others, 1992; Mueller and Snoke, 1993; Dohrenwend and others, 1996; Snoke and others, 1997; Mueller and others, 1999; Henry and others, 2001; Haynes and others, 2002; Howard, 2003; Colgan and Metcalf, 2006; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006; Henry, 2008; Wallace and others, 2008).

### Cenozoic Faults and Tilt Domains in the Wells Region

Most ranges around Wells are east-tilted and bounded by west-dipping normal faults along their western sides (fig. 1). The closest prominent Late Quaternary fault to Wells bounds the west side of the Snake Mountains and continues as a 70-km-long fault zone to the south along the west side of the East Humboldt Range and Ruby Mountains. This fault zone has undergone late Quaternary and even Holocene displacement (Sharp, 1939; Dohrenwend and others, 1996; Wesnousky and Willoughby, 2003; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006; dePolo, 2008). The fault zone fronting the west side of the Ruby Mountains and East Humboldt Range follows and may be a young manifestation of a gently west-dipping detachment fault system active since Miocene or earlier time (Misch, 1960; Howard, 1971; Mueller and Snoke, 1993; Snoke and others, 1997; Howard, 2000, 2003). A thick mylonite zone that is exposed along the west side of the Ruby Mountains and East Humboldt Range marks the detachment fault.

Eastward tilt of the southern part of the Snake Mountains is indicated by attitudes in Eocene and Miocene sedimentary and volcanic rocks, and in the northern part of the range by the eastward dip of Paleozoic rocks and thrust faults inferred to have been approximately horizontal before extension (figure 1, this paper; plate 1, in appendix A of this volume; Thorman and others, 2003; Henry, 2008). Eastward tilt of Clover Hill at the northeastern corner of the East Humboldt Range is indicated by attitudes in Eocene and Miocene sedimentary and volcanic rocks (Snoke and others, 1997), and in the Ruby Mountains by a thick, east-tilted Paleozoic section (Willden and Kistler, 1976; Howard and others, 1979). Thermochronologic data that are inferred to record exhumation of the Ruby Mountains – East Humboldt Range core complex along a west-rooted detachment fault zone are also consistent with eastward tilting (e.g., Howard, 2003). Other major east-tilted ranges bounded by west-dipping normal faults include the Pequop Mountains to the east of Wells

(Thorman, 1970; Camelleri and others, 1997), the Toano Range, and the Pilot Range on the Utah border (figure 1; Coats, 1987).

In addition to the preponderant west-dipping faults and east-tilted fault blocks, several major east-dipping faults are also present near Wells. The eastern side of the Windermere Hills northeast of Wells is bound by an east-dipping normal fault mapped as having Quaternary displacement along its central part, and a parallel east-dipping fault with Quaternary displacement lies within the range to the west (figure 1; Mueller, 1993; Henry, 2008; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006). Miocene and Eocene rocks form a 35° west-dipping homocline between these two major faults but are east-dipping in the Snake Mountains to the west. The change in dip may indicate an accommodation syncline between oppositely dipping fault zones (Faulds and Varga, 1998), but the location and even existence of this syncline is poorly constrained in the deformed pre-Cenozoic rocks of the western Windermere Hills (figure 1).

Three, major, en-échelon, east-dipping normal faults having late Quaternary displacement bound the eastern side of the Ruby Mountains, East Humboldt Range, and Clover Hill (the promontory east of the East Humboldt Range just southwest of Wells) (figure 1; Howard and others, 1979; Dohrenwend and others, 1996; Snoke and others, 1997; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006). Although the west-dipping faults along the west sides of the Ruby Mountains and East Humboldt Range have Holocene scarps, both the topography of the ranges and the age of fill in adjacent basins indicate significantly greater latest Tertiary and Quaternary throw on the east-dipping faults. Both ranges have steeper, more rugged east sides and more gently sloping west sides, which is consistent with westward tilting and recent slip on east-dipping faults (as originally noted by Sharp, 1939), although this faulting has been insufficient to reverse the strong eastward tilting of older units that occurred during earlier faulting. West of the Ruby Mountains, Miocene basin fill—the Humboldt Formation (as defined by Smith and Ketner, 1976)—ranges from about 16–9 Ma and was deposited during slip on the major west-dipping fault bounding the west side of the Ruby Mountains and East Humboldt Range (Smith and Ketner, 1976; Perkins and Nash, 2002; Wallace and others, 2008). These deposits are east-tilted and moderately dissected at the present land surface, indicating little deposition—and we infer little fault slip—since 9-10 Ma. In contrast, Ruby Valley on the east side of the Ruby Mountains and East Humboldt Range is the site of active deposition and intermittent lake basins that unconformably overlap older, tilted equivalents of the Humboldt Formation on the edges of the basin, although the thickness of this younger (post-9 Ma) basin fill is not known.

Regional tilt of the Wood Hills, south of the Wells earthquake, is uncertain. No major bounding faults are mapped around the east or west flanks of the range, but an inferred gently west-dipping fault (the Marys River fault; see below) is interpreted to superpose east-dipping, middle Miocene rocks along the north and northwest flanks of the range onto Paleozoic rocks in it (figure 1; Camilleri and others, 1997; Camilleri and Chamberlain, 1999; Camilleri, 2010). The gentle fault dip suggests that the fault and the Wood Hills are east-tilted (e.g., figure 14 of Camilleri and Chamberlain, 1999). Eocene (40 Ma) ash-flow tuff at the northern edge of the range dips 35° southeastward, and middle Miocene deposits at and west of Moor Summit along Interstate 80 slightly farther north dip 30° to 35° eastward (figure 1; Thorman and others, 1991; Camilleri, 2010). However, middle Miocene deposits along the west side of the range dip 25° southward (Thorman, 1970; Camilleri, 2010).

Two proposed structures near Wells are potentially important because they could influence or segment the major range-bounding faults and the Wells earthquake fault. The Wells fault is a west-northwest-striking, mostly high-angle, right-lateral fault zone that passes just north of Wells (figure 1; Thorman, 1970; Thorman and others, 1991). It was originally proposed based on juxtaposed contrasting Paleozoic units in the Pequop Mountains and inferred to be a Mesozoic fault (Thorman, 1970; Thorman and others, 1991). Alternatively, Howard (2003) suggested that it may be a nearly 10-km-wide, Cenozoic transfer fault zone that separated the highly-extended Ruby Mountains – East Humboldt Range core complex from less-extended crust to the north (and would thus have been active during Tertiary extension). Ponce and others (this volume) show that gravity and magnetic data define a lineament that strikes approximately 300°, close to but slightly oblique to the geologically defined Wells fault of Thorman and others (1991), and crosses the Wells fault near the epicenter of the 2008 Wells earthquake. The Wells fault zone approximately coincides with an abrupt right step in the western range-front fault of the East Humboldt Range at the north end of the range.

The Marys River fault system is a proposed middle Miocene to Holocene, west-dipping, low- to high-angle extensional fault system that was interpreted to include faults beneath Town Creek Flat and the Snake Mountains at depths of less than 1 to 1.5 km (figure 2; Mueller, 1993; Mueller and Snoke, 1993; Snoke and others, 1997; Mueller and others, 1999). The Marys River fault system of Mueller and Snoke (1993) also included segments above the Snake Mountains and Quaternary and Holocene high-angle faults that form the western range front of the Snake Mountains. This definition of the Marys River fault system differs from that of Effimoff and Pinezich (1981), who used the term for the faults bordering the west side of the Ruby Mountains.

## Timing of Extension in the Wells Region

The presence of Quaternary scarps on all range-front faults and some lesser faults in Town Creek Flat and many others in the Wells region demonstrates they have slipped in the Quaternary (figure 1; Ramelli and dePolo, this volume;

Dohrenwend and others, 1996; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006; dePolo, 2008). Although there is no consensus on the full history of Cenozoic extensional faulting in the Wells area, most workers agree on several points: at least some extension took place in the Eocene, an episode of major extension took place in the middle Miocene (ca. 16–10 Ma), and extensional faulting continues today at a slower pace. The timing and structural style of pre-Miocene extension are controversial, with some arguing for significant extension as early as the Late Cretaceous, Paleocene, or Eocene (Hodges and others, 1992; Mueller and Snoke, 1993; McGrew and Snee, 1994; Camilleri and others, 1997; Snoke and others, 1997; Mueller and others, 1999; McGrew and others, 2000), while others infer relatively little extension until the middle Miocene (Thorman and others, 1991; Colgan and Metcalf, 2006; Colgan and others, 2008; Henry, 2008; Wallace and others, 2008). Although of considerable scientific interest, the pre-Miocene history of the Wells area is of less relevance to the Wells earthquake than the period from the middle Miocene to the present, during which most of the modern ranges were formed. Geodetic data demonstrate the region is continuing to extend today but at a low rate (Bennett and others, 2003; Hammond and Thatcher, 2004, 2005).

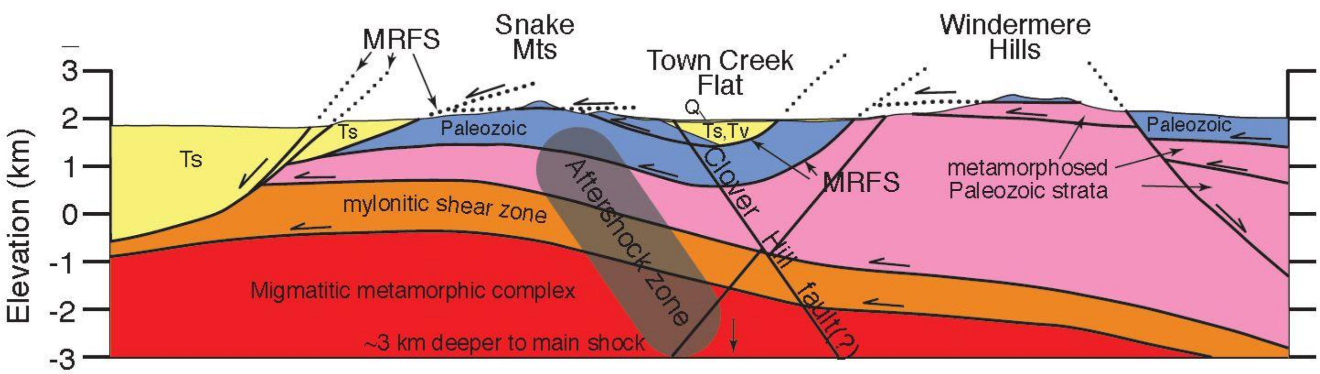


**Figure 2.** Central part of section B-B', plate 2 of Mueller and Snoke (1993). The section trends approximately 100° and crosses the Town Creek flat basin approximately 2.5 km north of the 2008 Wells earthquake epicenter (plate 1, in appendix A of this volume). Aftershock zone is from figure 10 of Smith and others (this volume). The Clover Hill fault (?) is the possible northeastward projection of the mapped Clover Hill fault to a small east-facing scarp in Town Creek Flat basin (see plate 1 in appendix A of this volume) As shown here, Mueller and Snoke (1993) interpreted the Marys River fault system (MRFS) to consist of numerous strands including two probably Middle Miocene, now sub-horizontal faults that pass below the Town Creek Flat basin at shallow depth; late Miocene or Pliocene, low-angle faults that pass through or just above the Snake Mountains; and Quaternary and Holocene high-angle faults that bound the west side of the Snake Mountains. Gravity data that indicate a depth to basement of 1.8 km beneath Town Creek Flat (Ponce and others, this volume) indicate that, if present, any Marys River faults must lie at greater depths. Also, Miocene and Eocene deposits that dip eastward at no more than 40° would nearly parallel the shallowest Marys River fault beneath Town Creek Flat.

## THE TOWN CREEK FLAT BASIN AND FAULTS

Town Creek Flat is a small, north-northeast-striking, eastward-tilted basin controlled by dominantly west-dipping normal faults along the east-side of the basin (plate 1 in appendix A of this volume). The part of the basin covered by Quaternary deposits is about 11 km long and a maximum of about 8 km wide. The structural basin—as defined by basin-bounding faults—is at least 15 km long, and exposed deposits are Quaternary throughout most of the basin. Paleozoic, Eocene, and Miocene deposits are exposed in the adjacent Snake Mountains to the west (Thorman and others, 2003; Thorman and Brooks, this volume), Windermere Hills to the east (Mueller, 1993), and Wood Hills to the south (Thorman, 1972; Camilleri, 2010); we assume they also underlie Quaternary deposits in Town Creek Flat. Eocene rocks consist of a few hundred meters of about 40 Ma ash-flow tuffs, andesite to dacite lavas, and minor volcaniclastic rocks (Thorman and others, 1991; Brooks and others, 1995; Thorman and others, 2003; Henry, 2008; Thorman and Brooks, this volume). Middle Miocene rocks in the southernmost Snake Mountains and north of the Wood Hills consist primarily of tuffaceous sediments with interbedded rhyolitic tephras. Thorman and others (2003) divided these rocks into three units about 1000 m thick in total and obtained zircon fission-track dates of 12 to 9 Ma on tephra from the middle unit. Wallace and others (2008) obtained a $^{40}Ar/^{39}Ar$ date of 10.5 ± 0.1 Ma on sanidine from tephra in the upper unit. Rhyolitic lavas with K-Ar dates between 15 and 13 Ma crop out in the Snake Mountains and at Clover Hill southwest of Wells and may underlie the tuffaceous deposits elsewhere (Snoke and others, 1997; Thorman and others, 2003). Miocene sedimentary and volcanic rocks in the Wells region thus range from 15–9 Ma, the same as similar rocks across a wide swath of northern Nevada (Perkins and Nash, 2002; Wallace and others, 2008; Colgan and others, 2008).

Along the west side of Town Creek Flat, Eocene and Miocene sedimentary and volcanic rocks in the southern Snake Mountains are concordant and tilted eastward between 15° and 40° (Thorman and others, 2003; Henry, 2008). In the eastern part of Town Creek Flat, between the western Windermere Hills and north end of the Wood Hills, the same units are concordant and dip about 30° to 35° to the east (Thorman and others, 1991; Camilleri, 2010). Fanning of dips is not evident in the Miocene rocks, but the 15 Ma rhyolite lavas do not crop out in the same area as the 12-9 Ma tuffaceous deposits, and the Miocene rocks in general have not been studied sufficiently to preclude shallowing of dips upsection. Mesozoic thrust faults in the Snake Mountains, probably were initiated in a nearly horizontal geometry but now dip moderately eastward (Thorman and others, 2003; Thorman and Brooks, this volume). The western Windermere Hills expose highly deformed pre-Cenozoic rocks (Mueller, 1993). Their position between east-dipping Eocene and Miocene rocks in the Snake Mountains and west-dipping rocks in the eastern Windermere Hills suggests they probably are gently east-tilted on the western side of the possible accommodation syncline.

Numerous west-dipping normal faults cut pre-Cenozoic rocks in the western Windermere Hills, and some west-facing scarps also cut Quaternary fans in the eastern part of the Town Creek Flat basin (plate 1, in appendix A of this volume; Ramelli and dePolo, this volume). The north-northwest-striking fault that separates Paleozoic rocks in the western Windermere Hills from Quaternary fans—effectively a range-front fault for the western Windermere Hills and herein named the west Windermere fault—appears to have the greatest displacement, but the attitude and amount of displacement on individual faults and total displacement for the basin are poorly constrained. Faults that cut Quaternary fans strike north-northeast to northeast and have small scarps (≤1 m). Quaternary faults probably dip no more steeply than about 60°, but the initially Miocene (?) west Windermere fault could dip as shallowly as about 25-35° if it was tilted along with the Eocene and Miocene deposits. Total displacement of Eocene rocks across the basin on these faults could be as much as 3 km based on eastward extrapolation of dips in Eocene and Miocene rocks in the Snake Mountains. Displacement on the west Windermere fault appears to decrease northward, where bedrock (Mississippian Melandco Sandstone) reappears in the hanging wall and Ordovician Pogonip Group is in the footwall (plate 1, in appendix A of this volume; Mueller, 1992, 1993). To the south, this fault either steps sharply eastward about 2 km or is offset eastward by an east-striking cross fault, then continues south through Moor Summit where approximately 30-35° east-dipping Miocene deposits are downfaulted against Paleozoic rocks (plate 1, in appendix A of this volume; Thorman and others, 1991; Mueller and Snoke, 1993; Camilleri and others, 1997; Camilleri, 2010). The fault through Moor Summit is interpreted by Mueller and Snoke (1993) to be part of the low-angle Marys River fault system (see below).

A single, east-facing Quaternary scarp identified by us cuts fan deposits along the west side of Town Creek Flat (plate 1, in appendix A of this volume; Ramelli and dePolo, this volume). The scarp strikes north-northeast, is about 370 m long, and has approximately 30 cm of relief in the one location it could be well identified on the ground. A discontinuous line of possibly fault-controlled springs roughly aligns with the scarp and stretches for about 1.5 km in either direction from it. The aftershock swarm projects to the surface about 3 km west of this east-facing scarp, in bedrock in the highest part of the Snake Mountains, and defines a 55° southeast-dipping fault plane that extends to a depth of about 10 km below sea level (Smith and others, this volume). Ramelli and dePolo (this volume) recognize several lineaments along the surface projection, but Thorman and others (2003) did not map a fault along this trend (see also plate 1, in appendix A of this volume). The surface projection has an uncertainty of as much as several kilometers, although the most likely corrections would shift the projection farther west (K. Smith, personal commun., 2011). Therefore, it is unlikely that the east-facing scarp is the surface manifestation of the fault that ruptured.

Gravity data indicate the depth to pre-Cenozoic basement, or thickness of low-density sedimentary fill, beneath Town Creek Flat is about 1.8 km (figure 1; Jachens and others, 1996; Ponce and others, this volume). The deepest part is along the eastern margin of the Town Creek Flat basin, which is consistent with the eastward tilt of the basin toward the west-dipping west Windermere fault along the basin's east side. As noted by Ponce and others (this volume), the basin is deep given its small size. The thickness of low-density deposits may include some Eocene and Miocene rocks that were deposited before formation of the Town Creek Flat basin and also have low densities. Miocene deposits are about 1 km thick in the southern Snake Mountains (plate 1, in appendix A of this volume). Eocene deposits are locally several hundred meters thick but discontinuous along the east side of the Snake Mountains (Thorman and others, 2003; Henry, 2008). Similar Eocene and Miocene deposits could contribute to thicknesses of other basins in the region (e.g., Satarugsa and Johnson, 2000).

The Marys River fault system as interpreted by Mueller (1993), Mueller and Snoke (1993), Camilleri and others (1997), Snoke and others (1997), and Camilleri (2010) is an inferred, multi-strand, shallowly down-to-the-west, large displacement, normal fault system (figure 2). The Marys River fault system was inferred to have formed at a moderately high angle, similar to its westernmost parts shown on figure 2. As the fault slipped, tilting of the fault and adjacent rocks rotated the fault to progressively lower angles. Eventually, the oldest part of the fault system rotated to such a low angle that it became mechanically unfavorable for continued slip, and a new fault formed in the hanging wall at a higher angle. With continued slip, multiple strands formed, were rotated, and were abandoned. Mueller and Snoke (1993) interpreted the range-front fault along the west side of the Snake Mountains to be the youngest and active part of the Marys River fault system.

The near surface trace of the oldest and structurally lowest part of the proposed Marys River faults lies beneath Quaternary fans in the eastern part of Town Creek Flat, roughly 1-3 km west of the west Windermere fault (figure 2; and plate 1, in appendix A of this volume). From there the fault was inferred to curve south, then cut east to trend approximately through Moor Summit, then cut west to separate Miocene deposits from metamorphosed Paleozoic rocks in the northern Wood Hills (Mueller and Snoke, 1993; Camilleri, 2010). Mueller and Snoke (1993) portray the oldest parts of the Marys River fault system dipping about 25° to the west in the shallow subsurface, then flattening westward and even dipping shallowly eastward beneath Town Creek Flat and the Snake Mountains at maximum depths of about 1.5 km. The Snake Mountains, the northeastern East Humboldt Range, and all Eocene and Miocene rocks of plate 1, in appendix A of this volume would therefore be in the hanging wall of these oldest proposed Marys River faults (Mueller and Snoke, 1993). Younger strands of the Marys River fault system were inferred to pass over the Snake Mountains (figure 2).

### Timing of Faulting in the Town Creek Flat Basin

The February 21, 2008 earthquake and Quaternary scarps demonstrate that faulting is ongoing in Town Creek Flat, but when the Town Creek Flat basin itself began to form is uncertain. Ideally, dating of basin fill beneath Town Creek Flat is the best way to determine its time of formation, but Quaternary deposits cover the basin. The presence of a 1 km thickness of middle to late Miocene (15-9 Ma) lava and tuffaceous sediments in the southern Snake Mountains demonstrates that a basin had formed by about 15 Ma. Similar deposits accumulated in fault-bounded basins regionally, and major faulting and tilting began at that time throughout the region, including along the Ruby Mountains – Snake Mountains fault zone (Colgan and Metcalf, 2006; Colgan and others, 2008; Wallace and others, 2008). Thick, coarse conglomerates composed of angular to subrounded clasts that occur at the base of the middle unit (12–9 Ma) of the Miocene deposits (Thorman and others, 2003) indicate formation of a nearby topographic highland and possibly a fault scarp. However, exhumation of the middle to late Miocene sedimentary and volcanic rocks on the flank of Town Creek Flat suggests that this early basin may be unrelated to the Town Creek Flat basin.

If tilting resulted from faulting that generated Town Creek Flat basin, then tilt relationships tell us something about the timing of faulting there. The eastward tilt of apparently concordant Eocene and Miocene deposits indicates that faulting in Town Creek Flat postdates 9 Ma and thus negates significant faulting between about 40 and 9 Ma in this area. However, as noted above, the middle Miocene deposits have not been studied enough to preclude an angular contact between them and the Eocene rocks in some parts of the region. Thorman (personal comm., 2008) notes that Eocene and Miocene volcanic rocks are concordant in other ranges nearby, including the Silver Islands and Toano-Goshute Ranges.

## DISCUSSION AND IMPLICATIONS

### Which Fault Slipped?

When we first heard about the Wells earthquake, we assumed that it occurred along a west-dipping fault, which is clearly not the case (Smith and others, this volume). Three possibilities are presented below for the relationship between the earthquake fault and the major, west-dipping west Windermere fault, which forms the range front of the western Windermere Hills and generated the Town Creek Flat basin (plate 1, sections A and B, in appendix A of this volume).

(1) The earthquake fault is antithetic to the west-dipping west Windermere fault, which is interpreted to be the master fault for the basin. This is highly unlikely because an antithetic fault would be expected to terminate where it met the master, west-dipping fault—and the master fault would also slip during the earthquake. For example, late aftershocks on an antithetic fault to the 1983 Borah Peak, Idaho earthquake fault ended at the plane of the main fault (Payne and others, 2004). Aftershocks of the Wells earthquake extend to a depth of about 12 km (Smith and others, this volume) and demonstrate that the earthquake fault extends much deeper than—and presumably cuts—the "master," west-dipping west Windermere fault. The earthquake fault would cut the proposed low-angle Marys River fault at even shallower depth (figure 2).

(2) The earthquake fault is a reactivated Mesozoic or older thrust fault such as is now exposed in the Snake Mountains (section A, plate 1, in appendix A of this volume). Eastward tilting of the Snake Mountains during the Miocene has tilted several formerly sub-horizontal thrust faults such that they now strike north-northeast and dip about 40° to 60° to the southeast (Thorman and others, 2003; Thorman and Brooks, this volume). These thrust faults are approximately parallel to and along strike with the earthquake fault, in a favorable position to be reactivated as younger normal faults, and closest mapped faults to the aftershock zone. However, it is unlikely that these tilted faults now extend as continuous planes to a depth of more than 5-6 km. The exposed thrust faults juxtapose unmetamorphosed Upper Paleozoic and Mesozoic rocks (Thorman and others, 2003), thus formed and were active at shallow depths (≤5 km; Roberts and others, 1958; Thorman

and others, 1991), and have not been buried to greater depths by large thicknesses of younger deposits. For example, 40 Ma ash-flow tuffs rest on Paleozoic and Mesozoic rocks cut by these thrust faults, so—although they may once have been continuous over a large area—these thrust faults were no deeper than about 3 km in the Eocene. Thrust faults that juxtapose metamorphosed Paleozoic beds formed at and are probably still present at greater depths (Camilleri and others, 1997; Howard, 2003) but are not exposed in the Snake Mountains. Moreover, the west-dipping Cenozoic normal faults that tilted the exposed thrust faults to their present geometry would have cut them in multiple places and left the disconnected pieces kilometers apart, stranded near the surface. Given that the earthquake initiated at a depth of about 8 km on a fault that extends to about 10-12 km, it is unlikely the earthquake nucleated or ruptured along one of these tilted thrust faults.

(3) Our best interpretation is that the earthquake occurred on a previously unrecognized northern strand of the Clover Hill fault, part of the en-échelon system of east-dipping faults along the east side of the Ruby Mountains, East Humboldt Range, and Clover Hill (figure 1; and plate 1, in appendix A of this volume). These faults have similar orientations (high-angle, north- to northeast-strike, eastward dip) and senses of slip (down-to-the-east) as the earthquake fault defined by aftershocks (Smith and others, this volume). The Clover Hill fault—the closest mapped of these faults to Town Creek Flat—strikes north along the east side of Clover Hill towards the western edge of Town Creek Flat (Snoke and others, 1997). North of Clover Hill into the western part of Town Creek Flat, Coats (1987), Snoke and others (1997), and Thorman and others (2003) show a normal stratigraphic contact between Miocene sediments on the west and Quaternary deposits on the east. However, Dohrenwend and others (1996), U.S. Geological Survey and Nevada Bureau of Mines and Geology (2006), and dePolo (2008) show Quaternary displacement on the Clover Hill fault and the Miocene-Quaternary contact north of Clover Hill to be a fault having Holocene–Latest Pleistocene movement to within about 1 km south of Interstate 80. We propose that (1) the Miocene–Quaternary contact is generally the Clover Hill fault, (2) the Clover Hill fault continues northward, possibly as more than one strand toward the Snake Mountains and along its east side (figure 1; and plate 1, in appendix A of this volume), and (3) the earthquake of February 21, 2008 occurred along one of these northern segments of the Clover Hill fault.

Plate 1 (in appendix A of this volume) shows two “end-member” continuations of the Clover Hill fault. The western alternative follows the approximate contact between mapped Miocene and Quaternary deposits in the southern Snake Mountains and projects toward the surface projection of the aftershocks. The eastern alternative heads toward the newly recognized east-facing scarp near the east edge of bedrock outcrop in the Snake Mountains. The western alternative is favored by its possible correlation with the aftershock zone, whose location, however, has a large uncertainty (Smith and others, this volume). Moreover, absence of a mappable fault in the Snake Mountains along this projection indicates that total slip on a western alternative fault is minor. The eastern alternative is probably precluded by its lack of correlation with the aftershock zone. However, an east-facing scarp is present, and total slip could be significant but is unconstrained without subsurface information. Similar east-facing scarps occur along the east flank of the Snake Mountains 45 km north of Wells (Ramelli and dePolo, this volume; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006).

Morphology of the eastern sides of the Ruby Mountains, East Humboldt Range, and Clover Hill is consistent with progressively less slip on the east-dipping fault system to the north and east. The Ruby Mountains have the largest and steepest eastern face, approximately 1500 m total relief in a distance of about 5 km perpendicular to the face. The east side of the East Humboldt Range has nearly as much relief, about 1400 m in 5 km, but lacks the deep hanging-wall basin. Clover Hill has only about 500 m total relief but over a shorter distance of about 2 km. These relations suggest that either the Ruby Valley fault has been active longest and faulting propagated northward over time—with the Clover Hill fault originating most recently—or that all three faults formed at the same time but have slipped at progressively lower rates, thus lesser total slip, to the north. Down-to-the-east faulting within or along the east side of the Snake Mountains has not generated a recognizable scarp, which suggests either it is particularly young or the rate of displacement has been consistently low. If the Clover Hill fault is propagating into the Snake Mountains or Town Creek Flat, it is cutting the west-dipping, basin-generating fault(s), e.g., the west Windermere fault, and may be reversing the eastward tilt. However, none of the east-dipping faulting has measurably reversed tilts in the Ruby Mountains or East Humboldt Range.

## Implications for the Wells Fault Zone

The Wells fault zone, whether a Mesozoic fault (Thorman and others, 1991), a Tertiary fault, or a Tertiary fault that reactivated a Mesozoic fault (Howard, 2003), crosses our proposed northern continuations of the Clover Hill fault at nearly 90° (figure 1). The west-northwest-striking magnetic and gravity boundaries identified by Ponce and others (this volume) are close to but slightly oblique to the geologically defined Wells fault and cross it near the epicenter of the 2008 Wells earthquake. Whatever the exact character and location of these structures, they could serve as rupture barriers for displacement along the Clover Hill fault, which would have implications for the length of fault that could slip in an earthquake and for the earthquake magnitude. We do not know how much of the Clover Hill fault slipped during the main earthquake, but aftershocks extended both north and south of the geologically and geophysically defined locations of the Wells fault zone. Thus, these structures did not act as rupture barriers for the total slip during the main earthquake and aftershocks.

### Implications for the Proposed Marys River Fault System

Both gravity data and implied low cutoff angles cast some doubt on the presence of the Marys River fault system as portrayed by Mueller and Snoke (1993), as present at shallow depths beneath Town Creek Flat. As shown in figure 2, Mueller and Snoke (1993) interpreted two strands of the Marys River fault system beneath Town Creek Flat. The shallower strand is at a maximum depth of less than 1 km and has unmetamorphosed Paleozoic and Mesozoic rocks in its footwall. The deeper strand is at a depth of about 1.5 km and has metamorphosed Paleozoic and Mesozoic rocks in its footwall. All these rocks should have high densities. However, the gravity data that show a depth to basement of 1.8 km (Ponce and others, this volume) preclude these rocks being at such shallow depths. Mueller and Snoke (1993) show the shallower strand surfacing along the east side of the Snake Mountains, coinciding with a fault mapped as a thrust by Thorman and others (2003). Also, Eocene and Miocene rocks throughout the area that were interpreted to be in the hanging wall of the low-angle Marys River fault dip no more than about 40° (plate 1, in appendix A of this volume). This would imply an abnormally low cutoff angle of less than 50° and commonly that the beds parallel strands of the Marys River fault system. For example, Eocene ash-flow tuffs dipping 20°-30° eastward rest depositionally on Paleozoic rocks in the eastern Snake Mountains just north of the Mueller and Snoke (1993) cross section in figure 2 (Thorman and others, 2003; confirmed by our observations). Mueller and Snoke (1993) apparently interpreted this contact to be the shallower strand of their Marys River fault system, which requires that the Eocene rocks dip parallel to the fault.

If such a low-angle fault were present below the Snake Mountains, it obviously would have “befooted” any east-dipping thrust faults. In this case, the footwall parts of the mapped thrust faults of the Snake Mountains would lie far to the east.

## SOME QUESTIONS FOR EARTHQUAKE GEOLOGISTS

If the Clover Hill fault is propagating into the Snake Mountains or Town Creek Flat, does this represent a significant structural change with real implications for earthquake hazards? Are the west-dipping faults that created Town Creek Flat basin dying out and being replaced by an east-dipping fault system? Both east- and west-dipping faults in Town Creek Flat and in the region have slipped in the Quaternary (Sharp, 1939; Dohrenwend and others, 1996; Wesnousky and Willoughby, 2003; U.S. Geological Survey and Nevada Bureau of Mines and Geology, 2006; dePolo, 2008; and Ramelli and dePolo, this volume), so whether such a change is happening is uncertain. Even if there is a change, it may be occurring over such a long time so as to be irrelevant for earthquake hazards on a human time scale.

More immediately, the Wells earthquake occurred on a fault that was only recognized in hindsight. Thorough mapping of the area might have revealed the faint east-facing scarp as evidence for an east-dipping fault zone, and the scarp was not recognized until after the earthquake (Ramelli and dePolo, this volume). A thorough, pre-earthquake study of the seismic potential of the region would also have recognized the many west-facing scarps and the dominant east tilt of the area. Much earthquake risk assessment is based on recognizing young fault scarps and attempting to assess their timing, frequency, and magnitude of slip, so would greater earthquake potential have been assigned to these abundant west-dipping faults? Both east- and west-dipping faults are probably close enough to Wells that a similar magnitude earthquake on either set may have affected the area similarly. But is one or the other fault set more likely to generate a damaging earthquake, either because of potential for a larger magnitude earthquake or because of a greater likelihood of recurrence? For example, are older structures such as the Wells fault zone more likely to segment and serve as rupture barriers to one or the other set of faults? Again, in terms of shaking intensity it may not matter if an earthquake occurs on an east- or west-dipping fault, but the specific fault may matter a great deal when assessing the potential for damage from the surface break itself. Although no surface break has been found for the Wells earthquake, the Clover Hill fault crosses U.S. Interstate 80 and the Southern Pacific railroad just west of Wells. A future surface-breaking earthquake on this fault or some other unrecognized Nevada fault could easily break and shut down these vital transportation corridors.

## ACKNOWLEDGMENTS

We appreciate informative discussions with Ken Smith, John Bell, Chuck Thorman, and Alan Ramelli and very helpful reviews by Keith Howard, Chuck Thorman, and Alan Wallace.

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