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Bedrock Geology of the Ranges Bounding the Wells Earthquake of February 21, 2008

by

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ABSTRACT

The Wells 6.0 magnitude earthquake of February 21, 2008, occurred on a previously unrecognized northeast-striking southeast-dipping fault situated beneath Town Creek Flat, a few miles north of Wells, Nevada. Focal depth of the earthquake was 5 miles (8 km). Bedrock geology in the surrounding ranges did not indicate the existence of the fault prior to the earthquake, and no surface rupture has been observed related to the earthquake. Faults with a similar trend and attitude had not been observed in the southern Snake Mountains. Correlation of the earthquake fault to structures south of Wells that bound the East Humboldt Range and Clover Hill is plausible. High-angle northwest-trending faults in the southern Snake Mountains and Windermere Hills, adjacent to the earthquake foci, may have been responsible for partitioning aftershocks.

This fault, referred to as the Wells earthquake fault (WEF), is an approximately 55° southeast-dipping normal fault (Smith and others, this volume). Its dip direction is opposite to that of most recognized Cenozoic (Neogene) high-angle faults in the immediate vicinity that are related to uplift of the Snake Mountains and Windermere Hills northwest and northeast of Wells, respectively. The geometry of the WEF was resolved by Smith and others (this volume) based on 3-D resolution of the main earthquake and subsequent aftershocks. The bedrock geology of the southern Snake Mountains, Windermere Hills, Clover Hill and northern East Humboldt, and Wood Hills, which bound the earthquake area, provided no suggestions that a fault, especially one capable of producing a large earthquake, was present at the surface location of the WEF. Attitudes of bedding-parallel faults and of stratigraphic units in the southern Snake Mountains are roughly parallel to the WEF, and thus, following the earthquake, it was initially postulated that there might be a relationship between the two. However, this does not appear to be the case. Rather, the earthquake fault may be related to a system of east-dipping normal faults south of Wells that bound the eastern flanks of the Ruby Mountains, East Humboldt Range, and Clover Hill (figure 1).

Aftershocks from the main earthquake were distributed in a belt extending north from Wells and occurred in two major clusters/groups with an intervening area of lower occurrence (figure 2). Based on bedrock geology in the southern Snake Mountains and Windermere Hills, we interpret the frequency distribution of the aftershocks to be influenced/controlled by two or more high-angle west-northwest-striking faults, rather than a single northeast-striking fault. This interpretation suggests that the west-northwest-striking faults are deep-penetrating structures and of regional significance, as proposed by Thorman and Ketner (1979). It follows that future earthquakes may occur where oblique high-angle faults intersect range-bounding faults in the Basin and Range Province. This paper focuses on the nature of the west-northwest-trending faults, their ages, recurrent movements, and lateral and vertical continuity.

In deciphering the geology of these ranges, comprehending the regional and local stratigraphy and structures is critical. As in much of the Basin and Range Province, it is impossible to do one without understanding the other.

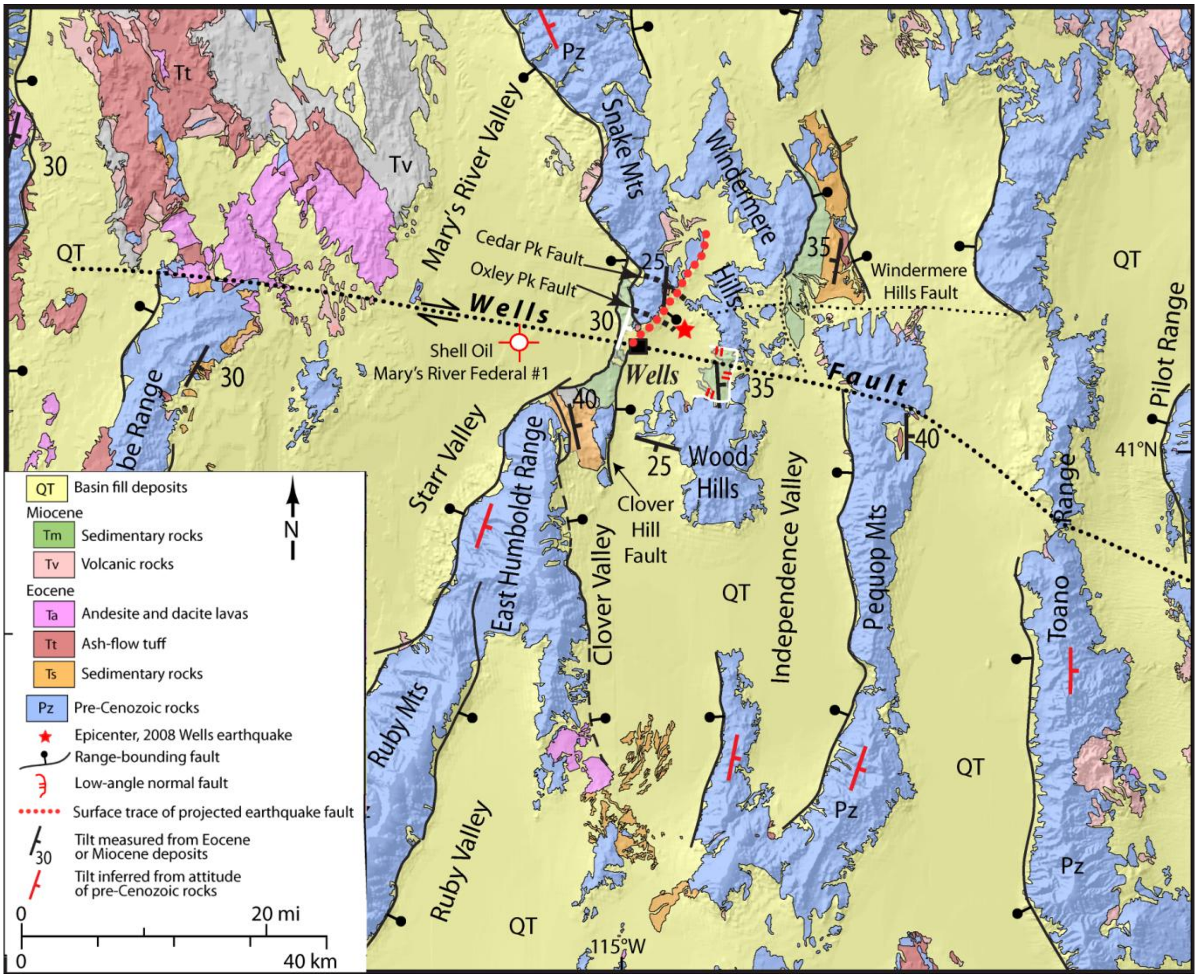


Figure 1. Index map modified from Henry and Colgan (this volume) showing epicenter of Wells earthquake (red star). Location of Shell Oil Co. Mary's River Federal No. 1 oil well that bottomed at 12,125 ft (3,696 m) is shown west of the town of Wells.

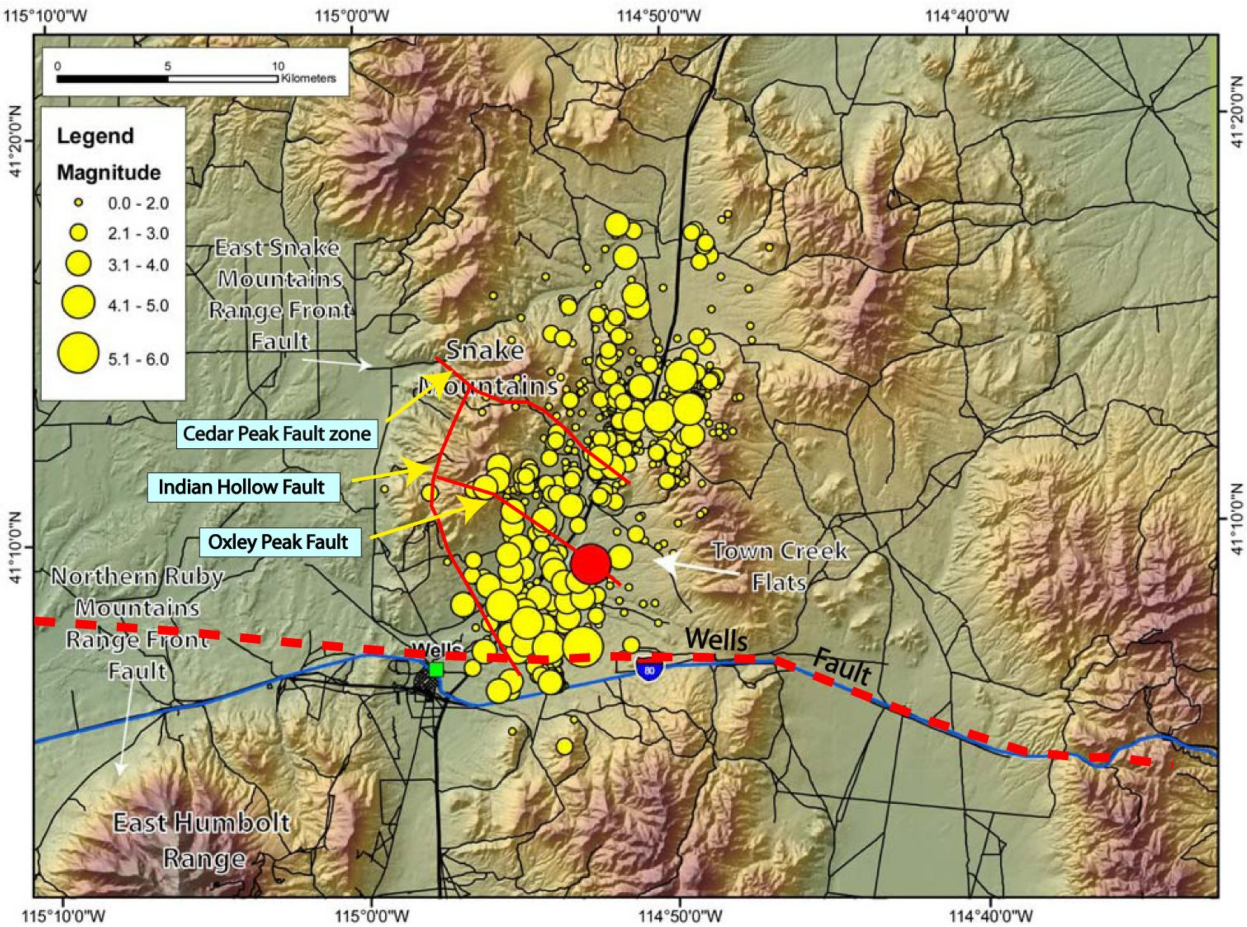
REGIONAL SETTING

The Wells earthquake, which was a response to the continual regional extensional tectonics that have formed the Basin and Range Province during approximately the past 20 million years, occurred along a fault that had not been recognized by previous surface mapping (Thorman, unpublished mapping, 1967–68; Thorman and others, 1991; Mueller, 1993; Thorman and others, 2003). A brief review of the regional structural setting sheds light on a possible relationship to similar structures south of Wells, as pointed out by Henry and Colgan (this volume). Three major structural elements come together in the vicinity of Wells, and the interaction between them plays an important role in understanding the regional setting of the Wells earthquake. These are the Ruby Mountains-East Humboldt Range, the Wells fault (not to be confused with the earthquake fault), and the Mary's River and Starr Valleys (figure 1).

Ruby Mountains-East Humboldt Range - As shown in figure 1, the east sides of the Ruby Mountains and East Humboldt Range are bounded by east-dipping normal faults (Sharp, 1942; Snelson, 1957). These ranges are part of the Ruby-East Humboldt metamorphic core complex that was exhumed from the Oligocene to the early Miocene (Sullivan and Snoke, 2007) and subsequently attained its present form in late Tertiary time. During the exhumation of the ranges, Paleozoic, Mesozoic, and early Cenozoic rocks, both metamorphic and nonmetamorphic, moved westward along a low-angle brittle-ductile normal listric/detachment fault zone an unknown distance. This detachment zone is marked by a prominent mylonite fabric/foliation that is generally interpreted to have formed in a subhorizontal position. The present geometry of the mylonite foliation in the northern Ruby Mountains and East Humboldt Range is that of north-trending, north-plunging en- échelon, asymmetric (steep on the east and gentle on the west) antiforms that are truncated on the east by major east-dipping normal faults. The west flanks of the ranges are bounded by west-dipping normal faults.

Topographic expression of the ranges is asymmetric, steep on their east flanks and gentle on the west flanks. This asymmetry and structural development of the Ruby Mountains and East Humboldt Range were both noted by Sharp (1939, 1942). Henry and Colgan (this volume) propose a direct relationship between the east-bounding normal faults of the East Humboldt Range and Clover Hill and the Wells earthquake fault.

Figure 2. Map showing superposition, in red, of west-northwest-trending high-angle faults (Thorman and others, 2003) on HYPODD relocations of Wells earthquake aftershocks (Smith and others, this volume, figure 4). We interpret these faults to have influenced the frequency distribution of the aftershocks into two main clusters: one south of the Oxley Peak fault and the other north of the Cedar Peak fault.



A closer look at these high-angle faults at the north end of the East Humboldt Range, just south of Wells, shows two faults that diverge. The western fault strikes northwest and terminates against a fault on the west flank of the range, and the eastern fault strikes northerly approximately through the town of Wells towards the east flank of the southern Snake Mountains (Henry and Thorman, plate 1, in appendix A of this volume). The eastern fault is herein referred to as the Clover Hill fault. If the Clover Hill fault, which this paper suggests is related to the Wells earthquake fault, extends north of Clover Hill, then it must pass through or west of Wells and continue along the east flank of the Snake Mountains.

Wells Fault - Thorman (1970) and Thorman and Ketner (1979) defined the Wells fault as a west-northwest-trending fault system with about 40 miles (65 km) of right slip (figure 1). The location of the fault was originally based on the juxtaposition of markedly contrasting structures and Paleozoic stratigraphic units in the Snake Mountains, Windermere Hills, and northern Pequop Mountains on the north against rocks of similar age in the northern East Humboldt Range, Wood Hills, and central Pequop Mountains on the south. The magnitude of slip was based primarily on the correlation of structures and stratigraphic units on opposite sides of the fault in the northern Adobe Range and the southern Snake Mountains, as well as on regional structures and stratigraphic trends. This is considered a fundamental fault system inherited from Precambrian basement structures that were reactivated numerous times in the Paleozoic (?), Mesozoic, and Cenozoic. Paleozoic movement along the Wells fault system may have occurred as vertical and/or horizontal movement, influencing sedimentation patterns, and/or as a simple flexural bend in the continental margin. The juxtaposed stratigraphic and structural relationships along numerous splays of the Wells fault system, as reflected in the bedrock geology of the region, is attributed to strike-slip faulting during Jurassic (Elko Orogeny) and/or Cretaceous (Sevier Orogeny) contraction. Subsequent movement, primarily vertical, occurred along several strands of the system in the Cenozoic. Such high-angle faults in other areas may have been responsible for the abrupt offsetting of range-front faults commonly observed throughout the Basin and Range Province, as shown by Stewart (1971) where he illustrates the nature of sets of east- and west-tilted ranges throughout the Province.

Mary's River Valley - The greatest structural relief in northeastern Nevada occurs where the Wells fault and the East Humboldt Range intersect west of Wells, a fundamental structural intersection. The structural relief between the crystalline basement rocks at the highest structural and stratigraphic point in the northern East Humboldt Range (south of the fault) to comparable rocks in Mary's River Valley (north of the fault) is on the order of 40,000+ ft (12,192 m). Metamorphosed Precambrian and Paleozoic rocks underlie the crest of the East Humboldt Range, but the Shell oil well[1] drilled in Mary's River Valley to a depth of 12,125 ft (3,696 m) north-northwest of the range-bounding fault that delimits the northwest side of the range, did not penetrate Paleozoic rocks. We interpret this structural relief to be mostly due to the Wells fault system.

The Mary's River Valley fault system formed as a westward-directed listric normal fault along the west side of the Snake Mountains (Effimoff and Pinezich, 1981). We interpret the Wells fault to have acted as a partition that permitted independent development of structures north and south of it. The Ruby-East Humboldt terrain was uplifted tens of thousands of feet more on the south side of the Wells fault than the terrain beneath Mary's River Valley to the north; we believe the magnitude and nature of extension related to the faulting was markedly different north and south of the fault. Starr Valley, south of the Wells fault, is shallower than the Mary's River Valley north of the fault. The Ruby Mountains and East Humboldt Range are tilted to the west (the mylonite fabric/foliation dips 20° to 40° westerly), whereas the Snake Mountains are tilted to the east 35° to 45° based on the attitude of Miocene and concordant Eocene and Paleozoic rocks.

STRUCTURE – STRATIGRAPHY

Major structures mapped in the ranges that bound Town Creek Flat, site of the Wells earthquake, include: (1) Paleozoic(?) and Mesozoic easterly-directed, younger-over-older and older-over-younger bedding-parallel thrust faults; (2) coeval(?) west-northwest- to west-trending high-angle strike-slip faults interpreted to be genetically related to, and coeval with, the thrust faults (e.g., the Wells fault); and (3) Cenozoic west-dipping, north-trending, high-angle normal faults and rejuvenated west-northwest-trending faults. The thrust and strike-slip faults were formed during contractional Paleozoic and Mesozoic deformation and control the areal distribution of pre-Cenozoic lithotectonic units. Locally, the strike-slip faults were rejuvenated during the Cenozoic. We suggest that these strike-slip faults are deep penetrating features and had a role in controlling/partitioning the areal distribution of the Wells earthquakes.

The Cenozoic west-dipping north-trending high-angle normal faults are responsible for the present range and valley geomorphic expression of the region. A west-dipping listric normal fault (Thorman, unpublished mapping, 1967–68; Thorman and others, 1991; Mueller, 1993) that surfaces on the east side of Town Creek Flat may have an important relationship to the earthquake. The development of these faults is discussed below. In addition, Mueller (1993) interprets a series of low-angle faults in the Windermere Hills to be detachment faults that had westerly-directed movement related to the Tertiary extensional faulting coeval with uplift of the Ruby-East Humboldt metamorphic core complex; we propose an alternate explanation for these low-angle faults below.

Central Nevada to western Utah has undergone at least five east-directed deformational events beginning with the Devonian-Mississippian Antler Orogeny during which siliciclastic/western facies rocks were thrust eastward over carbonate/eastern facies rocks. Subsequent Paleozoic orogenies include the Pennsylvanian Humboldt and Permian-Triassic Sonoma Orogenies. During the Mesozoic, two more orogenies affected the region, the Middle Jurassic Elko and medial Cretaceous to early Tertiary Sevier Orogenies. No data, at the present time in the area under consideration, allow us to determine how many of these orogenies caused the structures discussed below, though most likely at least the Antler and Elko and/or Sevier Orogenies were involved.

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[1] *This is based on the vertical distance between the crest of the East Humboldt Range at ~11,000 ft (~3,355 m) and the bottom of Shell Oil Co.'s Mary's River Federal No. 1 oil well in sec. 30, T38N, R61E which bottomed in possible Paleozoic rocks at 12,125 ft (3,696 m), a difference of 23,000 ft (7,010 m). The Shell well most likely penetrated only Cenozoic rocks. In addition, a possible thickness of upper Precambrian to Triassic strata is in excess of 15,000 ft (4,572 m) if a complete section is present, which is unlikely. Also, the depth to crystalline basement, as seen in the East Humboldt Range, would be even greater. Thus, a figure of 40,000 ft (12,192 m) is used as an estimation of total stratigraphic separation or structural relief.*

Ordovician to Recent sedimentary and volcanic rocks underlie the mountain ranges and valley that mark the site of the Wells earthquake of February 21, 2008. Pre-Cenozoic rocks are divided into distinct stratigraphic successions that are bounded by a combination of low-angle thrust faults, high-angle west- to northwest-trending tear or strike-slip faults, and north-trending high-angle normal faults (figure 3). These stratigraphic successions are differentiated on the basis of their depositional environment, ages, and present areal distribution.

The Ordovician to Devonian strata comprise two markedly different successions based on their depositional environment. Carbonate facies rocks were deposited along the western margin of the North American continent in generally shallow marine conditions on the continental shelf and primarily include limestone and dolomite, with minor sandstone and shale. In contrast, coeval siliciclastic facies rocks were deposited in deeper water an unknown distance to the west of the carbonate facies on the continental slope and rise and primarily include shale, siltstone, and chert, with subordinate limestone and sandstone.

A major structural element of the Antler Orogeny is the Roberts Mountains thrust fault (RMT), along which siliciclastic facies rocks were transported eastward over carbonate facies some unknown distance, generally accepted to be on the order of more than 100 miles (160 km). The upper plate is referred to as the Roberts Mountains Allochthon (RMA). This basic terminology is used herein, but only as a descriptive and not an age indicator because the RMA is juxtaposed against rocks as young as Triassic in this area, which presumably occurred during a post-Antler deformational event. In the southern Snake Mountains, siliciclastic rocks (the RMA) were thrust over Upper Mississippian Melandco sandstone along a major thrust (RMT) and are juxtaposed against Triassic strata along a high-angle tear/strike-slip fault that is unconformably overlain by Eocene limestone and volcanic rocks. This juxtaposition of the RMA was post-Antler and related to a Mesozoic event or events.

Thus, in this part of Nevada, siliciclastic facies rocks of the RMA were last deformed in post-Triassic to pre-Eocene time, in contrast to many locales in north-central Nevada where no post-Mississippian deformation of Roberts Mountains Allochthon siliciclastic facies rocks has occurred. We interpret the siliciclastic facies rocks in the Snake Mountains to have been deformed and thrust eastward initially during the Antler Orogeny based on regional considerations, but there is no evidence in the range to confirm this. It is important to note that this inferred relationship and the lack of definitive information in this part of Elko County hinders us in refining the sedimentary and structural record.

Low-angle, near-bedding-parallel thrust faults are dominant structures (both older-over-younger and younger-over-older faults) in the Snake Mountains, Windermere Hills, and Wood Hills. Disrupting this thrust fault terrain are strike-slip, or tear, faults in the Snake Mountains and Windermere Hills, but such strike-slip/tear faults are absent in the Wood Hills south of the Wells fault. These strike-slip faults were active during the Mesozoic and may have been active during the Paleozoic. They juxtapose markedly different stratigraphic sequences, including the siliciclastic and carbonate sequences, and structures in both ranges. Following are descriptions of the stratigraphic and structural features and their interpreted sequence of formation in the three ranges that bound Town Flat.

Southern Snake Mountains - Two major structural plates separated by the RMT underlie most of the range. The lower plate rocks include Ordovician to Devonian carbonate facies rocks and overlying Mississippian Tripon Pass Limestone and Melandco sandstone. The upper-plate rocks (RMA) include two distinct sedimentary packages, Ordovician to Mississippian siliciclastic facies rocks and overlying post-RMA Permian Murdock Mountain Formation limestone and Triassic Thaynes Formation shale and limestone (figures 3 and 5).

Three west-northwest-trending strike-slip faults/fault systems cut the southern Snake Mountains, dividing it into four structural domains juxtaposing contrasting structures and stratigraphy. From south to north, these are: the Oxley Peak fault, the unconformity fault system, and the Cedar Peak fault system (figures 3, 4, and 5).

Limestone of the Permian Murdock Mountain Formation rests unconformably on the siliciclastic rocks in the northeastern part of the range north of the Cedar Peak fault, along a strike length of approximately five miles (figures 4 and 5, north of Cedar Peak fault; Henry and Thorman, plate 1, in appendix A of this volume). The siliciclastic rocks below the unconformity are complexly deformed, whereas the overlying Murdock Mountain Formation does not reflect this deformation. Here in the southern Snake Mountains, the unconformity has a hiatus ranging from Late Devonian to Middle (Guadalupian) Permian and corresponds to a Late Pennsylvanian event that extends from the northern Basin and Range to Arizona. In contrast, the unconformable stratigraphic hiatus is almost nonexistent in several areas south and east of the Snake Mountains. Furthermore, deposition of Permian strata on siliciclastic rocks was recognized by Steele (1959 and personal communication, 1962) and referred to as the “Northeast Nevada High”. Across northeastern Nevada, rocks below this unconformity range in age from Silurian–Devonian to Middle Pennsylvanian and those above the unconformity from Late Pennsylvanian to Late Permian (Steele, 1959).

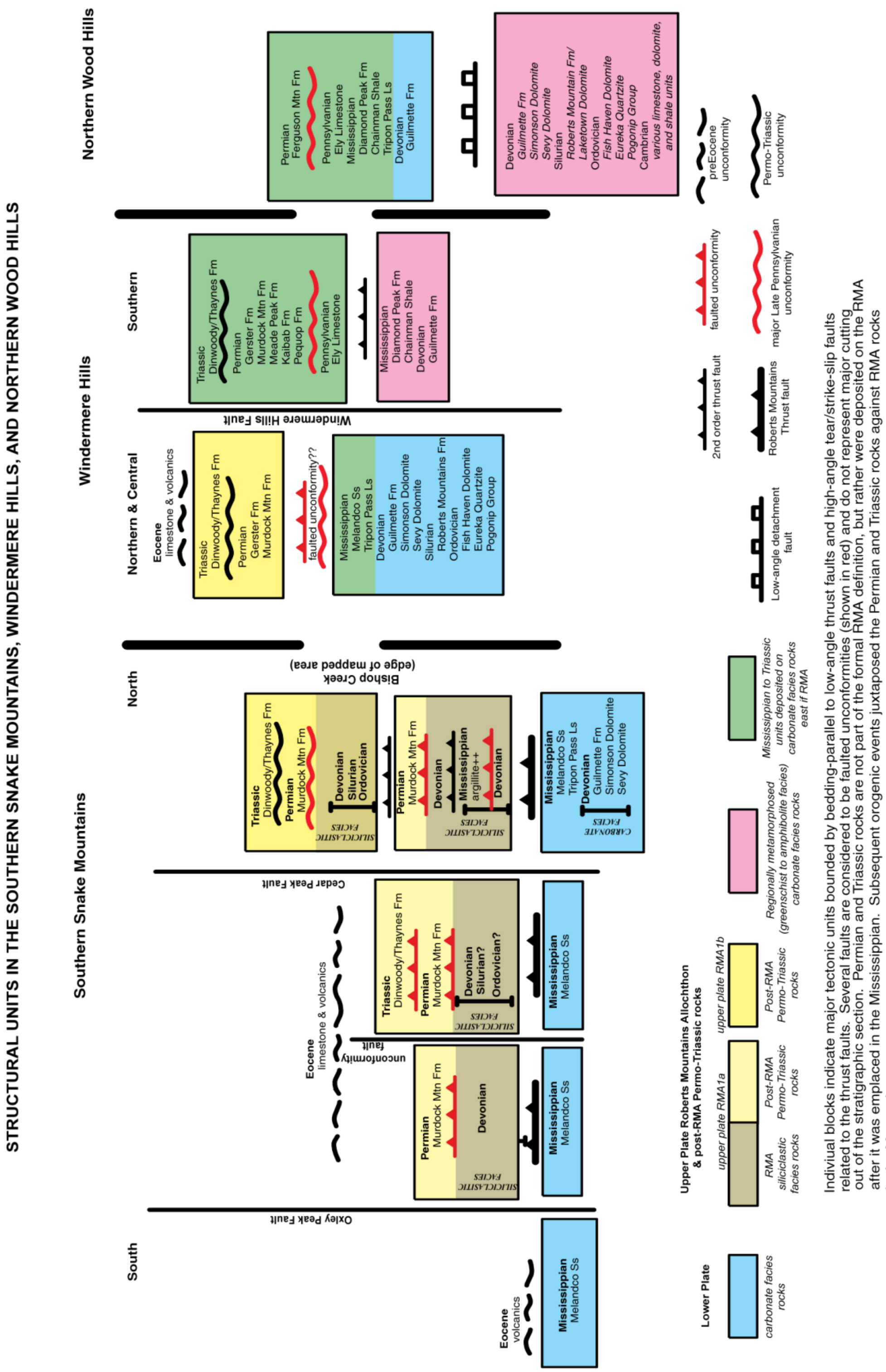

Figure 3. Structural plates and stratigraphic units contained in each structural plate in the southern Snake Mountains, Windermere Hills, and Wood Hills.

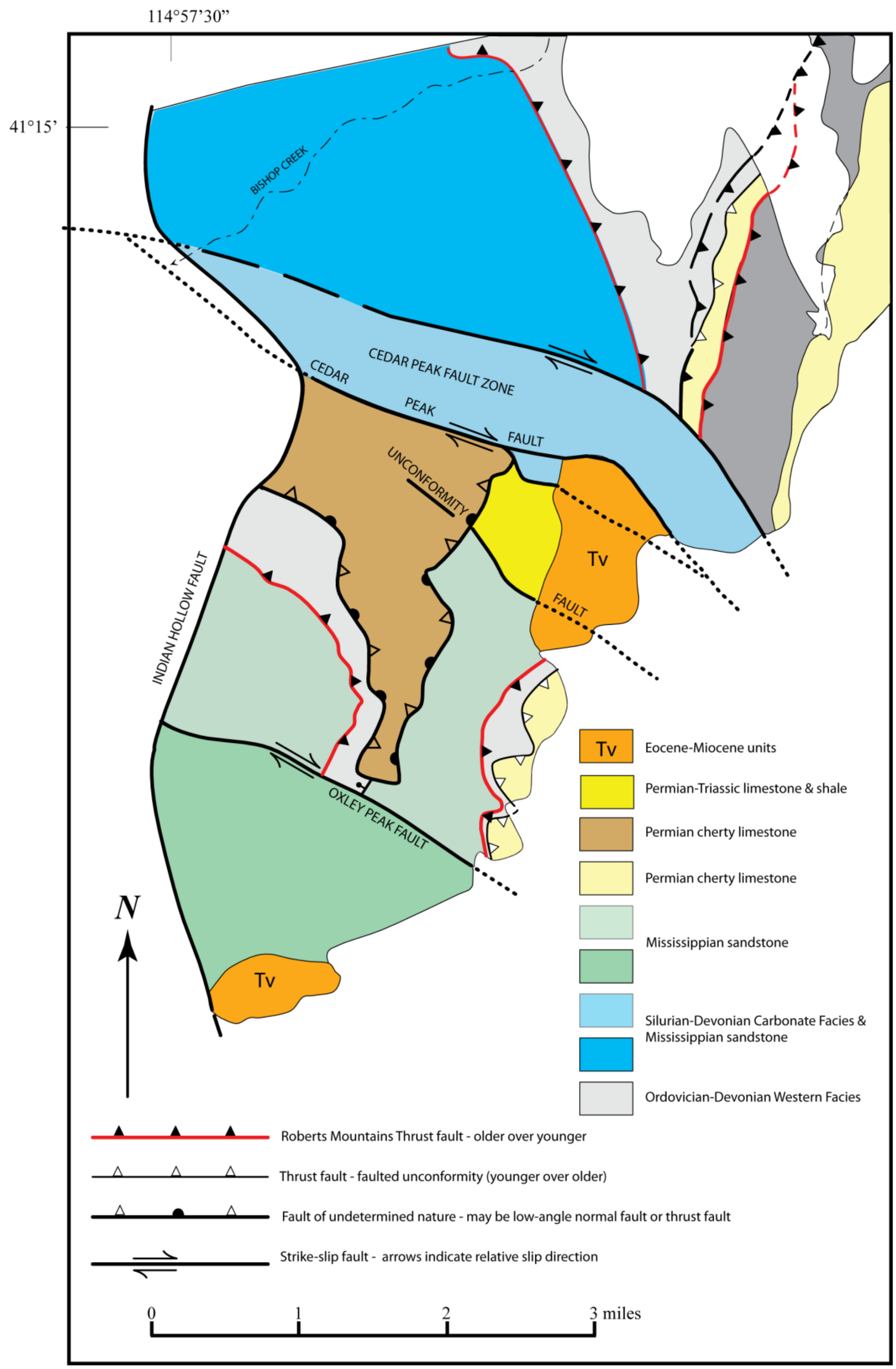

Figure 4. Simplified litho-tectonic map of the southern Snake Mountains showing the major faults in the range, the areal distribution of major structural plates, and their contained lithologies. See figures 3 and 5 for names of formations contained in each structural unit.

The upper plate (RMA) has been repeated twice between the Cedar Peak fault system and Bishop Creek. In the lower of the two repetitions (figure 5, RMA 1a), the Murdock/siliciclastic unconformable contact proved, during later compressional deformation, to be structurally weak and locally became a thrust fault. Due to structural complexities in the siliciclastic rocks, it is not possible to determine the magnitude of this disruption. However, the fact that the Murdock rests depositionally on the siliciclastic units in the upper repeated plate (figure 5, RMA 1b) indicates that this is not a major fault and thus is shown on the geologic compilation map of the Wells area, prepared for this volume (Henry and Thorman, plate 1, in appendix A of this volume), as a second-order structure. This faulted unconformity is not, in our consideration, a low-angle normal (detachment) fault of Cenozoic age that has cut out intervening strata. However, if one is unfamiliar with the regional stratigraphy, then this relationship might be interpreted as a major low-angle/detachment fault with large-scale stratigraphic separation of unknown thickness with the middle to late Paleozoic section being tectonically cut out. In addition, an unnamed Mississippian argillite occurs as a tectonic sliver within the siliciclastic imbricated rocks. This entire succession of rocks narrows to the south and is terminated at the Cedar Peak fault system.

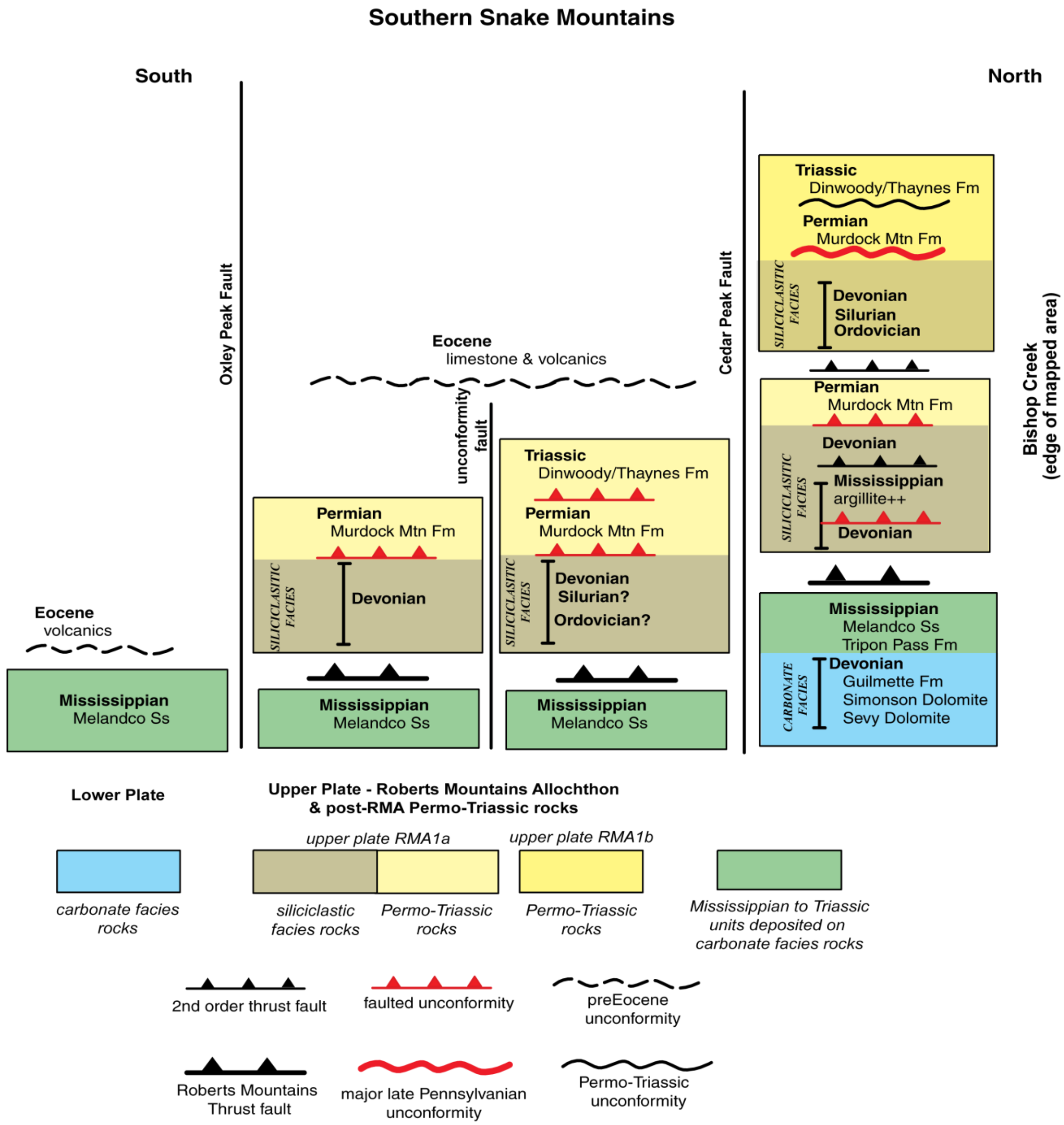

Figure 5. Diagram showing the structural and Paleozoic units in the southern Snake Mountains. Blue boxes represent the autochthonous strata beneath the Roberts Mountains thrust, and include carbonate facies rocks and overlying Mississippian strata. Dark yellow-tan boxes are the siliciclastic upper-plate rocks of the Roberts Mountains Allochthon, and the light to bright yellow boxes are Permo-Triassic rocks that unconformably overlie them.

Between the Oxley Peak and Cedar Peak faults, the upper plate (RMA) is exposed on the east and west sides of the range. This repetition is due to a north-trending, west-dipping high-angle fault exposed on the south slope of Oxley Peak that repeats the upper and lower plates. A plate of moderately deformed and highly silicified Permian Murdock Mountain Formation covers this high-angle fault and is smeared along the crest of the range from Oxley Peak north to the Cedar Peak fault system. The tectonic origin of this plate is not clear. The base of the plate may be a thrust fault, a low-angle normal fault, or a combination of the two. A northeast-plunging, southeast-vergent fold in the Murdock Mountain Formation is at the base of this upper plate on the west side of the range. And, the geometry of the RMT northwest of Oxley Peak is a broad, open, northeast-plunging antiform. These folds have the same general orientation as small-scale folds in the Tripon Pass Limestone in Bishop Creek Canyon and in Ordovician carbonate facies rocks at Antelope Peak in the central Snake Mountains (north of Bishop Creek), which is suggestive that these folds are related to east- to southeast- directed contractional deformation of Mesozoic age (Elko and/or Sevier orogenies).

Both the lower and upper plates continue to the north in the Snake Mountains for many miles and include a wide range of units not observed south of Bishop Creek. Ordovician, Silurian, and Devonian units of the lower plate are exposed in windows on the west side of the central and northern Snake Mountains beneath the RMT (Smith and others, 1983; Gardner, 1968; Coats, 1987). Mapping by Gardner (1968), Smith and others (1983), and McFarlane (2001) has shown that a wide range of upper plate RMA units are preserved in a structurally complex fashion. The RMA thins tectonically to the south of Bishop Creek Reservoir between several thrust faults. Overlying the RMA in a normal depositional position is the middle Permian Murdock Mountain Formation and younger Permian and Triassic units.

Windermere Hills - Structural and stratigraphic settings in the Windermere Hills are, in part, correlative to those in the Snake Mountains (figure 6). The range has Ordovician to Devonian carbonate facies rocks, which are equivalent to those in the Snake Mountains, but lacks siliciclastic facies rocks. Lower Mississippian Tripon Pass Limestone is overlain by the Melandco sandstone. Structurally overlying the Melandco is the Permian Murdock Mountain Formation along a low-angle fault (Mueller, 1993). This same relationship is observed in the Snake Mountains in the lower repeated RMA (RMA 1a), except that there the Murdock is in the upper plate and rests on siliciclastic facies rocks. Numerous bedding-parallel faults are present and a major west-striking strike-slip fault, the Windermere Hills fault, divides the range into two contrasting stratigraphic/structural domains.

The carbonate facies rocks north of the Windermere Hills fault are overlain by the same Mississippian units that overlie carbonate facies rocks in the Snake Mountains. The next youngest units recognized in this part of the range by Mueller (1993) are the Upper Permian Murdock Mountain and Gerster Formations. Missing are Upper Mississippian to Middle Permian units, which occur south of the Windermere Hills fault. Mueller interprets the lack of rocks of this age to be due to normal extensional faulting along which Upper Mississippian to Middle Permian units were cut out. We suggest, based on our regional studies, that this is not the case, but rather that this is a faulted unconformity (Northeast Nevada High of Steele, 1959 and personal communication, 1962) similar to what was observed in the Snake Mountains, and that the 'missing units,' if they were deposited in the area, were subsequently eroded during uplift of the Northeast Nevada High. Thus, in our interpretation, the northern Windermere Hills are structurally and stratigraphically similar to the Snake Mountains in that a large removal of strata is not required to explain the juxtaposition of Middle Permian Murdock Mountain on Mississippian Melandco sandstone.

In the southern part of the Windermere Hills, south of the Windermere Hills fault, Mississippian through Permian rocks comprise a distinctly different stratigraphic succession from that to the north. Metamorphosed Upper Devonian (Guilmette Formation) and Mississippian (Chainman Formation and Diamond Peak Conglomerate), and possibly unmetamorphosed Lower to Middle Pennsylvanian (Ely Limestone), structurally underlie Leonardian (upper lower Permian) Pequop Formation to Lower Triassic Thaynes/Dinwoody. The only contact between the upper and lower plates south of the Windermere fault is at Wells Peak where Permian Gerster rests on metamorphosed Chainman. The Chainman and Diamond Peak Formations, which are not present north of the Windermere Hills fault, are lithologically similar to Chainman-Diamond Peak rocks in the northern Pequop Mountains, the next range to the east. Rocks in the upper plate are like those in the northern Pequop Mountains, where the section appears to be relatively undisturbed (Thorman, 1970). Thus, this low-angle fault appears to have not removed a thick stratigraphic succession.

Triassic strata (Thaynes or Dinwoody? Formation) overlie the Murdock Mountain Formation in the Snake Mountains and Windermere Hills. There may be additional stratigraphic differences in the upper Paleozoic between the northern and southern Windermere Hills, but it is beyond the scope of this report to discuss these complexities.

The Windermere Hills fault is herein considered to project eastward just north of the end of the Pequop Mountains and to be a major strike-slip fault that was reactivated in Miocene and/or younger time, against which the northern Pequop Mountains terminate.

Wood Hills - This low range, which lies south of the Wells fault, forms the southeastern boundary of Town Creek Flat and is underlain by a succession of regionally metamorphosed and folded Cambrian through Devonian carbonate facies rocks (Thorman, 1970; Camilleri, 1994; Camilleri and Chamberlain, 1997) and tectonically overlying isolated unmetamorphosed Devonian to Lower Permian and Eocene-Miocene blocks (figure 7). At the juncture between the Windermere Hills and the northeastern Wood Hills in Town Creek Flat, a succession of Miocene fluvio-lacustrine and

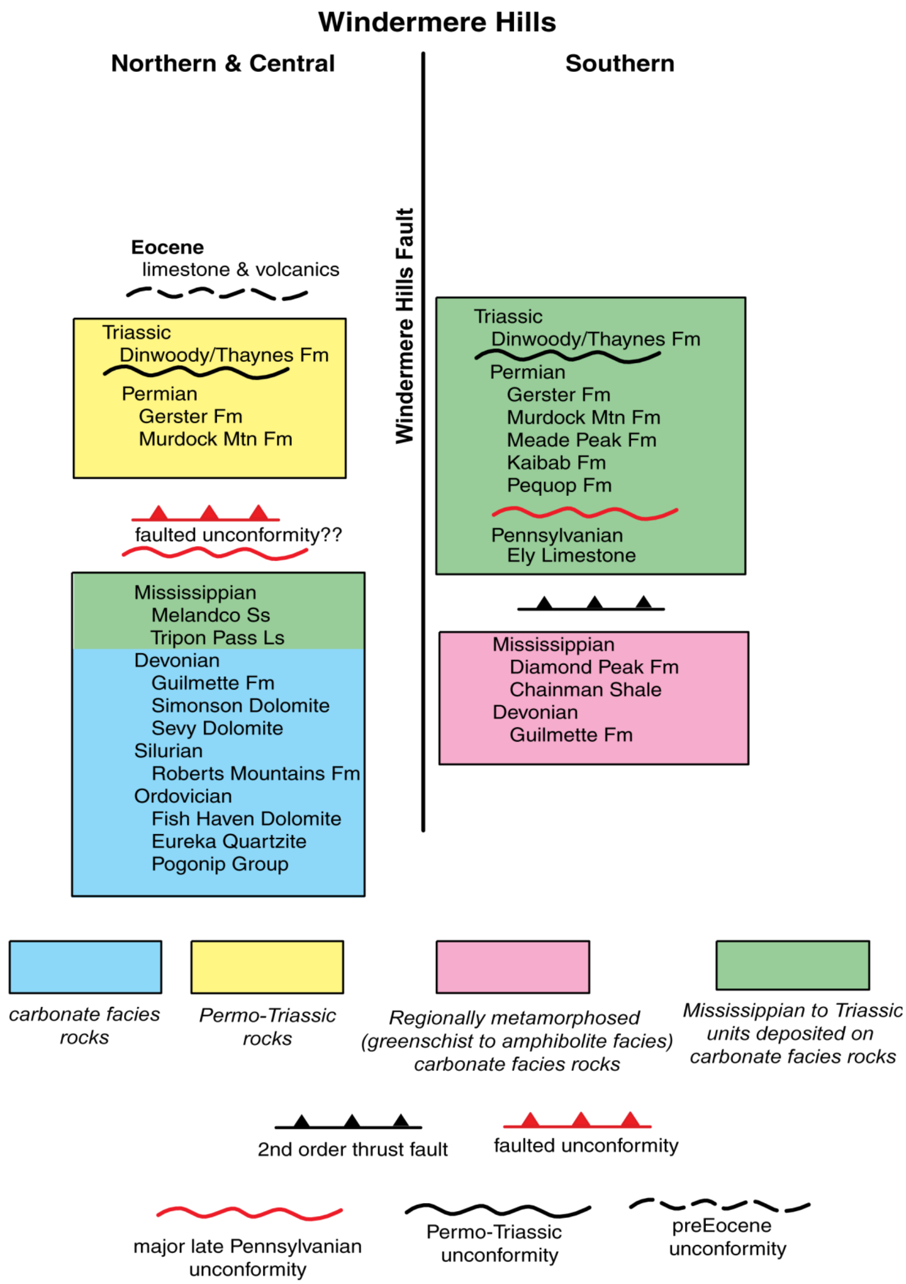

Figure 6. Diagram showing the structure and Paleozoic to Triassic units in the Windermere Hills. The green box shows the unmetamorphosed units of the upper plate of a second-order thrust fault south of the Windermere Hills fault; the only depositional? contact between the upper and lower plates is Gerster Formation resting on Chainman/Diamond Peak. North of the Windermere Hills fault, Murdock Mountain rests tectonically on Melandco sandstone.

volcanic ash units (Tts on map, Henry and Thorman, plate 1, in appendix A of this volume) dip moderately eastward into underlying Paleozoic rocks along a west-dipping listric normal fault (Thorman, 1967–68, unpublished mapping; Thorman and others, 1991; Mueller, 1993). The northern end of the Wood Hills is underlain by south-dipping Cambrian–Ordovician marbles and quartzite. In the northwest corner of the range, unmetamorphosed Devonian through Lower Permian rocks are moderately faulted. Similar rocks are present on the eastern flank of the East Humboldt Range, a few miles to the west. Lithologically, they are strikingly different from rocks of the same age in the southern Snake Mountains and Windermere Hills, north of the Wells fault. For example, siliciclastic facies rocks are north of the fault and not on the south, and Mississippian through Permian strata south of the fault are typical of the carbonate facies terrain and are not present on the north. This is one of the criteria for projecting the Wells fault between the Snake Mountains and the Wood Hills-East Humboldt Range. Along this trend, in the vicinity of the town of Wells, Miocene and younger fluvial lacustrine and volcanic rocks conceal the projected trace of the Wells fault (see plate 1, Henry and Thorman, in appendix A of this volume).

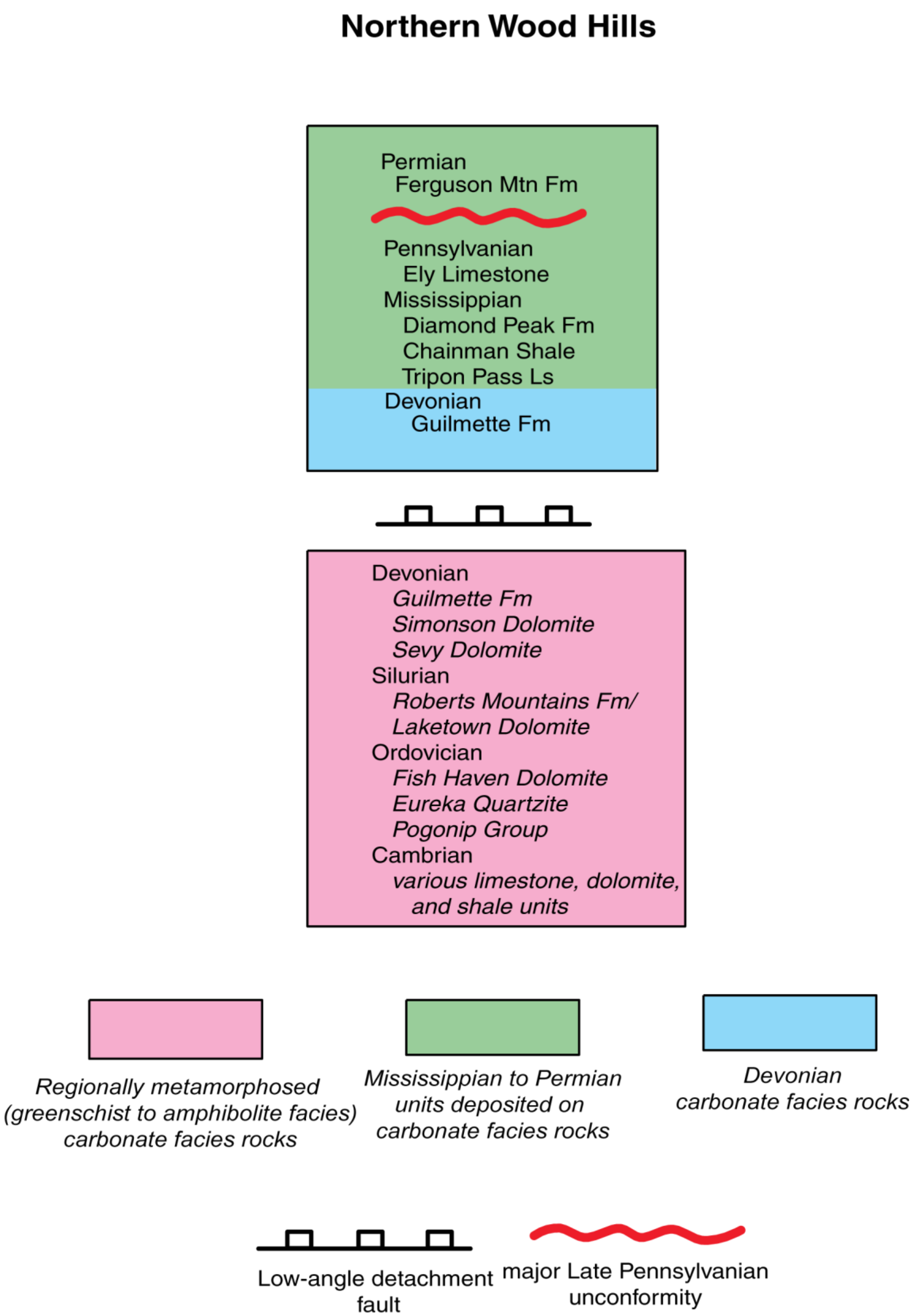

Figure 7. Diagram showing the structural and Paleozoic units in the Wood Hills. The green and blue box shows unmetamorphosed units of the upper plate of a low-angle detachment fault of probable Miocene age. Strata of the Guilmette Formation, Ely Limestone, and Ferguson Mountain each rest tectonically on lower-plate rocks in separate fault blocks.

RELATIONSHIP OF HIGH-ANGLE FAULTS TO WELLS EARTHQUAKE

The documented high-angle west-northwest-striking strike-slip/tear faults in the southern Snake Mountains project to and through the area of the Wells earthquake and its aftershocks. The orientation of these faults is very similar to that of the aftershock clusters, and we propose that they had an influence/partitioning effect on the frequency distribution of the Wells aftershocks. These faults have strike-slip displacements, are parallel to or at low angles to the Wells fault, and are considered to be part of the greater Wells fault system, a major west-northwest-striking right-slip fault that we believe was inherited from the Precambrian basement and reactivated numerous times during the Paleozoic(?), Mesozoic, and Cenozoic. All of these strike-slip faults occur north of the main Wells fault in the area under consideration. Several factors are presented in support of this apparent partitioning effect. First, the aftershocks occur north of the Wells fault (figure 2). Second, the frequency distribution of the aftershocks (figure 2) forms two crude clusters, one south of the Oxley Peak fault and the other north of the Cedar Peak fault. The lowest frequency of aftershocks is between the Oxley Peak and Cedar Peak faults. Third, the continuation of the Cedar Peak fault to the northwest into the Mary's River Valley (Ponce and others, this volume) indicates that these secondary Wells fault structures are deep features and can have strike lengths of tens of miles. The following observations and speculations are intended to provoke thought into future earthquake research regarding the correlation between relative ages of cross faults to major earthquake slip surfaces and how the two may interact.

The aftershocks, with the exception of a few small events (figure 2), are north of the Wells fault along the northeast-striking Wells earthquake zone (Smith and others, and Ramelli, this volume) for approximately 15 miles (25 km). The nearly total restriction of the earthquake events to north of the Wells fault is, in our opinion, a strong indication that the Wells fault is a fundamental structural feature that extends to great depth (Henry and Thorman, plate 1, in appendix A of this volume). The suggestion by Henry and Colgan (this volume) that the Wells earthquake fault zone is the northern continuation of the Clover Hill fault is logical as the two faults have the same general northeast strike and southeast dip, and are down-to-the-southeast normal faults. The projected continuation suggests that no lateral slip has occurred on the Wells fault in this area since the most recent uplift of the Clover Hill and the Snake Mountains. Lateral slip may have occurred on the Wells fault during the Cenozoic in the immediate area; research into such possible movement needs to be carried out through detailed mapping along the fault in the Wells area. At least two Wells fault zone structures – the Oxley Peak and Cedar Peak faults and possibly the eastern end of the Windermere Hills fault at the north end of the Pequop Mountains – were reactivated during Basin and Range development in Miocene and younger events.

The aftershocks display two major frequency distributions, one south of the Oxley Peak fault and the other north of the Cedar Peak fault (figure 2). Fewer aftershocks have taken place between these two faults. The reason for this distribution is uncertain, but it may be related to the nature of the two faults. Aftershocks occurred at depths ranging from near surface to more than 7.5 miles (12 km) (Smith and others, this volume). Both faults had post-Miocene slip, as evidenced by offset Miocene volcanic rocks, whereas the youngest faulting in the block between them was pre-Eocene as indicated by Eocene volcanic and sedimentary rocks unconformably resting on faulted Paleozoic and Triassic units (Thorman and others, 2003). The southern termination of the aftershocks is bounded by the southeastward extension of the Indian Hollow fault, which juxtaposes Paleozoic and Miocene units.

Gravity data in Ponce and others (this volume, reproduced here as figure 8) show a major structure in the basement of Mary's River Valley with right slip that projects directly into the Cedar Peak fault of Thorman and others (2003). As discussed above, the Cedar Peak fault juxtaposes contrasting tectonic and stratigraphic units and is thus a major structural feature. The projection of the fault into Mary's River Valley is approximately 20 miles (32 km). In addition, they indicate that the Cedar Peak fault, or some related feature, projects 12 miles (20 km) to the southeast. This suggests that the fault is an extensive, deep penetrating feature. More work needs to be done to determine the significance and magnitude of this fault.

CONCLUSIONS

The 6.0 Wells earthquake of February 21, 2008, occurred along a northeast-trending, southeast-dipping normal fault that previously was unrecognized, despite detailed mapping in all surrounding areas by numerous workers. The frequency distribution of aftershocks along the Wells earthquake fault is interpreted to have been influenced by pre-existing high-angle northwest- to west-northwest-trending faults that are part of the Wells fault system and that were reactivated in post-Miocene time. This suggests that these faults extend to great depth, perhaps in excess of 7.5 miles (12 km). Future research regarding the distribution of aftershocks should consider the possible influence of intersecting faults with the main earthquake fault and the relative stability of blocks between the intersecting faults.

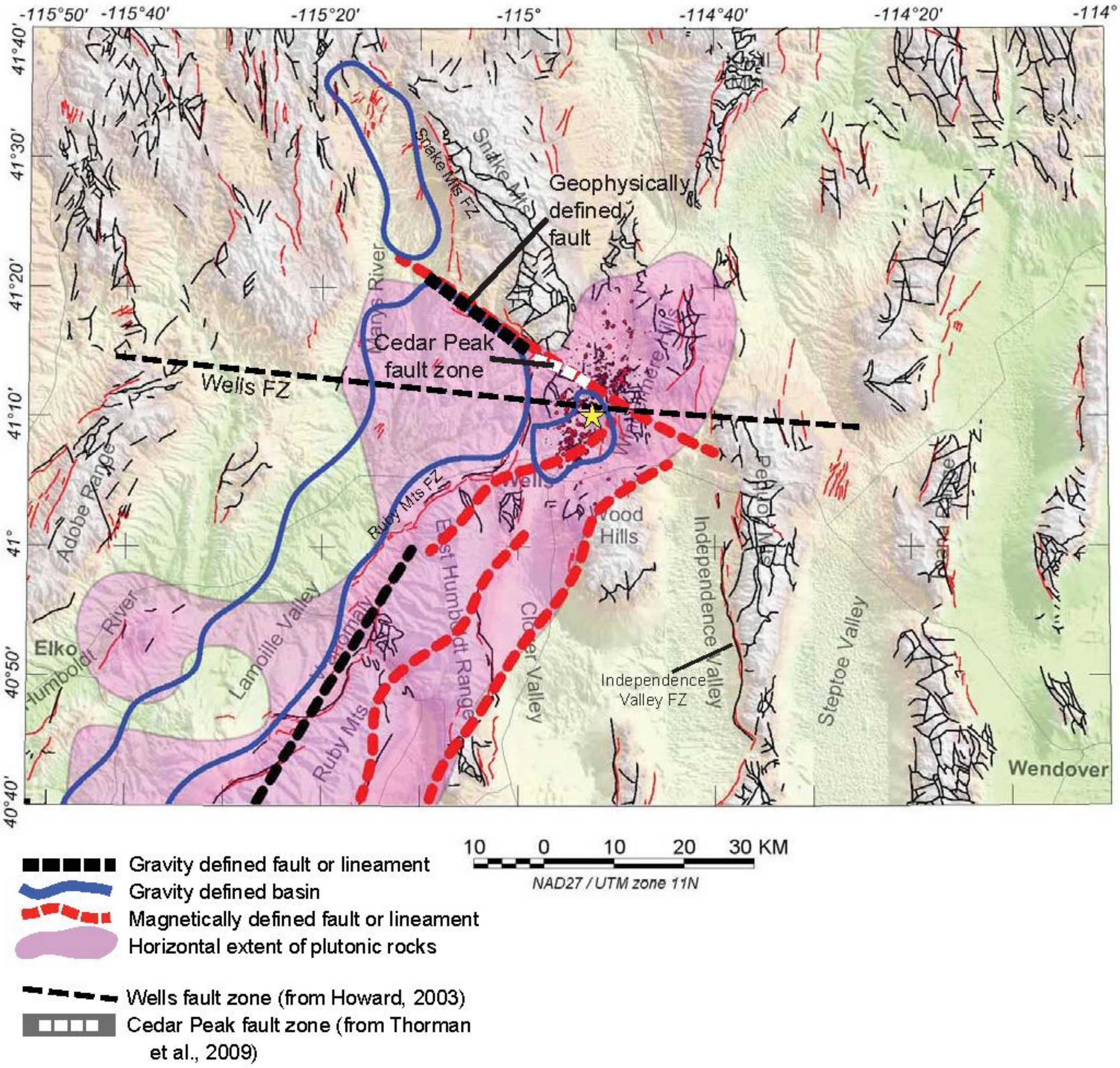

Figure 8. Map from Ponce and others (this volume) showing location of a geophysically-defined west-northwest-trending fault in Mary's River Valley that projects into the Cedar Peak fault zone (white dashed line) mapped by Thorman and others (2003) in the southern Snake Mountains. This supports the premise of the high-angle northwest to west-northwest-trending faults to be major structural features that penetrate to great depth.

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