Working to Protect Native Species and Their Habitats

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September 17, 2012

John Russell, Project Manager
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Via email to Lost_Crk_Mine_WY@blm.gov

Dear Mr. Russell:

The following are the additional comments of Biodiversity Conservation Alliance, Californians for Western Wilderness, and Western Watersheds Project on the Lost Creek In Situ Leaching Uranium Project Final EIS. These comments supplement our comments during the Draft EIS comment period. We ask BLM to respond to both sets of comments pursuant to NEPA's mandates during the course of this NEPA process. In our Draft EIS comments we included a great deal of applicable scientific findings, which we will not repeat here, but we do ask BLM to examine in detail each scientific article cited in the Literature Cited section of these comments. In addition, we would have BLM review our comments on the Nuclear Regulatory Commission NEPA process for this same project, which we have attached to our FEIS comments as Attachment 1. These comments supplement our Draft EIS comments, and we ask BLM to respond to both sets of comments to the extent that the agency has not already done so.

Analysis of traffic impacts in the EIS is invalid

BLM reports a sevenfold increase in estimated tractor-trailer traffic, from 2-5 tractor-trailers per week as published in the Draft EIS to 2-5 tractor-trailers per day, attributing this to "an error in reporting." FEIS Appendix F-34. The impacts analysis for sage grouse and other sensitive wildlife is predicated on the lower level of traffic, and does not appear to have been adjusted to reflect the greater level of traffic disclosed in the FEIS Response to Comments. BLM has not shown that it has adjusted its Impacts Analysis sections for various sensitive resources (e.g., air quality, wildlife) to reflect the actual much heavier amount of truck traffic that has been disclosed in the Response to Comments section of the FEIS.

BLM concedes "The major concern regarding the East and West Access Roads is their location with respect to sage-grouse leks." FEIS 2-94. Both proposed access roads do pass through 0.6-mile buffers for active leks. FEIS at 2-96. BLM notes that WDFG "determined" that reconstructing the proposed East and West Access Roads would have less impact than constructing or reconstructing other roads for access. *Id.* However, WGFD did no actual data

analysis nor did they rely on any scientific information in reaching this "determination;" it was merely an opinion. We find this determination arbitrary and capricious of WGFD, and it merits little deference in the FEIS process. During the EQC process, WGFD used the original traffic data presented in the Draft EIS, not the increased heavy truck traffic disclosed in the FEIS, invalidating their conclusions by way of analyzing a level of traffic that is inapplicable to the project presently before the BLM for consideration. WGFD considered one eighteen-wheeler per day along these access routes. FEIS at 2-96. In fact, the real traffic estimate later amended by BLM in the FEIS is 2-5 eighteen wheelers per day plus 50 SUVs per day (FEIS at Appendix F-34), a level of traffic not considered by WGFD. In addition, WGFD never considered both of the alternate access routes proposed by BCA, which were recommended subsequent to the WDEQ permitting process, and thus BLM cannot rely on WGFD recommendations to evaluate these alternate routes against proposed East and West Access Roads. Given that both of these main haul roads are within 2.0 miles of active sage grouse leks, and indeed within 0.6 miles, this is problematic in light of state and federal policy regarding Core Area impacts management.

Impacts analysis for sage grouse was flawed

Four occupied and active leks are within 2 miles of the project. FEIS at 3.8-29. BLM addresses only alternate access routes presented prior to the BLM's EIS in the state process that did not account for newly identified sage grouse leks, not alternate routes that DO account for newly identified leks, as recommended by BCA in our Draft EIS comments. FEIS at 2-98. This failure to examine this reasonable alternative violates NEPA.

There is an overlap between noise restriction hours in EO 2011-5 and project activities, between 7 and 8 am. FEIS at F-34. Sooner and Sooner Oil Leks are within 1000 feet of the access roads, BLM claims that other leks will have "negligible noise impacts." *Id.* By extension, noise impacts at the Sooner and Sooner Oil leks will be non-negligible. According to BLM, "Given that the Sooner and Sooner Oil Leks are within 1,000 feet of Sooner Road, traffic increases along this road could impact lek attendance at these leks." FEIS at F-34.

There is no "action alternative" that would comply with WY IM 2012-019. This IM limits drilling pads or mining locations to an average of one per 640 acres. See FEIS at ES-6. It is abundantly clear that the drilling pads for this project will be spaced at a density approaching 100 per square mile in developed areas. The Mine Unit 1 diagram provided shows 43 sites for monitoring wells alone. FEIS at Figure 3.6-5. The DDCT cannot be used to dilute well density, and the consideration that all of the various pods of wellsites be pooled together and considered a single wellpad is arbitrary and capricious and circumvents the intent and black-letter direction of state and federal core area protection policies.

Figure 2.1-4 shows the configuration of monitoring wells in a "typical mine unit." FEIS at 2-8, 2-9. Twenty production wells and 40 injection wells are expected for each header house. Id. In addition, there is one monitor well every four acres, spaced 500 feet apart along the perimeter. Id. Is there one header house per mine unit? Presumably so; this should be disclosed. The specific number of mine units are considered "conceptual" at this point. Id. Layout of mine units would occur later, as part of the WDEQ-LQD permitting process. FEIS at 2-28. In order to approve the project and take the legally required "hard look," the number of mine units should be

determined with finality, disclosed in the FEIS, and their impacts on site-specific sensitive resources such as sage grouse leks, occupied pygmy rabbit habitat, and Wyoming pocket gopher occupied burrow complexes should be evaluated.

BLM has failed to assess the effectiveness of mitigation measures

BLM relies on mitigation measures for sage grouse contained in IM 2012-019 and state Executive Order 2011-5, but the effectiveness of these measures has never been established, and all available science points to the conclusion that they are inadequate. BLM needs to undertake an analysis of the mitigation measures in these two policy documents to determine the level of impact to sage grouse populations when these measures are applied in the context of an in situ uranium project, as well as more generally, in order to meet NEPA requirements in this regard.

Maximum 5% surface disturbance within DDCT area

In terms of surface disturbance, the EIS claims that the level of impact is consistent with limits prescribed under the state's Density Disturbance Calculation Tool (DDCT). FEIS at 4.9-26. The BLM asserts that WGFD "approved the way the analysis was carried out" and found that "the results indicated that the surface disturbance resulting from the Project was in line with the SGIT stipulations." Id. However, the EIS includes no analysis of what this level of impact in terms of percentage of land surface disturbed would have on sage grouse. And the state SGIT likewise never analyzed what the impact of having 5 percent of the land area within a DDCT zone would have on sage grouse, nor did the agency even consult the applicable science to see if there was any rational basis for selecting the prescribed threshold. The DDCT process has a crippling flaw: Instead of examining the density of impacts on a per-square-mile basis in the area to be developed, it expands the land area far beyond the Project Area boundary, thereby masking ecologically damaging levels of surface disturbance by adding in undeveloped lands far away from the project in question. Thus, BLM calculated using the DDCT that the percentage of land undergoing surface disturbance would be 0.9% (FEIS at 4.9-27), while the actual percentage of the Project Area that would undergo surface disturbance would be 345 acres in a 4,254-acre Permit Area (FEIS at ES-2), which amounts to 8.1% surface disturbance within the Permit Area. And even this index is skewed conservatively, because much of the peripheral acreage of the Permit Area is not slated for any surface disturbance or activity at all. See project footprint in FEIS at Figure 4.9-3. Of note, it appears that the DDCT analysis was undertaken using the actual acreage of project area disturbed, but for the sites per square mile analysis, it appears that an arbitrary line was drawn around the collective perimeter of all well sites (FEIS at 4.9-32). What would be the acreage under the DDCT if the "one-site" approach espoused in this sectionb of the FEIS was applied to the DDCT analysis? The complete absence of any analysis of the level of impact to be experienced at this threshold of percentage of land disturbed is a violation of NEPA's hard look requirements and also a failure to examine the adequacy of mitigation measures pursuant to NEPA.

According to BLM, "the area of impacted vegetation at any one time should be less than eight percent due to the sequential nature of the Mine Unit Development as well as ongoing Restoration and Reclamation." FEIS at 4.2-5. This statement addresses the percent disturbance at any one time, rather than the cumulative surface disturbance over the life of the project. This is a key distinction, because once surface disturbance occurs, it will take 80 to 100 years for

sagebrush to recolonize and return to a mature state where it will fully function as sage grouse habitat. At no point has BLM (or WGFD, for that matter) made the assertion that 8.1% surface disturbance within a project area will avoid significant impacts on sage grouse populations as long as there is a significant expanse of undeveloped sage grouse habitat on adjacent lands. Indeed, an examination of the available science on industrial impacts to sage grouse (including studies cited by BLM in the FEIS) includes studies where similar intensities of wellfields have been developed adjacent to unimpacted sage grouse habitat, and the result has been both displacement of sage grouse and population decreases.

No Surface Occupancy buffer of 0.6 mile around active leks

BLM claims that the Project complies with the Executive Order requirement that No Surface Occupancy measures apply within 0.6 mile of active sage grouse leks. In fact, the project does not comply with this measure – both the East and West Access Roads are proposed for reconstruction from two-track trails to major haul roads within 0.6 mile of active leks. While a 0.6-mile buffer around the leks is asserted to be the 'loafing area' for males during lekking periods, it does nothing to protect nesting habitat around the lek (which can extend out to 5.3 miles), and BLM has never even presented scientific data that industrial development 0.6 mile for the lek site, at the edge of the 'loafing area,' will avoid any impacts even to loafing males, much less nesting and breeding females. The WGFD argued that upgrading the East and West Access Roads would create less impacts to sage grouse than alternate routes considered during the WDEQ state permitting process. FEIS at 4.9-29. But WGFD never considered the impacts compared to the two access routes recommended by BCA, which were proffered at the Draft EIS stage, after the WDEQ process was completed. Thus, application of the 0.6-mile buffer is arbitrary and capricious.

But even if the Project did comply with the 0.6-mile lek buffer requirement, neither the BLM nor WGFD or any other agency has ever analyzed the effectiveness of this mitigation measure. In our own research, we have been able to track down this spurious lek buffer distance only to reports that it corresponds to the 0.6-mile loafing area for male sage grouse around the lek during the breeding season. But there have never been any tests to determine that if a wellsite or other facility is sited exactly 0.6 mile from the lek's periphery (which is allowable under this standard), that there would be no significant impact on loafing male sage grouse during the breeding season (let alone impacts on breeding females, impacts on nesting females – which concentrate their nesting on lands within 4 to 5 miles of the lek). Indeed, the best available science has indeed tested how far from the lek industrial facilities – including oil and gas wells quite similar in their effects as the uranium wells proposed under this project – must be to reduce their impacts to insignificance. Indeed, the available scientific studies suggest that the 0.6-mile buffer is woefully inadequate to prevent major impacts to sage grouse populations.

Incomplete impacts analyses for other BLM Sensitive Species

Pygmy rabbit active habitat and locations are mapped for the project area. FEIS at 3.8-54. Yet there do not seem to be alternatives that would avoid mapped pygmy rabbit habitat. The impacts analysis is sparse to nonexistent (see FEIS at 4.9-43), evading NEPA's hard look requirements.

Wyoming pocket gopher locations are mapped for the project, and overlapped with predicted project activities in at least a crude way. FEIS at 3.8-57. The impacts analysis is sparse to nonexistent (see FEIS at 4.9-43), evading NEPA's hard look requirements.

Groundwater and Surface Water Impacts

We remain concerned about the potential for contaminated fluids to be spilled at the surface into drainage channels that connect during stormwater events to playas, lakes, and wetlands to the southwest. In these types of uranium mining operations, leaks are "common" and the most common sources of leaks are outlined in the FEIS at page 4.6-6. The BLM FEIS references the NRC EIS for Lost Creek for more detail on surface leaks and their potential impacts to surface waters. But while the NRC EIS mentions in passing the possibility of leaks and spills (NRC DEIS at 4-23), it in no way evaluates the possibility of a leak or spill from a well sited in or near an ephemeral well channel on downstream lakes, playas, and/or wetlands (see NRC DEIS at 4-26). BLM's impacts analysis does not consider the potential impacts of a surface leaks and contamination that occurs during a rainfall event during which surface water flows could carry contaminated fluids far to the southwest via ephemeral drainage channels. In general, wells will be sited 20 feet from ephemeral drainage channels, but in rare instances, wells may even be installed within or immediately beside an ephemeral drainage channel. FEIS at 4.6-3. This puts facilities at grave risk for immediate transport of spilled fluids to downstream locations distant from the Project Area.

The upper portion of the Battle Springs formation is where the uranium mineralization occurs in the permit area. FEIS at 3.3-11. The aquifers in the Battle Springs formation are comprised of thick deposits (typically 100 feet) of sandstone interbedded with shale layers that serve as aquitards or aquicludes, with the result that different sandstone member are separated vertically (but not necessarily horizontally). FEIS at 3.3-13. There is an anticline (the Lost Soldier Anticline) to the northeast of the Project area, with a steep southwest dip toward the Project area, but the dip is reduced to three degrees in the Project Area itself. FEIS at 3.3-14. According to BLM, "The main discharge area for the Battle Springs/Wasatch aquifer system is to a series of lakes, springs, and playa lake beds near the center of the [Great Divide] Basin." FEIS at 3.6-1. This aquifer is among "[t]he most important water-bearing aquifers within the Basin…." FEIS at 3.6-4. The Lost Creek Fault, which traverses the Project Area, slows but does not halt groundwater flow (FEIS at 3.6-34); mine units for the project will be located on both sides of this fault (see FEIS at Figure 3.6-14). "From the permit area, the potentiometric surface dips southwest" toward the lakes, playas and wetlands to the south and southwest of the project area. FEIS at 3.6-6. For the Project Area itself, "Based on the potentiometric surface map, groundwater is inferred to flow to the west-southwest, generally consistent with the regional flow system." FEIS at 3.6-22. Beyond these inferences, the FEIS does not present information on groundwater flows to the south and west.

There are several mapped springs on Battle Springs Flat on the BLM's South Pass 1:100,000 scale topographic map. Battle Spring Draw leads to this flat, and is the primary surface watershed in the Project Area. See FEIS at 3.5-3. Attachment 3 is the Bedrock Geology Map from a USGS report called Water Resources of Sweetwater County, Wyoming, Scientific Investigations Report 2004-5214, by Jon P. Mason and Kirk A. Miller. This map clearly shows

that the Battle Spring formation, overlain in places by Quaternary sand and playa deposits, is the underlying bedrock for T24N R 94W, the township that contains these springs. This USGS report did not provide any baseline groundwater quality data for these springs (testing only wells in this area), and the BLM's FEIS didn't provide them either. These springs are also in proximity to seasonal lakes and wetlands that are part of the Chain Lakes complex, likely feeding into these seasonal lakes and wetlands. Heller et al. (2010) lumped together the Battle Springs Flat and Chain Lakes Flat playas and described them as being underlain by several formations, including the Battle Springs formation specifically. See Attachment 2. It is possible that hyporheic flows from the Battle Springs formation may feed into these playa lakes and wetlands, but BLM's impacts analysis does not consider nor evaluate this possibility. Indeed, BLM's analysis of potentially affected wetlands is limited to the Project Area itself. FEIS at 3.5-18. Circle Bar Lake and the Chain Lakes proper, located in 23/93 and 23/92, are part of the Chain Lakes Wildlife Habitat Management Area under the Rawlins RMP. These are also clearly underlain by the Battle Springs formation surface outcrop, as can be seen in Attachment 3. Groundwater flows generally from northeast to southwest through the Battle Springs formation, from the project area toward the playa lakes found in the WHMA. We are concerned that groundwater contamination from excursions within the Project Area will result in significant impacts to wetlands, playas, and lakes to the south and southwest of the Project Area through hyporheic flows of groundwater, resulting in unmitigated loss of wetland function in violation of Executive Orders 11990 and 11988.

BLM continues to emphasize the lack of hydraulic connection between the target formation and surface waters <u>within the project area</u> (FEIS at 4.7-1), but is still turning a blind eye to the real issue, which is where the target aquifer connects with springs <u>outside</u> the Project Area. BLM's description of surface water uses is limited to lands within 3 miles of the Project Area boundary. FEIS at 3.5-11. BLM also proposes not to monitor these springs in its off-site groundwater monitoring protocols. FEIS at 4.7-11. The Affected Environment section of the FEIS fails to disclose which of the neighboring springs are fed by the target aquifer. See FEIS at 3.6-4. Water quality in the Battle Springs aquifer in and near the project area is considered comparatively high. FEIS at 3.6-49. This high water quality would be expected to be degraded with the injection of lixiviants, which themselves may be toxic, as well as the liberation of uranium, a major source of radioactivity. Appendix F of the FEIS also contains no response to the comments of BCA et al. in this regard.

Radioactive contaminants have an extremely long half-life, measured in thousands of years. In addition, the lixiviant is expected to liberate various heavy metals (FEIS at 4.7-17, 4.7-30), which can also be toxic. Although water quality is already low in target formations, injection of lixiviant will decrease water quality there significantly. FEIS at 4.7-31. BLM notes that a release of pregnant lixiviant into the DE Horizon groundwater through a spill would result in impacts that "would be high and long-term." FEIS at 4.7-21. This is the same fluid that will be produced in the target horizons as a matter of course, and the fluid that would be released in the event of an excursion. Despite the fact that the mine units will be ringed by monitoring wells, "excursions" can and do occur on a regular basis at in situ uranium mines (due to factors outlined in the FEIS at 4.7-31). See Appendices 1, 2, and 3 to these comments for examples of the excursion records of similar in situ uranium leaching projects in Wyoming. So it should be expected that

contaminated groundwater will at some point (maybe more than once) be released into the Battle Springs aquifers and be carried wherever groundwater flows take them. How long does it take for groundwater in the Project Area to reach the lakes, wetlands, and playas at the center of the Great Divide Basin, where the Battle Springs formation crops out at the surface? If contaminants are injected, or radioactive compounds are liberated through the use of lixiviants in the Project Area, where would groundwater flows carry them in terms of the discharge area at the surface? These questions remain unanswered by the EIS (despite the fact that BCA has previously raised them and BLM has a responsibility to respond to comments made at the Draft EIS stage), an indication that the legally required 'hard look' has not occurred.

BLM discloses various potential chemicals used in lixiviants for the project (FEIS at 4.7-17), but does not evaluate the levels of toxicity or potential environmental impacts for these compounds. This fails NEPA's 'hard look' standards.

While BLM proposes a methodology to deal with "excursions," or release of contaminated fluids beyond the monitoring wells (FEIS at 4.7-4), by definition BLM and the Project Proponent will be unable to determine the geographic extent of the excursion once it gets past the ring of monitoring wells because there will be no system to track such groundwater excursions beyond the monitoring well ring. Nor does BLM provide any impact analysis for the off-site potential impacts of such a contaminant plume.

We also remain concerned that wellbores, both for injection wells and for older, uncontrolled wellbores that already exist in the Project Area, will lead to cross-contamination of deeper aquifers by pregnant lixiviant. All wells for this project appear to be open-hole completions, lacking casing. BLM expects "mud filter cake" to seal the wellbores and prevent cross-contamination (FEIS at 4.7-21), but provides no evidence that drilling muds can or will seal an open-bore well completed through the target formation to deeper aquifers. In addition, BLM does not analyze the extent to which previously existing wellbores, which are legion (see FEIS at Figure 3.4-15), will serve as avenues for cross-contamination through shale layers between target strata where uranium will be placed into solution and other aquifers.

The expected drawdown of groundwater is also expected to extend at least 3 miles from the Project Area boundary. FEIS at Figure 4.7-2. What will be the impact of the drawdown of aquifers feeding lakes, playas, wetlands and springs to the south and southwest of the Project Area, as described above? BLM's impacts analysis does not appear to address this issue.

Conclusion

Overall, the approval of this project demonstrates the BLM's willingness to go to great lengths to approve industrial projects inside Core Areas that are fundamentally inconsistent with Core Area conservation principles. In approving projects like this, BLM demonstrates the inadequacy of the Core Area policy as a conservation measure to protect sage grouse, and illustrate the problem that even in Core Areas, sage grouse habitats function can be reduced to zero by an industrial project. BLM needs to require that the project proponent utilize directional drilling and well clustering (for monitoring, injection, and production wells) such that a maximum wellpad density of one wellpad per square mile is achieved for the project. If this proves infeasible, then BLM

should withhold approval of the project rather than approve a project that very clearly will have strongly detrimental impacts on sage grouse populations within the Core Area. The U.S. Fish and Wildlife Service will be making a determination prior to 2015 on whether Core Area protections constitute "adequate conservation measures" to avert Threatened or Endangered Species listing, and BLM's handling of this project thus far undermines the credibility of Core Area protections, and indeed indicates that federal and state agencies are willing to go to great lengths to avoid applying even the meager and inadequate conservation measures committed to in the state's Core Area policy. If the Core Area protections are never applied in practice, then the Core Area policy is merely a paper exercise that has no impact on the ground, and cannot be relied upon as an alternate path to Endangered Species Act protections. BLM should remain aware that a negative Endangered Species listing in 2015 is likely to be scrutinized in the courts, and that the agency needs to be on its best behavior lest it build the record that Core Area protections are being skirted when industrial projects are proposed in Core Area lands. Thus, BLM would be wise to deny approval to the Lost Creek in situ project until it is substantially modified to comply with the intent of the Core Area policy, and will lower impacts to sage grouse below the threshold of significance through measures that have the support of the best available science. There are also unanswered questions remaining regarding the impacts that will occur to groundwater and to groundwater-fed springs and lakes to the south of the project area.

Please address all of these issues prior to issuing a Decision for the project.

Respectfully yours,

Erik Molvar

Signing on behalf of

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Appendix 1: Spills and excursions from Uranium One Christiansen Ranch/Willow Creek/Irigary ISL project, site last visited 9/3/12.

Latest NRC Event Reports referring to Uranium One's Willow Creek (ex Christensen Ranch / Irigaray) ISL site in Wyoming:

- Jun. 30, 2012: 1,500 gallon spill of injection fluid (0.9 ppm U)
- Jun. 18, 2012: 1,200 gallon spill of recovery fluid (7.5 ppm U)
- Jun. 18, 2012: 300 gallon spill of injection fluid (1.0 ppm U)
- Jun. 17, 2012: 500-700 gallon spill of injection fluid (1.4 ppm U)
- Apr. 20, 2012: 1,020 gallon spill of injection fluid (1.0 ppm U)
- Apr. 12, 2012: Monitor well placed on excursion status
- Apr. 3, 2012: Two monitor wells placed on excursion status
- Mar. 29, 2012: Two monitor wells placed on excursion status
- Jan. 5, 2012: Monitor well placed on excursion status
- Dec. 14, 2011: 1,500 gallon spill of RO brine fluid (3.8 mg/L U)
- Oct. 2, 2011: Aerial release of yellowcake powder
- Sep. 23, 2011: 4,000 gallon spill of injection fluid (0.87 mg/L U)
- Aug. 24, 2011: Monitor well placed on excursion status
- "around August 4 or 5, 2011": approx. 7,000-10,000 gallon spill of NaCl brine solution
- Jun. 21, 2011: 1,500 gallon spill of injection solution (3.5 ppm U)
- Apr. 19, 2011: Monitor well placed on excursion status
- Apr. 12, 2011: Sampling missed for months at 24 monitoring wells, at least
- Mar. 29, 2011: 1,000 gallon spill of barren injection fluid
- Mar. 23, 2011: Monitor well placed on excursion status
- Mar. 8, 2011: Monitor well placed on excursion status
- Jun 10, 2010: Monitor well placed on excursion status
- Jun 8, 2010: 1,200 gallon spill of permeate water
- Jun 3, 2010: Evaporation pond leak
- Dec 16, 2009: Monitor well placed on excursion status
- Sep 15, 2009: Monitor well placed on excursion status
- Mar 12, 2009: Monitor well placed on excursion status
- Apr 17, 2008: Monitor well placed on excursion status
- Mar 11, 2008: Two monitor wells placed on excursion status
- Sep 5, 2007: Monitor well placed on excursion status
- Apr 25, 2007: Monitor well placed on excursion status

Find more events under decommissioning issues

- Jul 22, 2004: Monitor well placed on excursion status
- Apr 28, 2004: Two leaks detected in evaporation ponds
- May 31, 2001: Monitor well placed on excursion status
- Jan 23, 2001: 13,392 Gallon spill of restoration water

- Aug 10, 2000: Monitor well placed on excursion status
- Oct 28, 1999: Monitor well placed on excursion status
- Oct 5, 1999: Monitor well placed on excursion status
- Jul 8, 1999: Monitor well placed on excursion status
- May 8, 1999: 15,000 Gallon Mining Injection Solution Spill
- Apr 12, 1999: 32,400 Gallon Injection Solution Spill
- Apr 3, 1999: 13,000 Gallon Spill of Restoration Water
- Mar 29, 1999: 23,520 Gallon Mining Injection Solution Spill
- Mar 26, 1999: 60,918 Gallon Mining Injection Solution Spill
- Feb 17, 1999: Monitor well placed on excursion status
- Dec 22, 1998: Monitor well placed on excursion status
- Nov 19, 1998: Monitor well placed in excursion status
- Sep 2, 1998: Shallow monitor well is in an excursion status
- Aug 6, 1998: Ground water monitor well placed in excursion status
- Jul 22, 1998: Minor leakage of byproduct solution from the evaporation pond
- Jul 8, 1998: 28,000 Gallons of water containing low level of U3O8 spilled onto ground
- Mar 5, 1998: Perimeter monitor well in excursion status
- Oct 3, 1997: Monitor well in excursion status
- Sep 16, 1997: Spilled 2,440 gallons of waste water containing 78.5 ppm natural uranium
- Sep 12, 1997: Well in excursion
- May 16, 1997: Two perimeter monitoring wells in excursion status
- Mar 12, 1997: Perimeter well in excursion status
- Dec 31, 1996: Perimeter well in excursion status

(details on post-Nov.1,1999, events available through ADAMS, Docket No. 04008502)

Appendix 2: License Violations at Power Resources, Inc. Highland Uranium Project, Wyoming, USA. http://www.wise-uranium.org/umopuswy.html#HIGHLVIOL **,** site last visited 9/3/12.

- Aug. 8, 2012: Monitor well placed on excursion status
- Aug. 1, 2012: Monitor well placed on excursion status
- Mar. 10, 2012: 344 gallon spill of production fluid (4.1 ppm U)
- Mar. 9, 2012: 1202 gallon spill of injection fluid
- Mar. 7, 2012: 774 gallon spill of injection fluid
- Feb. 29, 2012: Monitor well placed on excursion status
- Jan. 12, 2012: Monitor well placed on excursion status
- Jun. 16, 2011: Monitor well placed on excursion status
- Jun. 7, 2011: Monitor well placed on excursion status
- Mar. 8, 2011: Sampling missed for seven monitoring wells
- Mar. 8, 2011: Monitor well placed on excursion status
- Sep. 10, 2010: Monitor well placed on excursion status
- Jun. 8, 2010: Monitor well placed on excursion status
- Jan. 29, 2010: 224 gallon spill of injection solutions (1.3 ppm U3O8)

- Jan. 13, 2010: Monitor well placed on excursion status
- Nov. 23, 2009: Monitor well placed on excursion status
- Sep. 24, 2009: Release of 90,600 gallons of treated process water
- July 31, 2009: Monitor well placed on excursion status
- July 7, 2009: Monitor well failure
- May 26, 2009: 5050 gallon spill of injection fluid (3 ppm U3O8)
- May 21, 2009: Monitor well placed on excursion status
- May 11, 2009: 6500 gallon spill of production solutions (19.8 ppm U3O8)
- Apr. 16, 2009: Monitor well placed on excursion status
- Mar. 30, 2009: Monitor well placed on excursion status
- Feb. 13, 2009: Monitor well placed on excursion status
- Jan. 10, 2009: 1,820 gallon spill of injection/production water containing 15 ppm uranium
- Nov. 18, 2008: Monitor well placed on excursion status
- Nov. 12, 2008: Monitor well placed on excursion status
- July 10, 2007: Monitor well placed on excursion status
- June 25, 2007: 3747 gallon spill of production fluid (21 ppm U)
- June 22, 2007: 198,500 gallon [751 cubic meters] spill of injection fluid (8.1 ppm U)
- May 21, 2007: 700 gallon spill of injection fluid (1.2 ppm U)
- May 1, 2007: monitor well on excursion status
- Dec. 30, 2005: 1000 gallon spill of restoration injection fluid, containing approx. 0.7 mg/L uranium
- Aug. 30, 2005: 1000 gallon spill of production fluid (15.4 mg/L U)
- May 17, 2005: 20,700 gallon spill of injection fluid, containing approx. 1.1 mg/L uranium
- Feb. 26, 2005: 3000 gallon spill of production fluid, containing 11.5 mg/L uranium
- Jan. 10, 2005: 300 gallon spill of injection fluid, containing 1 mg/L uranium
- Sep. 12, 2004: 1000 gallon spill of production fluid (10.5 mg/L uranium)
- May 3, 2004: 800-1000 gallon spill of production fluid, containing about 11 mg/L uranium
- Feb. 11, 2004: 400-600 gallon spill of injection fluid (1.3 mg/L U308)
- Feb. 8, 2004: 500-1000 gallon spill of injection fluid (1.1 mg/L U308)
- December 20, 2003: Spill of 600 gallons of injection fluid containing approx. 1.5 mg/L of uranium
- October 20, 2003: Spill of 2800 gallons of injection fluid containing approx. 1.5 mg/L of uranium
- September 29, 2003: Spill of 5000 gallons of injection/recirculation fluid containing approx. 2.0 mg/L of uranium
- March 13, 2003: Spill of approx. 1100 gallons of wellfield injection fluid
- November 7, 2002: Monitor well placed on excursion status
- July 1, 2002: Monitor well placed on excursion status
- March 21, 2002: Monitor well placed on excursion status
- July 7, 1999: Spillage of 3-5 Gallons of Water Containing LSA of Uranium Byproduct Material
- June 1, 1999: Spillage of 4000 Gallons of waste fluid

- Feb. 5, 1999: Monitor well placed on excursion status
- Feb. 5, 1998: Monitor well placed on excursion status

> For reports on many more spills, download WY DEQ's spill databases !

The Nuclear Regulatory Commission has issued a Notice of Violation to Power Resources, Inc., of Denver, Colorado, for violations of NRC requirements at the Highland Uranium Project in Converse County, Wyoming.
Power Resources, Inc. is a wholly owned subsidiary of Cameco Corp.

Appendix 3: License violations at Smith Ranch in-situ leaching site. http://www.wise-uranium.org/umopuswy.html#SMITHRVIOL, site last visited 9/3/12.

- Aug. 20, 2012: Monitor well placed on excursion status
- Dec. 6, 2011: 1,779 gallon spill of injection fluid (0.7 ppm U3O8)
- Nov. 7, 2011: Leak in East Evaporation Pond
- Sep. 12, 2011: Monitor well placed on excursion status
- Aug. 19, 2011: 85 gallon spill of injection fluid
- Aug. 15, 2011: Leak in East Evaporation Pond (158 mg/L U)
- July 22, 2011: 53 gallon spill of injection fluid
- July 8, 2011: 1,190 gallon spill of restoration recovery fluid containing 2.4 ppm U3O8
- June 13, 2011: Leak in East Evaporation Pond (248 mg/L U)
- May 19, 2011: 790 gallon spill of solution containing 17 ppm U-nat, spill length 2,112 feet (644 m), width 3 feet (0.9 m)
- May 3, 2011: 1,500 gallon spill of production fluid, impacting 12,077 square feet (1,122 m^2)
- Sep. 10, 2010: 960 gallon spill of solution containing 1.5 ppm U3O8
- Jul. 20, 2010: leak in East Storage Pond
- Jul. 8, 2010: 1,440 gallon spill of injection fluid containing 1 ppm U3O8
- Nov. 19, 2009: 560 gallon spill of injection solutions containing 1.4 ppm U3O8
- Aug. 26, 2009: 1,500 gallon spill of injection solutions containing 1.1 ppm U3O8
- Jun. 11, 2009: 190 gallon spill of injection solutions containing 0.7 ppm U3O8
- Apr. 23, 2009: leak in East Storage Pond (510 ppm U3O8)
- Feb. 27, 2009: leak in East Storage Pond (263 ppm U3O8)
- Feb. 9, 2009: 14,600 gallon spill of production solutions containing 7 ppm U3O8
- Jan. 9, 2009: 2,169 gallon spill of production solutions containing 11 ppm U3O8
- Dec. 29, 2008: 1,144 gallon spill of injection fluid containing 0.2 ppm uranium
- Oct. 30, 2008: 5,500 gallon spill of injection fluid containing 2 ppm uranium
- Sep. 17, 2008: 16,774 gallon spill of injection fluid
- Aug. 17, 2008: 7,965 gallon spill of injection fluid containing 1.4 ppm uranium
- July 24, 2008: 2,887 gallon spill of production water and 12,770 gallon spill of solution
- Aug. 23, 2007: 11,600 gallon spill of deep disposal well fluid
- June 27, 2007: 900 gallon spill of injection fluid containing 1.1 ppm uranium

- June 19, 2007: 900 gallon spill of fluid containing 41.2 ppm uranium
- Feb. 19, 2007: 6,000 gallon spill of production fluid (32.5 ppm uranium)
- Jan. 14, 2007: 5,000 gallon spill of injection fluid (2 ppm uranium)
- Dec. 13, 2006: 560 gallon spill of injection fluid (2 ppm uranium)
- Dec. 5, 2006: 10,000 gallon spill of mixed monitor well, restoration and waste fluids (1 ppm uranium)
- Nov. 22, 2006: 2,100 gallon spill of mine waste water
- Feb. 10, 2006: 1,000 gallon spill of production fluid, containing approx. 21 mg/L uranium
- Jan. 9, 2006: 6,240 gallon spill of injection fluid, containing approx. 1.7 mg/L uranium
- Oct. 21, 2005: 7,041 gallon spill of deep disposal well fluid
- Oct. 21, 2005: Leak detected in evaporation pond
- Sep. 2, 2005: 4,500 gallon spill of production fluid, containing approx. 8.6 mg/L uranium
- Aug. 16, 2005: 1,050 gallon spill of production fluid, containing approx. 2.1 mg/L uranium
- May 31, 2005: 4,700 gallon spill of injection fluid, containing approx. 1.1 mg/L uranium
- Oct. 9, 2004: 5,000 gallon spill of ground water sweep fluids containing 7 mg/L uranium
- Sep. 29, 2004: 2,000 gallon spill of injection fluid, containing 1.6 mg/L uranium
- Sep. 8, 2004: wellfield excursion at Mine Unit 4 monitoring well
- Sep. 6, 2004: 1,600 gallon spill of injection fluid
- July 22, 2004: 2,700-5000 gallon spill of production fluid
- Oct. 15, 2003: 5,000 gallon spill of injection fluid containing about 47 mg/L of U3O8
- Sep. 29, 2003: 5,000 gallon spill of injection fluid containing about 2 mg/L of U3O8
- Sep. 6, 2003: 20,800 gallon spill of injection fluid containing about 1.1 mg/L of uranium
- Feb. 9, 2003: 500 gallon spill of production fluid containing about 2 mg/L of uranium
- Jul. 30, 2002: 1,480 gallon spill of injection fluid
- Apr. 25, 2002: 3,500 gallon spill of injection fluid
- Apr. 24, 2002: 18,000 gallon spill of injection fluid
- Jan. 4, 2002: 1,800 gallon spill of production fluid containing about 18 ppm U308
- Dec. 5, 2001: 3,600 gallon spill of injection fluid
- Oct. 22, 2001: 62,400 gallon spill of injection fluid
- Jun. 18, 2001: 1,100 gallon spill of deep well disposal fluid
- Nov. 22, 2000: 1,870 gallon spill of injection fluid
- Oct. 22, 2000: 11,100 gallon spill of injection fluid
- Aug. 7, 2000: 780 gallon spill of production fluid
- Feb. 26, 2000: 3,780 gallon spill of production fluid
- Jan. 17, 2000: 6,900 gallon spill of production fluid
- Dec. 31, 1999: 3,000 gallon spill of injection fluid

(details available through ADAMS, Docket No. 04008964)

Biodiversity Conservation Alliance

Working to Protect Native Species and Their Habitats

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January 21, 2010

Chief, Rulemaking and Directives Branch
U.S. Nuclear Regulatory Commission
Mail Stop TWB-05-B01
Washington, DC 20555-0001

Comments on the Lost Creek ISR project

To Whom it May Concern:

The following are the comments of Biodiversity Conservation Alliance on the Lost Creek in-situ uranium recovery project.

The Draft Report for Comment underestimates impacts to several resources due to erroneous assumptions and unrealistically optimistic estimates of the effectiveness for mitigation measures to be applied.

Six production units are planned for the project. The production units would overlap in time, with up to 2 units on line at any one time. EIS at 2-20. This phased approach is far superior to having all pods of wells active at any one time.

Storage ponds are mentioned, and these would be fenced. See EIS at 4-3. We appreciate the netting and fencing requirements to assure that waterfowl, raptors, and/or songbirds would not come down to these pond to land or drink and be poisoned by toxins in the holding ponds.

Sage Grouse

Six Active sage grouse leks occur within 2 miles of the project t boundary, and the project area has been designated a sage grouse Core Area. EIS at 4-47. The Wyoming BLM has a new instruction memorandum regarding development within designated sage grouse Core Areas. Attachment 1. As this project will be approved almost entirely on BLM lands, we expect the project to comply with the directives contained in this policy, and NRC states that the project will comply with the Governor's policy (id.). At present, it does not, as the Governor's policy caps well density at 1 well per 640 acres within Core Areas.

Figure 2.7 graphically shows the layout of a wellfield. SEIS at 2-11. Between the injection wells, producing wells, and interior/perimeter monitoring wells, the total number of wells would total 104 in the space that appears to be less than a square mile. This is far denser than the one well per square mile limit recommended by state and BLM policy. The likely outcome will be the loss of habitat function in and near the facilities; Holloran (2005) found that producing gas wells during the post-drilling stage that were within 1.9 miles of a sage grouse lek correlated to

reductions in lek attendance among breeding grouse (more than 1 well per section correlated to declined in breeding populations as well under this study). We would expect the facilities proposed under this ISL project would have a similar level of impact to producing gas wells during the production phase of the uranium project. In addition, Holloran (2005) found that nesting females avoided areas of high well density (as is proposed under this project) and had lower success at raising young than grouse in undeveloped areas.

A two-mile overhead electrical transmission line accompanies the project. EIS at 2-14. This overhead powerline has the potential to serve as a perch for raptors, increasing rates of predation on birds and small mammals in the vicinity. Powerlines need to be buried within 3 miles of active sage grouse leks and within ¼ mile of active prairie dog colonies.

NRC states that impacts to sage grouse will be MODERATE to SMALL (EIS at 4-48), but this radically underestimates impacts to grouse. The Wyoming Game and Fish Department's recommendations for oil and gas development in sensitive wildlife habitats (WGFD 2009, http://gf.state.wy.us/downloads/pdf/OGRecommendationsNovember09.pdf) states that well densities greater than 3 wells per mile constitute an impact level that is "extreme" for sage grouse even in non-Core areas. The well densities for this ISL facility clearly exceed this threshold by a large margin. "LARGE" impacts "are clearly noticeable and are sufficient to destabilize important attributes of the resource." EIS at page xv. Impacts to sage grouse from construction and production activities and associated vehicle traffic clearly fall into this category. Additional, much stronger mitigation measures will be needed to reduce the level of impact.

Traffic levels are expected to be 30 to 35 light trucks per day during the construction phase decreasing to 20 light trucks per day during production, with 2 to 5 heavy trucks per day throughout the course of the project. EIS at 4-8. Holloran (2005) found that as road traffic increased, the number of breeding males on affected leks decreased. The level of truck traffic shown for this project is likely to have a major negative effect on sage grouse throughout the life of the project.

The sage grouse is rated as Native Species Status 2 ("NSS2") by the Wyoming Game and Fish Department. NSS2 species' habitats are ranked as "Vital" under the the Wyoming Game and Fish Commission's Mitigation Policy, which states that projects recommends that projects should cause "no loss of habitat function." See Attachment 2. This project appears to fail FLPMA's consistency requirement for state plans and policies in this regard.

Pygmy Rabbits

Pygmy rabbits have been documented in the project area. EIS at 3-44. The project will result in habitat fragmentation (*see* EIS at 4-42), which is a major problem for this species. Purcell (2006, 34) noted, "the conversion of big sagebrush communities to energy production sites within southwestern and southcentral Wyoming creates a concern for pygmy rabbits in these regions." NRC states that the extent of pygmy rabbit habitat in the project area is small (approximately 39 acres, EIS at 4-50); such a small area would be readily avoided by shifting of surface locations of project facilities. NRC should require the complete avoidance of pygmy rabbit habitats for the purposes of road and well construction as a condition of approval for the project.

Sagebrush Obligate Passerines

Although the portion of the landscape physically disturbed by roads, wellpads, and pipelines is often a relatively small percentage of the overall landscape, GIS analysis of full-field oil and gas development incorporating quarter-mile buffers to account for habitat degradation due to edge effects indicates that almost 100% of lands within a fully developed gas field are degraded (Weller et al. 2002). We would expect a similar result for ISL wellfields. In this way, the development of a wellfield results in widespread habitat destruction that extends well beyond the acreage of roads and wellpads that are bulldozed in.

Fragmentation of shrubsteppe habitats has a particularly strong negative impact on birds. Knick and Rotenberry (1995) and found that sage sparrows and sage thrashers decreased with decreasing patch size and percent sagebrush cover, and reached the following conclusion:

> "Our results demonstrate that fragmentation of shrubsteppe significantly influenced the presence of shrub-obligate species. Because of restoration difficulties, the disturbance of semiarid shrubsteppe may cause irreversible loss of habitat and significant long-term consequences for the conservation of shrub-obligate birds" (p. 1059).

Ingelfinger (2001) found significant declines in nesting songbirds within 100m of gas field roads, and also found that sage sparrows declined near pipelines. Kerley (1994) found that 67% of songbird species selected for the tallest available sagebrush stands, and nest success was associated with 41% shrub cover, while the two nests in 15% shrub cover were both unsuccessful.

Ingelfinger (2001) conducted a study of sagebrush birds in a western Wyoming gas field and found that as gravel roads increased, densities of sagebrush obligate birds, Brewer's sparrows, and sage sparrows declined, while horned larks (a grassland species) increased. According to his findings, "roads associated with natural gas development negatively impact sagebrush obligate passerines. Impacts are greatest along access roads where traffic volume is high" (p. 69), but "bird densities are reduced along roadways regardless of traffic volume" (p.71). Kerley (1994) found that small patches had fewer shrub-nesting species than large patches, and the green-tailed towhee, an interior sagebrush species, was entirely absent from small patches. Remnant patches smaller than 1 ha will not support sagebrush shrub-nesting birds (Kerley 1994).

Sage sparrows, Brewer's sparrow's and sage thrashers are BLM Sensitive Species which have been documented in the project area. EIS at 4-49. The analysis for passerine birds underestimates the true level of impact for these species. NRC contends that passerine birds will be displaced during construction activities (EIS at 4-42), which is true as far as it goes, but ignores the fact that vehicle traffic and dust will continue to displace passerine birds throughout the production life of the wellfields. NRC claims that impacts would not be outside the range of natural variability, and that impacts to populations would not be expected (id.), but this is simply an inaccurate statement.

Key Wildlife Analysis is Missing
The EIS references a Lost Creek Environmental Report, but this has not been included as an appendix to the EIS. See EIS at 4-3. It would seem that this report contains important information which should have been made available to the public for review as part of the NEPA process. We request that the NRC please send us a copy of this report as soon as possible. We would like to reserve the right to revise and extend our comments based on information contained in the report which may not be presented in detail in the EIS.

Groundwater Impacts
The impacts of in situ leach (ISL) mining are less visible, but ISL mining, by definition, involves the intentional pollution of groundwater, with the hope that the pollution can be extracted through the mining process. However, spills and leaks are common at ISL mines, and complete clean-up has proved impossible. The possibility of a pipeline rupture could lead to spills of lixiviant, either containing uranium or not. EIS at 4-20. In addition, NRC notes that "groundwater quality in the production zone is degraded as part of ISR operations." EIS at 4-33. In addition, excursions of lixiviant or pregnant lixiviant may occur. Id. No examples of reclamation that has returned the water to its original condition have been found in the United States. In fact, research indicates that mine areas that have been "reclaimed" return to a contaminated state. This is because, after the water pumping associated with reclamation ceases, contaminated water moves back into the mining area.[1]

The ISL process uses harsh chemicals collectively known as 'lixiviant' to mobilize uranium from ore rock and pump it to the surface. EIS at 2-15. Of course, it will be impossible to remove all of the lixiviant and mobilized uranium from the formation during production operations, so the fate of groundwater in and around the target formations is an important concern.

The uranium body in question to be tapped for in-situ leaching is the Battle Springs formation, which crops out at the surface in the project area and bears uranium to a depth of approximately 1,150 feet there. EIS at 3-10. It is also faulted by a 'scissors fault,' offsetting the uranium-bearing strata within the project area. Id. at 3-11. This fault complicates the ability of the operator to control flows of lixiviant and also complicates aquifer restoration efforts. EIS at 4-34.

Due to the thin nature of shale layers being counted on to contain the lixiviant, it is possible that vertical confinement of the lixiviant will not be achieved. EIS at 4-34. This leakage between

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[1] George Rice. 2006. *Effects of URI's Kingsville Dome Mine on Groundwater Quality*. Kleberg County URI Citizen Review Board, TX.; Dan Kelley. November 5, 2006. As uranium mines closed, state altered cleanup goals. *Corpus Christi, TX, Caller-Times*; World Information Service on Energy. In-Situ Leaching Decommissioning Projects – USA: Texas: General. www.wise-uranium.org/udusail.html. Accessed January 25, 2008; William P. Staub. January 9, 1999. Uranium ISL Ground-Water Testimony of William P. Staub, Ph.D. US Nuclear Regulatory Commission Docket No. 40-8968-ML. www.sric.org/uranium/WATERDAT.html. Accessedd March 24, 2008; J.K. Otton and S. Hall. In-situ recovery uranium mining in the United States: Overview of production and remediation issues. Lakewood, CO: US Geological Survey; Kenneth S. Wade. 1981. *Uranium In Situ Mining and Groundwater Quality at the Grover Test Site, Weld County, Colorado.* Thesis: Department of Earth Resources: Colorado State University.

strata was confirmed by tests in 2007. Id. This increases the likelihood that contamination will spread beyond the target formation.

The EIS discusses liquid wastes such as 'production bleed' and how they will be injected underground at deep injection wells. What are the chemical constituents of these liquid wastes? The EIS provides no information regarding this key point. Do they contain radioactive substances? Heavy metals? Caustic acids? The Mesa Verde formation seems to be the injection target. EIS at 4-35. We understand that the injection target strata for deep well injection must possess water quality equal to or worse than the liquid wastes that will be pumped into them. Is this going to be the case for the Lost Creek project, or will wastes be injected into a receiving aquifer of higher quality than the wastes?

Surface Water and Wetland Impacts

NRC contends that impacts to surface waters would be SMALL because they would occur in the Great Divide basin, which has no outlet to the sea and therefore does not contain any statutory Waters of the United States. EIS at 4-24. We agree that intermittent and ephemeral stream channels, springs and wetlands in the project area or likely to be affected by the project are indeed not Waters of the US pursuant to the Clean Water Act. However, the statutory classification of stream channels and wetlands has no bearing on the magnitude of environmental impact under NEPA. Their classification does not mean that spills or contamination would trigger the Clean Water Act's provisions, but nonetheless NEPA requires that an objective assessment of impacts take place, and does not specify a difference between wetlands that are Waters of the U.S. versus other wetlands. In addition, Executive Order 11990 requires the federal government to minimize to minimize the destruction, degradation, or loss of wetlands (regardless of their Clean Water Act status) and to preserve and enhance their natural and beneficial values. See http://www.epa.gov/wetlands/regs/eo11990.html.

The NRC is required to protect floodplains to the extent possible by Executive Order 11988. *See* http://www.epa.gov/wetlands/regs/eo11988.html. Battle Spring Draw passes through the project area. EIS at 3-13. The EIS states that drainage channels would not be able to be avoided entirely, and that well sites are expected to be built right in drainage channels in some cases. EIS at 4-25. This would seem to violate Executive orders regarding floodplain management, and we expect the NRC to require design of well arrays to ensure that no well site will be located within or across a drainage channel. Location of wellpads in drainage channels will certainly result in major increases in erosion and sedimentation, and also elevate the risk that any spill that occurs at a wellsite will spread downstream along the stream channel. These impacts are readily avoidable by shifting the locations of project facilities. NRC needs to prohibit siting of wellpads in stream channels and avoid floodplains to the extent possible to comply with EO 11988.

Historic and Cultural Resources

Three sites eligible for the National Register of Historic Places have been documented in the planning area. EIS at 3-59. NRC concedes that "The visual presence of wells and header houses coul also impact the natural setting and overall cultural landscape." EIS at 4-3. Under the National Historic Preservation Act, the federal government must protect not only the sites themselves but also their settings. We are concerned that improperly sited wellfields will impose

wellsites, access roads, and other forms of industrial facilities that are inconsistent with maintaining the historic settings of the sites in question. With this in mind, wellfields should be configured such that facilities do not occur within the viewsheds of NRHP-eligible sites.

Lost Creek Road needs to be Restored to a Two-track

The NRC notes that the Lost Creek Road would be upgraded from a two-track to an engineered gravel road for the project, and would likely remain as such after the project's completion. EIS at 4-24. This road should be required to be reclaimed following cessation of operations, whereupon it could revert to a two-track vehicle way. Currently the Red Desert has a large surplus of unnecessary engineered roads which contribute needlessly to habitat fragmentation and disturbance of wildlife, and there is no reason to perpetuate this project-related impact beyond the life of the in-situ uranium recovery. It is doubtful that the county (or any other entity) will have the funding to properly maintain such a road, and being abandoned for all practical purposes it would be subjected to erosion that may ultimately make it less passable than a two-track (this happens frequently in the Red Desert).

Conclusions

Given the sensitivity of sage grouse Core Areas and the likelihood that this project will impair or eliminate the habitat function for sage grouse within and adjacent to the project area, we recommend that NRC choose Alternative 2 (the "No Action" alternative) for this project. Thank you for the opportunity to comment, and please send all additional public information concerning this project.

Sincerely yours,

Erik Molvar
Wildlife Biologist

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Climate-induced formation of a closed basin: Great Divide Basin, Wyoming

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ABSTRACT

Large closed basins are often associated with regions of active tectonics. In contrast, we provide the example of the Great Divide Basin, in southern Wyoming, where climate change, through its impact on erosion and flexure, provides the primary mechanism of basin closure. Two- and three-dimensional flexural models that incorporate the effects of local basin abandonment due to aridity as well as minor extrabasinal extension demonstrate that basin closure with 40 m of basement relief (tilt) could have been achieved in the Great Divide Basin under reasonable assumptions of sediment rock density and flexural rigidity. The primary drive for basin abandonment was insufficient discharge that retarded river downcutting. Continued erosion in the surrounding drainage led to flexural rebound, against which erosion by the outlet from the Great Divide Basin was unable to compete. Eventually, the basin became detached and isolated from the surrounding drainage, and a few tens of meters of differential tilt developed between the basin floor and spillover point. An extra amount of tilt, up to a few meters, could have been attained by rift shoulder effects associated with minor nearby extension outside of the basin to the north. Hence, closure of the Great Divide Basin took place with no internal faulting, nor did it require any extrabasinal tectonic activity to force basin closure. Hence, basin closure and/or drainage reorganization need not record tectonic activity in all cases. Differential erosion provides an alternative hypothesis that does not reflect local tectonic timing. Our model of the evolution of the Great Divide Basin illustrates a mechanism by which basins can become closed by climatic effects alone.

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INTRODUCTION

Large closed basins are typically associated with active tectonism in a variety of settings. Examples include Pyramid Lake, Nevada (with 109 m relief between basin floor and spillover point), in an extensional setting; Death Valley, California (148 m), in a strike-slip setting; and Qinghai Lake, north-central China (28 m), in a compressional setting. Such basins may be dry or contain lakes, depending on water supply (Carroll and Bohacs, 1999). In all cases, closed basin formation occurs where rates of sediment supply derived from surrounding mountain ranges lag behind rates of space created (accommodation) by tectonic activity in the basin (Carroll and Bohacs, 1999; Humphrey and Konrad, 2000; Garcia-Castellanos, 2007). Accommodation may result from basin subsidence or rate of surface uplift of a bounding tectonic sill. Typically, closed basins are geologically short-lived—once tectonism abates, continued sediment supply, coupled with erosional downcutting of the spillover point, eventually eliminates topographic barriers to drainage.

The Great Divide Basin of south-central Wyoming (Fig. 1) stands in contrast to closed basins formed in tectonically active settings. The basin is a large (~10^4 km^2), internally drained, topographic depression that sits at high elevation (2100 m average) astride the U.S. continental divide. With tens of meters of closure between basin floor and spillover point, the basin is as large as or larger than most closed basins. In this part of the Rocky Mountains, there is thought to be little recent tectonic activity (Flanagan and Montagne, 1993) and no known recent faulting within the basin. As such, an obvious tectonic origin of the Great Divide Basin is a difficult case to make. Alternatively, we suggest here that basin closure was primarily the result of an isostatic response to the climatically induced isolation of the basin from the surrounding drainages. Such a mechanism may play a role in other closed basins not directly controlled by active tectonism along their margins.

GREAT DIVIDE BASIN

The Great Divide Basin was originally part of a foreland basin bounded by the Sevier fold-and-thrust belt to the west during Cretaceous–early Eocene time. In Late Cretaceous time, the Laramide orogeny partitioned the foreland region into individual basins bounded by narrow basement-cored ranges (Snoke, 1993). This event produced the thrust-bounded ranges and domal uplifts that surround the Great Divide Basin today (Fig. 1). During the early part of the Laramide orogeny, the basin was a part of the greater Green River Basin (Surdam and Stanley, 1980). Subsequent relative uplift of the Rock Springs Uplift to the west and the Rawlins Uplift to the east (Fig. 1) during Late Cretaceous through Paleocene time further defined the margins of the Great Divide Basin (Lillegraven et al., 2002; Mederos et al., 2005). The basin was not closed, however, until at least middle to late Miocene time (Hansen, 1986; Lillegraven and Ostresh, 1988). Prior to this time, the basin drained to the east, into the Platte River system.

Continued, subtle, post-Laramide tectonism has affected the Rocky Mountains, including regional doming that began after 8 Ma and was well on its way by ca. 4 Ma (McMillan et al., 2006). Local post-Laramide tectonism and volcanism close to the Great Divide Basin include the extensional collapse of the Granite Mountains (beginning ca. 11–7 Ma; Anders et al., 2009) to the north, the propagation of the Rio Grande Rift to the east of the Sierra Madre Mountains (beginning 10–8 Ma; Mears, 1998; Keller and Baldridge, 1999), and eruption of the Leucite Hills (3–0.8 Ma; Lange et al., 2000) around the Rock Springs Uplift on the western margin of the basin.

It is unclear exactly when the Great Divide Basin became isolated from the Platte River drainage. Regional studies indicate that the basin and adjacent parts of the Northern Platte River drainage were buried under >600 m of Oligocene–Miocene basin fill after the end of

GSA Bulletin; doi: 10.1130/B30113.1; 6 figures; 1 table; Data Repository item 2010158.

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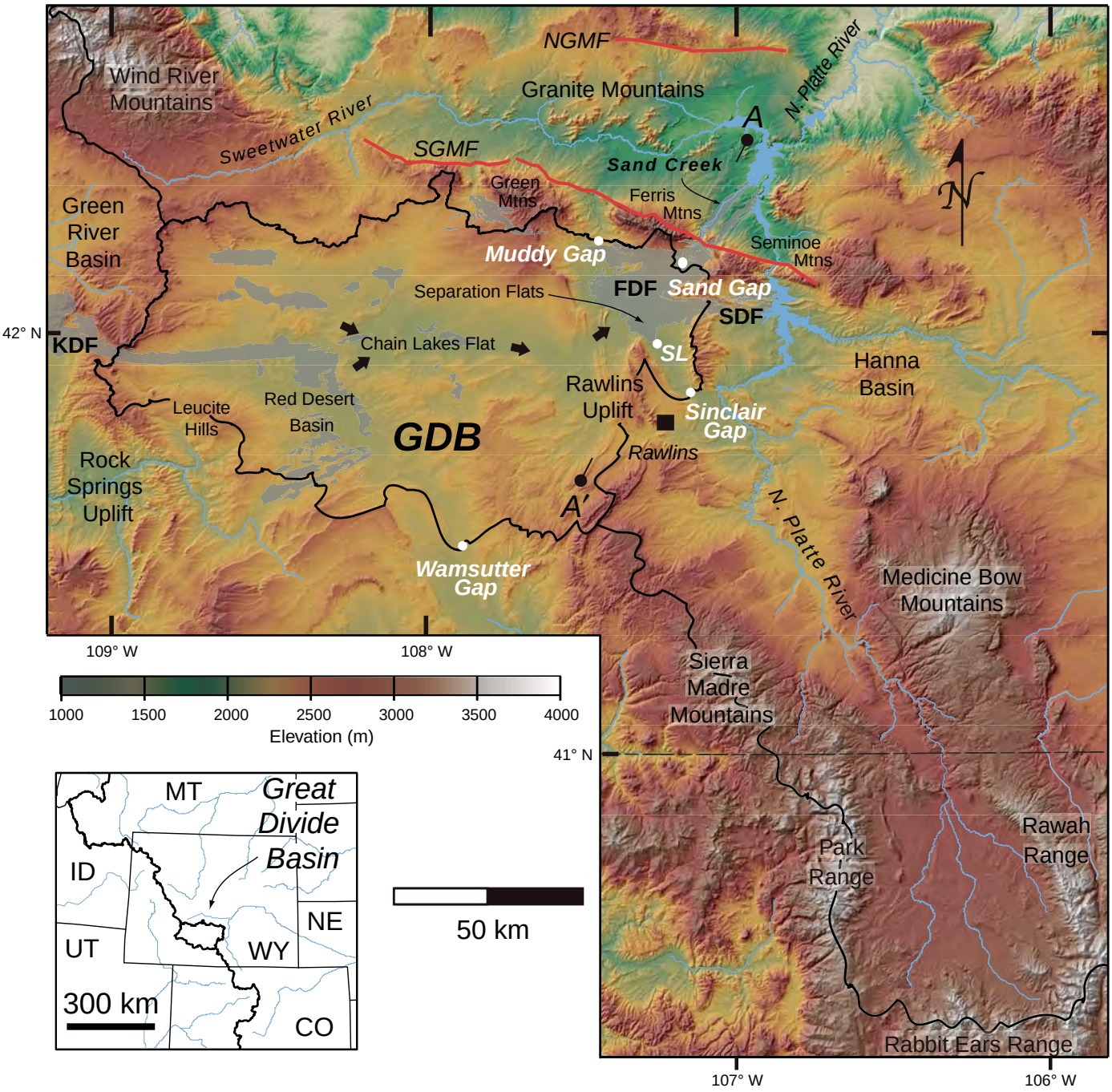

Figure 1. Location and topography of the Great Divide Basin (GDB), southern Wyoming. The basin is surrounded by the continental divide (bold line on inset map). Locations of likely outflows for the basin are shown in white. Young faults are shown in red (South Granite Mountain fault—SGMF; North Granite Mountain fault—NGMF). Gray shading shows location of significant sand dune deposits (KDF—Killpecker dune field; FDF—Ferris dune field; SDF—Seminoe dune field). SL—Separation Lake, the low point in the Great Divide Basin. Arrows indicate flow path of river that previously drained the basin. Cross section A-A′ is used for two-dimensional flexural model (Fig. 2).

the Laramide orogeny (McMillan et al., 2006). These alluvial deposits in areas surrounding the basin reach an elevation of ~2200 m, roughly 250 m above the present spillover point out of the basin. The switch from net aggradation to net incision of Laramide basins in this part of the Rocky Mountains took place after 6.75 Ma, the age of tuffs found at the base of the Moonstone Formation, located just north of the study area in the Granite Mountain block (Anders et al., 2009). Incision of the lowest 100 m of the Great Divide Basin took place over the past 1 m.y., based on the dates and elevations of lava flows found in the Leucite Hills, along the western edge of the basin (Lange et al., 2000). Abandonment of through-going drainage in the basin took place prior to 7 ka, the age of sand dunes shrouding the basin floor. Hence, closure of the Great Divide Basin by a few tens of meters took place between 1 Ma and 7 ka.

Today, the Great Divide Basin's internal drainage consists of ephemeral streams that flow into large playas and small perennial lakes, or disappear beneath active eolian sand dune and sheet deposits. These arid landforms are consistent with modern conditions of low mean precipitation and high mean evaporation rates. Sand dune fields cross into the basin on its western margin, occur on the leeward side of many playas within the basin, and blanket the basin's northeastern margin (Fig. 1). Dune fields trend west to east, parallel to the prevailing westerly wind direction. Winds blow on average 25 km/h in summer and 36 km/h in winter from the west southwest (Martner and Marwitz, 1982). The largest fields include the Killpecker, Seminoe, and Ferris dunes (Fig. 1). The dune fields are as old as latest Pleistocene and have been active throughout the Holocene, with periods of activity coinciding with periglacial conditions (Mayer and Mahan, 2004). Sedimentary and geomorphic evidence from study of the Ferris dune field suggests that wind strength, intensity, and direction have not varied much since the end of the Pleistocene (Gaylord, 1982).

Large playas coincide with the lowest elevations in the basin and broadly define three subbasins separated by ridges of resistant fine-grained sedimentary rocks. The three subbasins include the northwest-southeast–trending Red Desert Basin, an east-west–trending longitudinal valley made up of the Lost Creek Basin, Battle Spring Flat, and Chain Lakes Flat (hereafter identified collectively as the Chain Lakes Flat), and the northwest-southeast–trending Separation Flats (Fig. 1). The Red Desert Basin and Chain Lakes Flat are underlain by the predominantly fluvial and lacustrine deposits of the Tertiary Battle Spring, Wasatch, and Green River formations (Bradley, 1964). Separation Flats is underlain by Upper Cretaceous marine rocks of the Steele Shale, Cody Shale, Mesaverde, and Niobrara Formations (Barlow, 1953; Bayley, 1968).

TOPOGRAPHY

In order to determine where the Great Divide Basin drained prior to closure, we compiled a data set including elevations of divides and other potential overflow points, drainages, and possible burial of such features by eolian sand accumulations from a variety of sources including elevations from U.S. Geological Survey (USGS) digital elevation models (DEMs; 30 m resolution), spot elevations using mapping-grade Trimble differential GPS unit (DGPS) (20 cm resolution after postprocessing), available geologic mapping, and well-log data from the Wyoming Oil and Gas Conservation Commission and Wyoming State Geological Survey.

The average elevation of the Great Divide Basin is 2100 m above mean sea level. Total relief within the basin is significant at ~1100 m difference between the highest point along the crest of the Ferris Mountains (3050 m) and the lowest point in Separation Flats (1947 m). However, on average, the basin is quite flat. Over 80% of the basin area falls within the 1947–2150 m elevation range, and less than 4% of the basin area is above 2300 m above mean sea level. It is important to note that there is very little high topography, and therefore mountain drainage, in the Great Divide Basin catchment (Fig. 1). In contrast, the North Platte drainage, bounding the east and north sides of the basin, drains much of the high topography in this part of the central Rocky Mountains.

Low points in each of the subbasins occur at 2005 m in the Red Desert Basin, 1970 m in the Chain Lakes Flat, and 1947 m in Separation Flats. The lowest points within each subbasin step down in a generally west-to-east pattern. Similarly, the spillover points today between the subbasins step down from west to east from 2038 m between Red Desert Basin and Chain Lakes Flat, to 2005 m between Chain Lakes Flat and Separation Flats, to 1996 m between Separation Flats and the North Platte drainage (Fig. 1).

The lowest gaps along the basin divide (Fig. 1) include Wamsutter Gap (2051 m), Muddy Gap (2066 m), Sinclair Gap (1996 m), and Sand Gap (2097 m). The first three sites have exposed Cretaceous bedrock at the surface, and thus these are minimum spillover elevations. At the Sand Gap site, however, the minimum elevation is located among sand dunes within the Ferris dune field. Sand dunes have blown over Sand Gap and migrated partway down Sand Creek to the north (Fig. 1). Bedrock exposed among the dunes at Sand Gap is at an elevation of 1990 m, which is slightly lower than the elevation of the divide at Sinclair Gap. The largest horizontal distance between bedrock exposures in the Sand Gap area is ~120 m. Therefore, it is possible that sand hides a buried, narrow valley beneath which bedrock basement may be somewhat lower.

Sand Gap seems the most likely outflow from the Great Divide Basin. Not only is bedrock somewhat lower here than at other candidate areas, but Sand Creek, which runs through Sand Gap to join the North Platte River (Fig. 1), has well-developed and extensive high terraces several meters above the current small creek. Bedrock clasts among terrace remnants suggest significant outflow through Sand Creek. These terraces have been partially buried by migrating sand dunes. Thus, a river clearly flowed through the gap prior to the period of Holocene drying. Projection of terrace surfaces suggests that the spillover point at Sand Gap was not much below 1990 m. The maximum relief between the lowest spot in the basin, Separation Lake (at 1947 m), and the bedrock overflow at Sand Gap (1990 m) is 43 m. These sites are located roughly 30 km from each other. It is unclear what generated this closure.

ORIGIN OF BASIN CLOSURE

While there is no known tectonic activity along the northern basin margin, there is evidence of young normal faulting farther to the north, along the northern flank of the Ferris and Seminoe mountains. Love (1970) describes a west-northwest–trending normal fault, the South Granite Mountain fault (SGMF, Fig. 1) that bounds the southern edge of the Granite Mountain block. The structure is near vertical, probably becoming listric with depth (Blackstone, 1991) and places Miocene age deposits (Moonstone Formation) against basement rocks. Displacement along the fault reaches up to 610 m at the far west end of the South Granite Mountain fault (Love, 1970). However, cross sections constrained by well data indicate offset is closer to 200 m around the location of Sand Creek (Love, 1970; Blackstone, 1991). Subparallel faulting along the northern margin of the block (North Granite Mountain fault; Fig. 1) indicates that the Granite Mountains sit in a graben (Love, 1970). Available age constraints indicate that normal faulting began between ca. 11 and 7 Ma, and may be continuing today (Anders et al., 2009). Along the northern flank of the Seminoe Mountains, to the east of Great Divide Basin, truncated spurs provide geomorphic evidence of offset along the fault (Jaworowski, 1985). However, no similar topography is seen in the vicinity of Sand Creek, the proposed outlet of the Great Divide Basin (Fig. 1).

Impact of Extrabasinal Tectonics

It is possible that if there were young, significant normal fault offset along the South Granite Mountain fault, it could have played a role in closing the Great Divide Basin. Normal offset would not close the basin by building a tectonic dam along Sand Creek. In fact, normal fault offset, had it occurred along the drainage, would have led to the formation of a knickpoint, and would have accelerated erosion along the stream, facilitating downcutting. Instead, any significant reduction in tectonic load by thinning of the crust along the margin of the Granite Mountain graben could lead to flexural rebound adjacent to the graben margins. This phenomenon contributes to the formation of "rift shoulders" (Weissel and Karner, 1989; Chéry et al., 1992). Tilting to the south away from the graben would help provide a slope that, under the right conditions, could contribute to closing of the Great Divide Basin.

In order to evaluate this mechanism as a cause of tilting in the eastern Great Divide Basin, we constructed a simple two-dimensional flexural model using cross sections of the Granite Mountains provided by Love (1970). Two-dimensional modeling is appropriate because the load, the Granite Mountain graben, is an elongate feature, and we are modeling a location near the approximate midpoint of the graben margin, so that three-dimensional boundary effects are unlikely to play a significant role. The geologic history of the Granite Mountain block suggests that during, or following, downdrop of basement rocks, sedimentation took place. Assuming the South Granite Mountain fault does not offset the Moho, the result of the net effect of extension and basin filling is to replace basement rock (density ~2850 kg/m^3) with sedimentary rock of density between 2200 and 2500 kg/m^3. Thus, density contrast ranges from 350 to 650 kg/m^3. For simplicity, we assume a rectangular load shape for the graben geometry. Load width is the half-width of the graben, which along our cross section is 24 km. The elastic plate is assumed to be laterally infinite, and thus half the load is compensated for by that part of the plate that extends to the north. For flexural rigidity, we assumed values ranging from 10^{22} to 10^{23} N•m. This range includes the best-fit values for the subsidence geometry of the Cretaceous foreland basin across southern Wyoming (Jordan, 1981; Liu and Nummedal, 2004). Load height is ~200 m based on fault offset of the Split Rock Formation along a cross section near the modern Sand Creek (Love, 1970; Blackstone, 1991). We calculated the resultant relief (tilt) due to rift shoulder development between Sand Gap and Separation Lake (Fig. 2), which lie 30 km apart from each other. Sand Gap is located ~3 km south of the South Granite Mountain fault (Fig. 1). Our estimates of relief were calculated for a variety of likely sediment-fill densities and flexural rigidities. The tilt between Sand Gap and Separation Lake ranges from 2.5 m and 12.4 m, depending on the assumed density and rigidity (Table 1; Fig. 3, white bars). Such values fall far short of the required basement tilt of ~40 m that closes the basin.

Role of Climate Change

The Great Divide Basin today is very dry. The basin has low mean precipitation rates (12–30 cm/yr, avg. 1961–1990; U.S. Department of Commerce, 2005) coupled with high mean evaporation rates (>75 cm/yr of shallow lake evaporation, avg. 1956–1970; Farnsworth et al., 1982). Being on the continental divide,

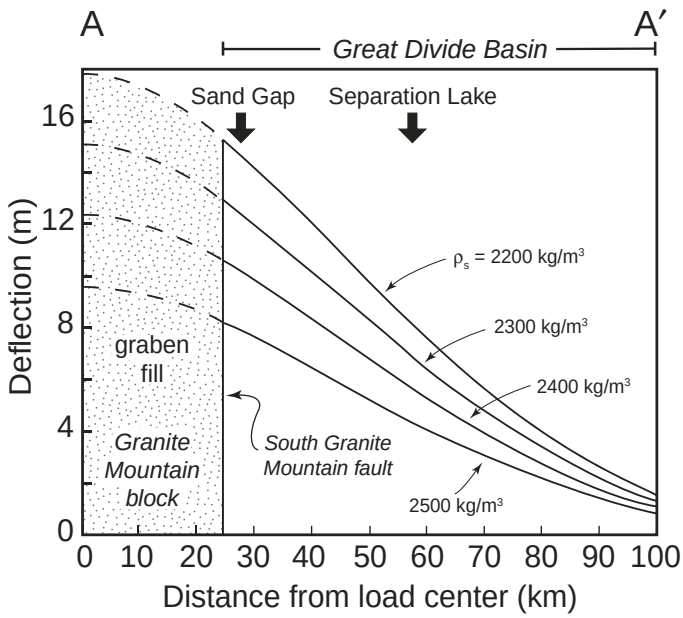

Figure 2. Calculated flexural rebound due to graben development along the Granite Mountain block. Cross section A-A′ (Fig. 1) runs from the Granite Mountain block across the Great Divide Basin. Flexural response is calculated for rigidity of $10^{22.5}$ N•m and assumes that density of sediment filling Granite Mountain graben ranges from 2200 to 2500 kg/m^3, replacing material that is 2850 kg/m^3. Results are calculated for fault offset of 200 m along the South Granite Mountain fault. Solid lines are flexural profiles within Great Divide Basin; dashed lines are profiles within Granite Mountain block. Locations of basin spillover (Sand Gap) and basin low point (Separation Lake) are shown.

TABLE 1. CALCULATED TILT RESULTING FROM RIFT SHOULDER AND REGIONAL EROSION

Flexural rigidity and equivalent effective elastic thickness (EET)	Sedimentary rock density (kg/m^3)	Rift shoulder tilt (relief) from Separation Lake to Sand Gap (M)	Erosional tilt (relief) from Separation Lake to Sand Gap (M)	Total tilt (m)
10^{22} N•m (EET = 11.7 km)	2200	12.4	50.6	63.0
	2300	10.5	56.6	67.1
	2400	8.6	63.7	72.3
	2500	6.7	72.0	78.7
$10^{22.5}$ N•m (EET = 20.0 km)	2200	6.6	27.1	33.7
	2300	5.6	29.7	35.3
	2400	4.6	32.6	37.2
	2500	3.6	35.9	39.5
10^{23} N•m (EET = 25.2 km)	2200	4.7	18.7	23.4
	2300	4.0	20.3	24.3
	2400	3.3	22.2	25.5
	2500	2.5	24.2	29.7

overall elevations are high; however, there is very little relief within the catchment and surrounding range crests. As a result, there is little, if any, orographic impact on prevailing westerly weather fronts to force precipitation within the basin. In contrast, the North Platte River, which flows just east of the basin, originates in the high ranges of northernmost Colorado (Fig. 1). The catchment drains high ranges (>3500 m) where orographic effects promote high precipitation rates (up to >152 cm/yr, avg. 1961–1990; U.S. Department of Commerce, 2005), yielding perennial river flow.

The stark difference in aridity between the adjacent drainages today raises the possibility that change in climate could have impacted the catchments in the past. Specifically, we consider the impact of differential changes in discharge between the Great Divide Basin and adjacent North Platte River drainage during Pleistocene time.

A change in climate alone need not yield any change in differential precipitation between the Great Divide Basin and North Platte River drainages. The nearly ten-fold difference in annual precipitation seen today due primarily to orographic effects could well have existed in Pleistocene time. In the study area, however, Pleistocene glaciation was limited to the headwaters of the North Platte River, with none forming along highlands of the Great Divide Basin (Pierce, 2004). Meltwater was released as glaciers retreated during times of warming climate. This led to periods of high discharge in the Platte river drainage and likely increased erosion. Meanwhile, the absence of glaciers, and thereby significant water storage, in the Great Divide Basin precluded similar magnitudes of stream incision. As a result, rapid downcutting along the Platte River during meltwater times was not matched in the Great Divide Basin—the latter of which was left literally high and dry.

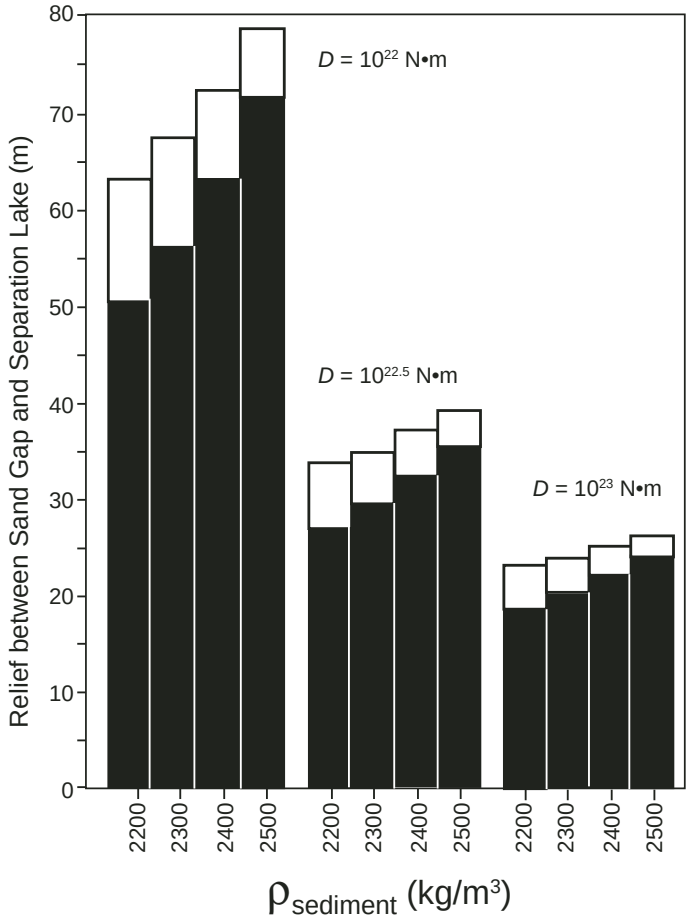

Figure 3. Calculated relative relief between the low point in the basin (Separation Lake) and the inferred spillover point (Sand Gap) due to flexural response related to unloading. Black bars result from removal of deposits along the North Platte River drainage as calculated from the three-dimensional (3-D) flexural model. White bars show tilt due to rift shoulder effects from normal faulting within the Granite Mountain block. Results are for a range of rigidities (10^{22}, $10^{22.5}$, 10^{23} N•m) and assumed density of sedimentary rocks (2200, 2300, 2400, 2500 kg/m^3).

Impact of Extrabasinal Erosion

While the North Platte River continued to erode down to its present position, the Great Divide Basin became abandoned and then closed. The North Platte drainage has eroded a deep, wide valley just northeast of the much higher Great Divide Basin. It therefore seems possible that the strong asymmetry in erosion rates between these drainages may have contributed to closure of the basin due to regional isostatic response (i.e., flexure). Was the flexural uplift due to removal of basin fill in the North Platte drainage enough to lead to the observed differential uplift between Sand Creek Pass and Separation Lake?

In order to evaluate the flexural effect of regional erosion, we applied a three-dimensional elastic flexural model to the northeastern Great Divide Basin, in the vicinity of the Sand Gap spillover point. To facilitate model construction, we assumed that the elevation of the Platte River near where the drainage from the Great Divide Basin once flowed was close to the present elevation of the spillover at Sand Gap, i.e., 1990 m. Thus, we assume that any incision by the North Platte drainage below this elevation took place after the Great Divide Basin was no longer connected to the Platte River. The removal of material below this elevation would then lead to isostatic rebound in the area affected by the flexural effects.

Figure 4 shows the present distribution of the 1990 m contour surrounding the modern Platte River. This contour line is assumed to represent the limits of Platte River erosion since isolation of the Great Divide Basin. We only modeled the region shown in Figure 4, an area of 100 × 120 km. This area includes the northeastern limit of the basin and adjacent parts of the North Platte River drainage from the towns of Rawlins to Casper, Wyoming. This modeled area is closest to the former spillover point at Sand Gap, where flexural impacts would have been greatest. Erosion farther downstream along the North Platte River would have added to the calculated flexural response; however, loads farther away have exponentially less impact on flexure in the area of interest and are considered to have minimal impact on our results.

To facilitate modeling, we broke this region into a series of cylindrical point loads, each 5 km in diameter (Fig. 4), the removal of which leads to flexural rebound. The height of each

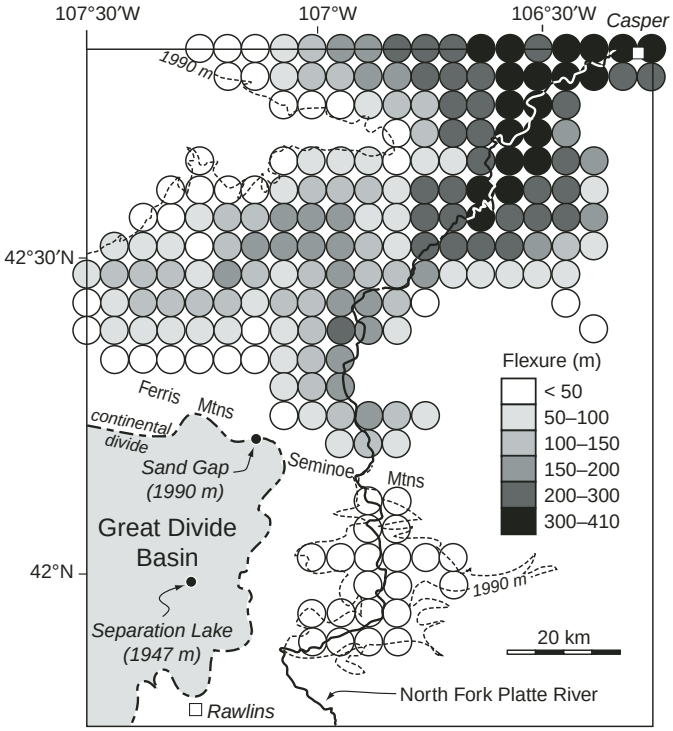

Figure 4. Area modeled in three-dimensional (3-D) flexure analysis. The northeast margin of the Great Divide Basin is shaded. The 1990 m contour (thin dashed line) is model datum. Incision into datum forms the erosional load for model runs. Location and thickness (binned) of eroded cylindrical loads are shown by shaded circles. Position of North Fork of the Platte River, continental divide, and location of the towns of Rawlins and Casper, Wyoming, are shown.

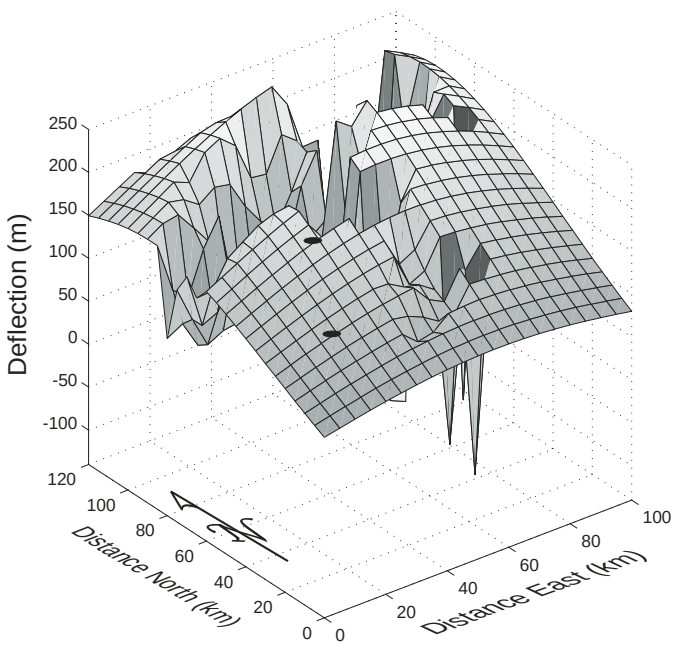

Figure 5. Results of three-dimensional flexural model. Graph shows position of an originally horizontal datum surface following erosion along the North Platte drainage as described in text and resulting flexural rebound ($D = 10^{22.5}$ N•m, $\rho_s = 2500$ kg/m^3). Positions of Sand Gap (to the north) and Separation Lake are shown by black disks.

eroded load was determined from the average elevation of each 5-km-square grid point over which these cylinders were centered. We calculated the difference between average elevation of each cell and the 1990 m datum representing the preerosion surface. The erosion of each grid point is available in the GSA Data Repository,[1] but the general heights of each load, binned, are shown in Figure 4.

Our flexural model assumes the elastic plate was infinite in all directions. Model runs used a range of densities of eroded sedimentary rock (2200–2500 kg/m^3) and flexural rigidities (10^{22}–10^{23} N•m, equivalent to effective elastic thickness of 12–25 km; Table 1). An example of a calculated flexural response to removal of the eroded material using a flexural rigidity of $10^{22.5}$ N•m is shown in Figure 5. Both the shape and magnitude of doming associated with regional erosion are shown. In the area of analysis, rebound generates between 19 and 50 m of relief, depending on assumed flexural rigidity value and the density of eroded material (Table 1). The model assumes that topography of the area prior to erosion was that of a flat surface at 1990 m. Therefore, we ignore any erosion that might have taken place in the preexisting mountains surrounding the region, which would only serve to increase the possible amount of rebound and tilt. Thus, we consider the model response to be a minimum estimate at that flexural rigidity.

DISCUSSION

In order to explain the basin closure with ~40 m of relief between the basin low point and the spillover at Sand Gap by flexural response, either the assumption of low flexural rigidity is required for the erosional model alone, or for the combined isostatic effects of regional erosion as well as tilting due to rifting to the north (Fig. 3; Table 1). We find that if we use the best-fit flexural rigidity determined by analysis of Cretaceous foreland basin deflection in southern Wyoming ($10^{22.5}$ N•m; Liu and Nummedal, 2004), we get excellent agreement with the observed relief of basin closure in the Great Divide Basin (34–40 m depending upon sedimentary rock density assumed; Fig. 3). An increase in flexural rigidity to 10^{23} N•m yields insufficient rebound to explain the observed relief (Table 1).

The flexural model described here has little impact on the paleoelevations of the other candidate overflow points. The position of Sand Gap, in the NE corner of the basin, allows it to

[1]GSA Data Repository item 2010158, Table of load magnitudes, is available at http://www.geosociety.org/pubs/ft2010.htm or by request to editing@geosociety.org.

be maximally impacted by both the area of greatest erosion along the North Platte River to the northeast and the normal faulting to the north. We have not observed any other erosional or tectonic patterns in the vicinity of the other potential overflow points around the basin that would yield comparable results from flexural modeling.

It is possible that some additional relief may have been generated by local wind deflation in the area of Separation Lake. We have observed occasional ventifact clasts in this part of the basin. Wind erosion on the order of 10 m would make it possible for the higher rigidity to provide a reasonable fit. Regardless, we find it interesting that rigidity of $10^{22.5}$ N•m best explains both the Cretaceous subsidence history of southern Wyoming as well as our Pleistocene to Holocene reconstruction. This suggests there has been little net change in regional rigidity over the past ~70 m.y. across southern Wyoming, despite the Laramide crustal thickening that occurred during this time.

Model of Basin Evolution

Our results suggest that climate, leading to low erosion rates in the Great Divide Basin in contrast to high erosion rates nearby, coupled with an isostatic flexural response can explain basin closure and most of the relief between the basin low point and spillover point. A key factor to this interpretation is that the Great Divide Basin, once tributary to the North Platte River, is arid and has very little potential to integrate much precipitation despite its large size. None of the ranges surrounding the basin has high enough relief to force much orographic precipitation today. In addition, none of the ranges has large enough catchment area to provide significant discharge to the basin.

During Pleistocene time, glaciers that formed in the headwaters of the North Platte River (Fig. 6), but not in the Great Divide Basin, provided a means for high discharge during meltwater events during periods of glacial retreat (e.g., Pelletier, 2009). Accelerated erosion along the North Platte River, but not the Great Divide Basin outflow, led to isolation of the latter from the Platte drainage. Erosion in excess of 200 m by the North Platte River led to isostatic rebound that flexed the northeast corner of the Great Divide Basin, creating significant relief in the area of the basin outlet (i.e., tens of meters), which forced basin closure. Rigidities of the order $10^{22.5}$ N•m generated a broad doming that affected the entire eastern part of the basin as well as nearby areas (Fig. 6). In addition, normal faulting along the Granite Mountain block to the north of the Great Divide Basin (SGMF in Fig. 6) that took place sometime in the past <11 m.y. encouraged minor back tilting due to flexural rift shoulder effects. This added to closed basin relief, albeit to a minor extent.

Finally, windblown dunes formed as a result of continued aridification of the central Rockies and adjacent Great Plains over Holocene time (Marrs et al., 1987). Dune fields are common along the Wyoming Wind Corridor, which runs east across the southern half of Wyoming including the Great Divide Basin. A discontinuous line of sand dunes can be traced across the basin into the area of the basin outlet at Sand Gap (Fig. 1). Sand dunes bank around the northeast basin margin and overtop the divide into the adjacent Platte River drainage. The dunes add as much as an extra ~100 m of relief to the basin closure in the area of Sand Gap.

CONCLUSIONS

Two- and three-dimensional flexural analysis suggests that closure of the Great Divide Basin was likely due to enhanced erosion in the adjacent North Platte River drainage. Enhancement of

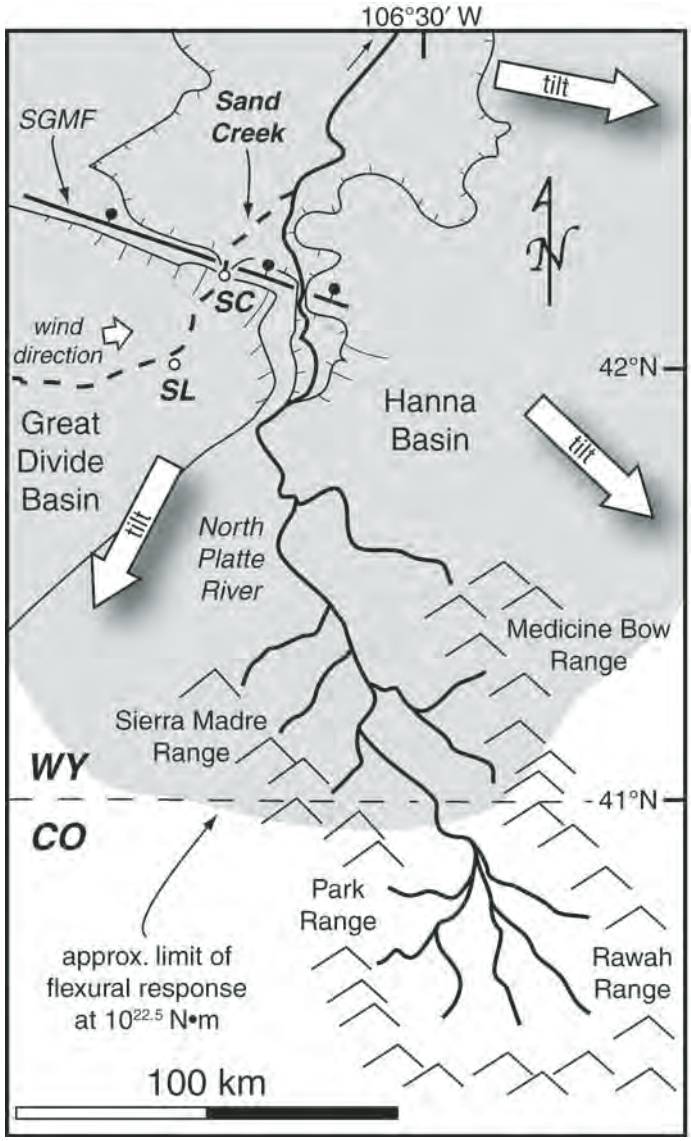

Figure 6. Key elements for interpretation of climatic cause of closure of the Great Divide Basin. Shaded region shows approximate area that underwent flexural response and unloading due to erosion by the North Platte River (assuming flexural rigidity of $10^{22.5}$ N•m) as well as thinning of the Granite Mountain block. Heavy dashed line follows approximate trace of previous drainage out of Great Divide Basin. SC—Sand Creek Gap, SL—Separation Lake.

this closure was due to minor extrabasinal tectonic impact and the encroachment of sand dunes due to increased aridification in Holocene time. In our model, differential erosion is caused by increased meltwater discharge during periods of deglaciation. Headwaters of the North Platte River were glaciated; the Great Divide Basin was not.

Because of the competition between the effects of rift shoulder and erosional tilt, the results are not very sensitive to the sediment density assumed. The greater is the sediment density, the more erosional rebound plays a role, and the less rift shoulder uplift contributes. The amount of calculated tilt is sensitive to the flexure rigidity of the lithosphere, producing a good fit with observed basin relief if a rigidity of $10^{22.5}$ N•m is used. This value is the best fit found by Liu and Nummedal (2004) in their study of Cretaceous foreland basin development across the same part of Wyoming. Hence, this suggests that net regional flexural rigidity has not changed over the intervening ~70 m.y.

Isostatic impacts caused by differential erosion may play roles in drainage reorganizations and basin closure, and locally enhance structural features in a variety of locales (e.g., Simpson, 2004). Deep incision of the Grand Canyon by the Colorado River has led to in excess of 300 m of flexural rebound (Pelletier, 2010). With broad wavelength deformation on the scale of 100 km, flexural rebound may have led to drainage reorganization and drainage reversal along the canyon rim. Similarly, Qinghai Lake, the largest lake in China, sits near the northeast margin of the Tibetan Plateau. The lake sits in a shallow closed basin that may owe its origins to basin closure due to nearby erosion by the Yellow River.

Our results indicate that the presence of a closed basin does not require, nor should be taken as proof of, tectonic activity. Flexural response to moderate differential erosion, as seen in this analysis, can generate tens of meters of tilt over wavelengths of many tens of kilometers. Such modest topography is sufficient to close basins in most settings. An even greater degree of closure would have occurred if more incision had taken place. Although perhaps atypical, it seems that under special circumstances, climate alone can lead to closed basin formation.

ACKNOWLEDGMENTS

Field assistance was graciously provided by Peter Beland, Max Garnier, Steve Holbrook, and Cliff Riebe. We thank Xiangyang Xie for allowing us to use his three-dimensional flexure program, and PASSCAL (IRIS) and Bryan Shuman for use of geophysical equipment used to determine depth to bedrock. We benefited from discussions with Bryan Shuman and reviews by Peter Molnar and Christian Koeberl. Funding was made available through the Petroleum Research Fund of the American Chemical Society.

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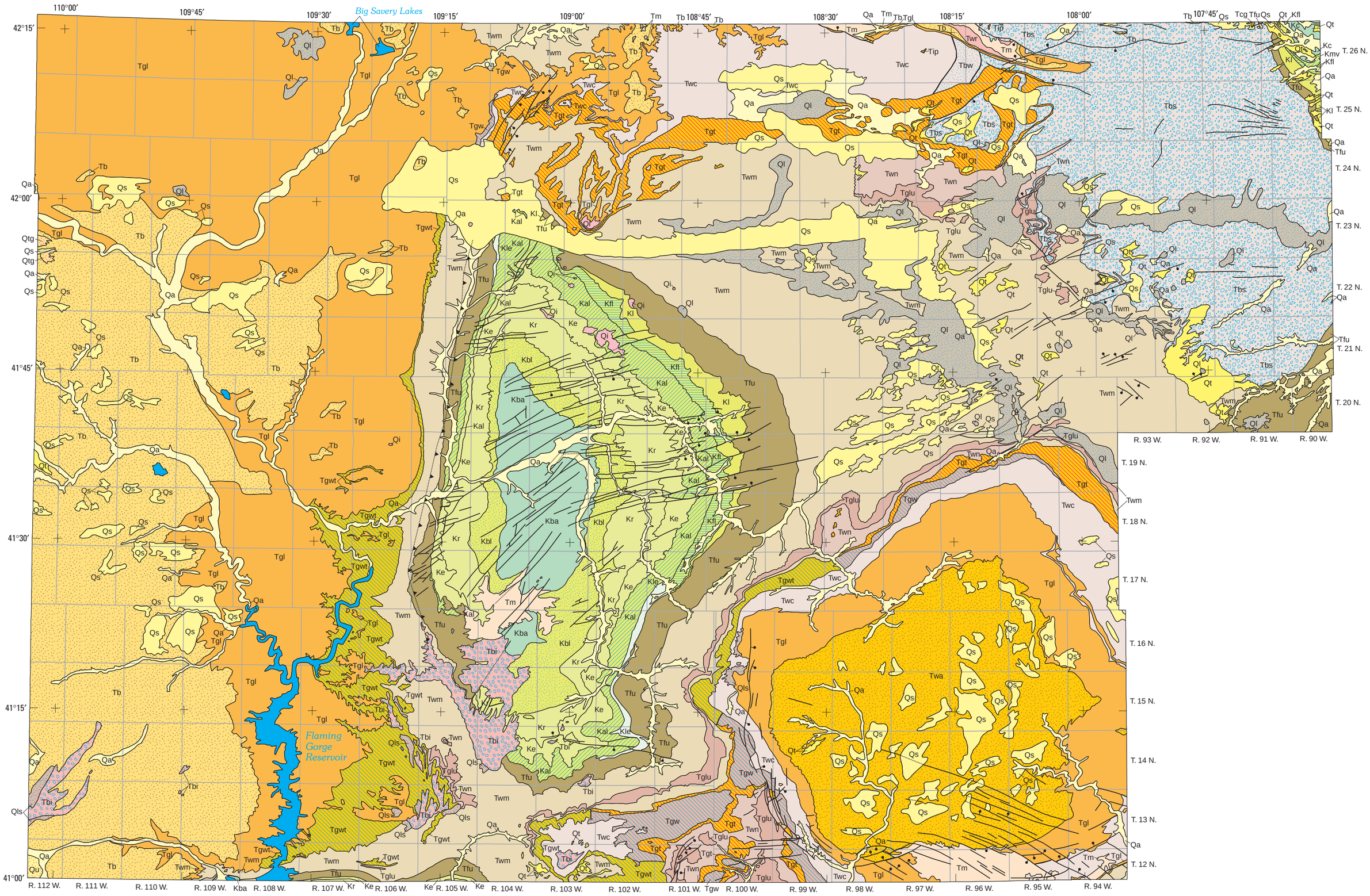
Manuscript Received 20 June 2009
Revised Manuscript Received 2 February 2010
Manuscript Accepted 4 February 2010

Printed in the USA



Planimetric base modified from U.S. Dept. of Commerce, Bureau of the Census digital data, 2001
Public land survey system from Wyoming Water Resources Center digital data, 1994
Hydrography modified from USGS National Hydrography Dataset (NHD) digital data, 1999
Lambert Conformal Conic projection
Standard parallels 41° and 42°, central meridian –108°45′

0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS

Geology from Love, J.D., and Christiansen, A.C., 1985

EXPLANATION

QUATERNARY UNCONSOLIDATED DEPOSITS AND IGNEOUS ROCKS

- Qa — Alluvium and colluvium
- Qt — Gravel, pediment, and fan deposits
- Qls — Landslide deposits
- Qs — Dune sand and loess
- Ql — Playa lake and other lacustrine deposits
- Qu — Undivided surficial deposits
- Qi — Alkalic extrusive and intrusive igneous rocks
- Qtg — Terrace gravel

TERTIARY SEDIMENTARY AND IGNEOUS ROCKS

- Tm — Miocene rocks
- Tbi — Bishop Conglomerate
- Twr — White River Formation
- Tip — Ice Point Conglomerate
- Twa — Washakie Formation
- Tb — Bridger Formation
- Tcg — Crooks Gap Conglomerate[1]

Green River Formation

- Tgl — Laney Member
- Tgw — Wilkins Peak Member
- Tgwt — Wilkins Peak Member and Tipton Shale Member or Tongue
- Tgt — Tipton Shale Member or Tongue
- Tglu — Luman Tongue

Wasatch Formation

- Twc — Cathedral Bluffs Tongue
- Twn — Niland Tongue
- Twm — Main body
- Tbw — Transitional unit between Battle Spring Formation and Wasatch Formation
- Tbs — Battle Spring Formation
- Tfu — Fort Union Formation

[1]The areal extent of the Crooks Gap Conglomerate in Sweetwater County is small and not shown on the stratigraphic chart.

MESOZOIC SEDIMENTARY ROCKS

- Kl — Lance Formation
- Kfl — Fox Hills Sandstone and Lewis Shale
- Kle — Lewis Shale

Mesaverde Group

- Kmv — Mesaverde Group undivided
- Kal — Almond Formation
- Ke — Ericson Sandstone
- Kr — Rock Springs Formation
- Kbl — Blair Formation
- Kc — Cody Shale
- Kba — Baxter Shale

WATER AREAS

CONTACT

FAULT--Dotted where concealed. Bar and ball on downthrown side

THRUST FAULT (CONCEALED)--Sawteeth on upper plate. Thrust fault approximately located on the basis of seismic data and drilling

PLATE 1A. BEDROCK GEOLOGY