THE WILDERNESS SOCIETY
COALITION TO PROTECT AMERICA'S NATIONAL PARKS * CONSERVATION LANDS FOUNDATION * DEFENDERS OF WILDLIFE * NATIONAL PARKS CONSERVATION ASSOCIATION * NATURAL RESOURCES DEFENSE COUNCIL * ROCKY MOUNTAIN WILD

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SUBMITTED VIA E-PLANNING

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Re: Comments on the Draft Environmental Assessments and Findings of No Significant Impact for the Bureau of Land Management New Mexico 2026 First Quarter Competitive Oil & Gas Lease Sale (DOI-BLM-NM-P020-2025-1005-EA & DOI-BLM-NM-F010-2025-0033-EA)

To Whom It May Concern:

Thank you for the opportunity to submit these comments on the Draft Environmental Assessments (Draft EAs)[1] and Draft Findings of No Significant Impact (Draft FONSIs)[2]

[1] BUREAU OF LAND MGMT., CARLSBAD FIELD OFFICE OIL AND GAS LEASE SALE ENVIRONMENTAL ASSESSMENT, EDDY AND LEA COUNTIES, NEW MEXICO, QUARTER 1 2026, DOI-BLM-NM-P020-2025-1005-EA [hereinafter CARLSBAD DRAFT EA]; FARMINGTON FIELD OFFICE COMPETITIVE OIL AND GAS LEASE SALE ENVIRONMENTAL ASSESSMENT, RIO ARRIBA AND SANDOVAL COUNTIES, NEW MEXICO, QUARTER 1 2026 DOI-BLM-NM-F010-2025-0033-EA [hereinafter FARMINGTON DRAFT EA].

[2] BUREAU OF LAND MGMT., QUARTER 1 2026 COMPETITIVE OIL AND GAS LEASE SALE ENVIRONMENTAL ASSESSMENT, DOI-BLM-NM-P020-2025-1005-EA, FINDING OF NO SIGNIFICANT IMPACT [hereinafter CARLSBAD DRAFT FONSI]; QUARTER 1 2026 COMPETITIVE OIL AND GAS LEASE SALE ENVIRONMENTAL ASSESSMENT, DOI-BLM-NM-F010-2025-0033-EA, FINDING OF NO SIGNIFICANT IMPACT [hereinafter FARMINGTON DRAFT FONSI].

analyzing 28 parcels covering 19,527.56 acres out of the Carlsbad Field Office and 2 parcels covering 831.28 acres in the Farmington Field Office under consideration for potential oil and gas exploration and development for the Bureau of Land Management's (BLM's) New Mexico 2026 First Quarter Oil and Gas Lease Sale. Our organizations and members are deeply invested in sound stewardship of public lands and committed to ensuring that public land management prioritizes the health and resilience of ecosystems, benefits the public and local communities, protects biodiversity, and mitigates the impacts of climate change.

As the BLM prepares for this lease sale and evaluates which parcels to offer for lease, the agency must continue to abide by its obligations under the law and existing policy, including relevant portions of the Fluid Mineral Leases and Leasing Process Rule (Leasing Rule). In carrying out this lease sale, the BLM must comply with all applicable federal, state, and local laws and regulations.

I. The BLM has not ensured that leasing is compliant with FLPMA.

As explained in scoping comments,[3] plans governing lands subject to this lease sale are old or inadequately analyze impacts. None of the RMPs covering the parcels under consideration for this lease sale adequately accounts for or addresses the environmental impacts on resources and land uses due to climate change:

- BLM Carlsbad Field Office, Approved RMP (Sept. 1988): no discussion of climate change or GHG emissions; nor does the 1997 Amendment do so.[4]
- BLM Farmington Field Office, Approved RMP (Dec. 2003): never discusses climate change or greenhouse gas emissions.[5]

Consequently, the BLM should defer leasing in these areas until the agency can consider new inventories and analyze how best to protect the resources. At the very least, the agency must undertake a thorough analysis that considers the potential impacts new leasing and development might cause.

Even where implicated RMPs were finalized within the last five years, the BLM must take a hard look at new resource inventories and stipulations to ensure that new leases comply with existing plans, reflect updated inventory data, and adequately protect sensitive resources. Failure to consider, analyze, and disclose these issues violates the National Environmental Policy Act (NEPA) and FLPMA.

II. The Draft EAs and Draft FONSIs do not adequately analyze the environmental effects of leasing.

[3] *See* TWS et al., Scoping Comments on Parcels for the New Mexico Bureau of Land Management 2026 Quarter One Competitive Oil & Gas Lease Sale (DOI-BLM-NM-P020-2025-1005-EA & DOI-BLM-NM-F010-2025-0033-EA) 4–6 (June 11, 2025).

[4] BLM CARLSBAD FIELD OFFICE, APPROVED RESOURCE MANAGEMENT PLAN (SEPT. 1988); BLM CARLSBAD FIELD OFFICE, APPROVED RESOURCE MANAGEMENT PLAN (Oct. 1997).

[5] BLM FARMINGTON FIELD OFFICE, APPROVED RESOURCE MANAGEMENT PLAN (Dec. 2003).

The BLM must evaluate the environmental impacts of this proposed lease sale under NEPA. *See, e.g.*, 42 U.S.C. §§ 4331–4347. NEPA fosters informed decision making by federal agencies and promotes informed public participation in government decisions. *See Balt. Gas & Elec. Co. v. NRDC*, 462 U.S. 87, 97 (1983). To meet those goals, NEPA requires that the BLM "consider every significant aspect of the environmental impact of a proposed action" and inform the public of those impacts. *Id.* (internal citation omitted); *accord Vermont Yankee Nuclear Power Corp. v. Natural Resources Defense Council, Inc.*, 435 U.S. 519, 553 (1978).[6] The BLM must take a "hard look" at the environmental effects before making any leasing decisions, ensuring "that the agency, in reaching its decision, will have available, and will carefully consider, detailed information concerning significant environmental impacts." *Robertson v. Methow Valley Citizens Council*, 490 U.S. 332, 349–50 (1989). Environmental "[e]ffects are reasonably foreseeable if they are sufficiently likely to occur that a person of ordinary prudence would take [them] into account in reaching a decision." *Sierra Club v. Fed. Energy Regulatory Comm'n*, 867 F.3d 1357, 1371 (D.C. Cir. 2017) (internal quotation omitted).

The BLM must adequately analyze site-specific resource conflicts and the environmental effects discussed below.

a. The Draft EAs fail to properly analyze leasing parcels in wildlife habitat.

The Draft EAs recognize that **<u>all</u>** parcels overlap sensitive wildlife habitat and designate **<u>all</u>** parcels as having a low preference for leasing. *See* CARLSBAD DRAFT EA at 184–85 Table C.1; FARMINGTON DRAFT EA at 112 Table C-1. Pursuant to its regulations, the agency must preference "lands that would not impair the proper functioning of [fish and wildlife] habitats or corridors." 43 C.F.R. § 3120.32(b). Nonetheless, the BLM is moving forward all parcels for leasing. We urge the BLM to consider parcel deferrals.

FLPMA requires the BLM to manage public lands "in a manner that will provide food and habitat" for all wildlife. 43 U.S.C. § 1701(a)(8). Six parcels are within lesser prairie-chicken habitat: NM-2026-02-0554; -0555; -0559; -6881; -6891; and -6892. Yet, the Draft EAs do not propose a reasonable modified alternative that would defer some or all of these parcels, as the BLM has proposed for lease sales in Wyoming where parcels intersect certain wildlife habitat, such as for the greater sage-grouse. We urge the BLM to consider such a modified leasing alternative here.

We appreciate that the BLM intends to include SENM-S-33-NSO stipulation or SENM-S-22-CSU stipulation for these parcels. However, SENM-S-33-NSO indicates that the BLM "*may*" issue the lease subject to the NSO stipulation and that the lease would be issued "with the

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[6] *See Kleppe v. Sierra Club*, 427 U.S. 390, 410, 413 (1976); *City of Rochester v. U.S. Postal Serv.*, 541 F.2d 967, 973–74 (2d Cir. 1976); *Concerned About Trident v. Rumsfeld*, 555 F.2d 817, 825 (D.C. Cir 1976); *City of Davis v. Coleman*, 521 F.2d 661, 666-677 (9th Cir. 1975); *Brooks v. Coleman*, 518 F.2d 17, 18 (9th Cir. 1975); *Natural Resources Defense Council v. Callaway*, 524 F.2d 79, 89 (2d Cir. 1975); *Envtl. Def. Fund, Inc. v. Corps of Eng'rs of U.S. Army*, 492 F.2d 1123, 1135 (5th Cir. 1974); *Swain v. Brinegar*, 517 F.2d 766 (7th Cir. 1975); *Minnesota Public Interest Research Group v. Butz*, 498 F.2d 1314, 1322 (8th Cir. 1974); *Natural Resources Defense Council v. Morton*, 458 F.2d 827, 834–36 (D.C. Cir. 1972); *Hanly v. Kleindienst*, 471 F.2d 823, 830-31 (2d Cir. 1972); *Calvert Cliffs' Coordinating Comm., Inc. v. U.S. Atomic Energy Comm'n*, 449 F.2d 1109, 1114 (D.C. Cir. 1971).

intention that it be developed by directional drilling." *E.g.*, CARLSBAD DRAFT EA at 183 Table B.1 (emphases added). We strongly urge that the BLM make this stipulation and its conditions mandatory.

Three parcels are within dunes sagebrush lizard habitat: NM-2026-02-0554; -0559; and -6891. As with the parcels that overlap lesser prairie-chicken habitat, the Draft EAs do not propose a reasonable modified alternative that would defer some or all of the parcels. We urge the BLM to consider such a modified leasing alternative here. Likewise, we appreciate that the BLM intends to include SENM-S-23-CSU and SENM-S-33-NSO and again strongly urge the BLM to make the NSO stipulation and its conditions mandatory.

b. The BLM should defer parcels in areas with high karst or cave potential and that are a critical karst or cave resource area.

The following parcels are in areas with high or critical karst and cave impact designations: NM-2026-02-0481; -0518; -0528; -0548; -0549; -0550; -0552; -0514; -6874; -6875; -6839; -0457; -6885; -6883; and -6884. *See* PECOS DRAFT EA at 62–63 Table 3.12. The Draft EA designates these parcels as having low preference for leasing under 43 C.F.R. § 3120.32(d), "presence of . . . important . . . resources." In fact, the BLM admits that these "[l]ow determinations" mean that the parcels are "incompatible with oil and gas development." CARLSBAD DRAFT EA at 185 Table C.1 n.§. Nonetheless, the BLM proposes moving forward with leasing these parcels because of stipulations and conditions of approval. *See id.* But such measures are inadequate to protect these areas. We therefore urge the BLM to follow its own policy and low preference for leasing designation of these parcels and defer them from this sale.

These parcels are located within an area in known soluble rock types with high or medium densities of significant cave systems or bedrock fractures that lead to the rapid recharge of karst groundwater aquifers from surface runoff. These areas provide critical drinking water supplies for major communities, ranching operations, and springs that support rivers and vital riparian habitat. Further, those cave and karst areas are close to the protected cave systems at Carlsbad Caverns National Park and could very well be connected through underground passages or fractures that have not yet been mapped.

The entire area which makes up the Carlsbad Field Office should be studied thoroughly to assess the vulnerabilities to aquifer resources and fragile karst resources, which can also be home to unique wildlife and habitat, as the cave and karst system throughout the region is deeply interconnected. Carlsbad Caverns is a designated World Heritage Area and indeed attracts visitors from around the world. A single leak from hydraulic fracturing or reinjection of "produced water," or seismic activity that has been linked to hydraulic fracturing and produced water, could have a devastating and irreversible impact on the National Park and on public health and safety. In recent years exploratory wells have run into empty space at about the same depth as Carlsbad's caverns. According to a 2007 NPS Geologic Resource Evaluation Report: Hundreds of producing oil and gas wells have been drilled north, east, and south of Carlsbad Caverns National Park. Exploratory wells have been drilled within a few thousand feet of the north and east boundaries of Carlsbad Caverns, and some of these have encountered voids at the same depth as major passages in Lechuguilla Cave (NPS 1996). At least 61 wells drilled near the park have encountered lost circulation zones in the Capitan and Goat Seep Formations, suggesting that unexplored cave passages were intersected during drilling (NPS 1993, 1996). Substantial hydrocarbon reserves and known cave resources exist immediately north of the park boundary. It is probable that exploratory drilling will intersect openings that connect with caves in the park. Resources inside the park could be at risk of contamination from toxic and flammable gases and other substances associated with the exploration and production of oil and gas. NAT'L PARK SERV., CARLSBAD CAVERNS NATIONAL PARK: GEOLOGIC RESOURCE EVALUATION REPORT 10 (2007) [Ex. 1], http://npshistory.com/publications/cave/nrr-2007-003.pdf.

A Stanford University study released in April 2018 documents seismic threats in the Permian Basin resulting from injection wells. STANFORD UNIVERSITY, SEISMIC STRESS MAP DEVELOPED BY STANFORD RESEARCHERS PROFILES INDUCED EARTHQUAKE RISK FOR WEST TEXAS, NEW MEXICO (Feb. 8, 2018) [Ex. 2], https://news.stanford.edu/2018/02/08/seismic-stress-map-profiles-induced-earthquake-risk-west-texas-new-mexico/. In addition, a Durham University Study released in February 2018 noted, "The risk of human-made earthquakes due to fracking is greatly reduced if high-pressure fluid injection used to crack underground rocks is 895m away from faults in the Earth's crust." Durham University, *Human-made earthquake risk reduced if fracking is 895m from faults*, ScienceDaily (Feb. 27, 2018) [Ex. 3], https://www.sciencedaily.com/releases/2018/02/180227233301.htm. Hydraulic fracking in the Permian basin was not remotely close to current levels 15 years ago. Not only does this underscore the issue of the BLM not adequately responding to comments, it also indicates the BLM is not using the best available science. NEPA requires the BLM to "ensure[] that the agency, in reaching its decision, will have available and will carefully consider detailed information concerning significant environmental impacts." *Robertson*, 490 U.S. at 349.

In addition to the potential impacts to cave systems, poorly planned leasing and oil and gas development can have a negative impact on a sustainable local tourism economy. Carlsbad Caverns and Guadalupe Mountains National Parks combined generated over $64.6 million in local economic output and supported 685 jobs in 2023.

The breadth and density of oil and gas development around Carlsbad Caverns is one of the factors that has already taken a toll on the park's popularity. Visitation to Carlsbad has decreased to 460,000 from an all-time high of 792,000 in 1989.

The development that might be driving visitors away includes blighting of the viewshed with drill rigs, pump jacks, and other industrialization, and the loss of dark night skies from excessive lighting and flaring in the area—all of which argues for the importance of taking care in managing leasing and land use activities near Carlsbad Caverns, Guadalupe Mountains, and other publicly accessible caves, recreational areas, groundwater resources, and agricultural activities in the area. As such, the BLM should develop a modified leasing alternative that considers deferring some or all of these parcels.

c. The BLM should defer parcels that overlap special designations and inventoried Lands with Wilderness Characteristics (LWC), Wilderness Study Areas (WSA), and Areas of Critical Environmental Concern (ACEC)

until management decisions are made for those lands in order to comply with NEPA and FLPMA.

FLPMA obligates the BLM to take its resource inventory into account when preparing management plans and authorizing uses, observing the principles of multiple use and sustained yield. *See* 43 U.S.C. §§ 1711(a), 1712(c); *see Ore. Natural Desert Ass'n v. Bureau of Land Mgmt.*, 625 F.3d 1092, 1122 (9th Cir. 2008). The BLM is also required to "prevent unnecessary or undue degradation of the lands." 43 U.S.C. § 1732(b).

In making decisions about leasing areas for oil and gas development, the BLM can and should protect wildlife, scenic values, recreation opportunities, and wilderness character on public lands. This is necessary and consistent with the definition of multiple use, which identifies the importance of various aspects of wilderness characteristics (such as recreation, wildlife, and natural scenic values) and requires the BLM's consideration of the relative values of these resources but "not necessarily to the combination of uses that will give the greatest economic return." *See id.* § 1702(c).

The BLM has exercised its discretion to defer parcels occurring on LWCs, WSAs, and ACECs where management direction has not been made or where lands are being managed under such designations. For example, the Grand Junction Field Office deferred lease parcels from its December 2017 lease sale in areas that the BLM inventoried and found to have wilderness characteristics. The BLM stated: "Portions of the following parcels were deferred due to having lands with wilderness characteristics that require further evaluation." DOI-BLM-CO-N050-2017-0051-DNA, at 1 (Dec. 6, 2017). The Grand Junction Field Office completed its RMP revision in 2015 but still determined that it was inappropriate to lease areas that had been inventoried and found to possess wilderness characteristics because the RMP was completed in order to allow the agency to consider management options for those wilderness resources. The BLM should similarly defer leasing in inventoried LWC, WSA, and ACEC for which management decisions have not been made or which are actively being managed based on these designations. This approach is consistent with agency policy and authority and is critical to preserving the BLM's ability to make management decisions for those wilderness resources through a public planning process.

The following parcels overlap proposed ACECs: NM-2026-02-6883; -6884; -0581; and -0457. These units are in field offices where the BLM has not yet made management decisions in its land use plans for how these areas will be managed relative to wilderness characteristics. The BLM must preserve its ability to decide whether and how to protectively manage wilderness resources in a public planning process. Such decisions could be foreclosed by leasing those lands to the oil and gas industry at this time. The BLM should defer all leases that overlap this proposed ACEC until the agency has the opportunity to make management decisions for those areas through a public planning process.

Seven parcels overlap New Mexico's Brantley Wildlife Area: NM-2026-02-0481; -0510; -0518; -0528; -0548; -0550; and -0552. As with the acreage in the proposed ACEC or lands with other special designations, the BLM must not lease lands in a state wildlife area. Leasing these parcels would directly conflict with the management of the Brantley Wildlife Area. We urge the

BLM to remove these parcels from the sale. At the least, the BLM must develop a reasonable modified leasing alternative that considers deferring these and the proposed ACEC parcels.

d. The Draft EAs do not adequately analyze greenhouse gas (GHG) emissions and climate effects or factor GHG emissions and climate effects into the leasing decisions.

The BLM must not only properly analyze and quantify the direct, indirect, and cumulative GHG emissions and climate impacts that may result from leasing, but it must also factor GHG emissions into its leasing decisions. *See Wilderness Soc'y*, No. 22-cv-1871 (CRC), 2024 U.S. Dist. LEXIS 51011, at *91 (D.D.C. Mar. 22, 2024). As one court explained: "Any claim that the analysis of GHG emissions was informational only and did not inform BLM's decision-making is hard to square with [NEPA's] purpose." *Id.* at *87. The agency must also consider unquantified effects, recognize the worldwide and long-range character of climate change impacts, and incorporate this analysis of ecological information into its environmental analysis. *See* 42 U.S.C. §§ 4332(2)(A), (B), (D), (I) & (K). The BLM has the tools to undertake this analysis, but the Draft EAs do not do so.

The MLA requires the Secretary of the Interior to lease lands for oil and gas development only in the public interest. *See* 30 U.S.C. § 192. In its NEPA analysis, the BLM can and must consider adverse effects to health and the environment—part of the public interest—when determining whether to lease. *See* 43 U.S.C. § 1732(b) (requiring the BLM to prevent unnecessary and undue degradation); *cf. Sierra Club v. Fed. Energy Regulatory Comm'n*, 867 F.3d at 1373–74 (explaining that whether an agency must analyze certain environmental effects under NEPA turns on the question, "What factors can [the agency] consider when regulating in its proper sphere," and holding that the agency must consider direct and indirect environmental effects because the statute at issue indeed vested the agency with authority to deny the project based on harm to the environment (internal quotation marks omitted)). Such adverse environmental effects include those caused by GHG emissions and impacts on the climate.

Court decisions establish that NEPA mandates consideration and analysis of the indirect and cumulative climate impacts of BLM fossil fuel production decisions, including at the leasing stage.[7] The BLM must ensure it fully considers not only the GHG emissions from prospective

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[7] *See, e.g.*, *350 Mont. v. Haaland*, 50 F.4th 1254, 1266–70 (9th Cir. 2022); *Vecinos para el Bienestar de la Comunidad Costera v. FERC*, 6 F.4th 1321, 1329–30 (D.C. Cir. 2021); *Sierra Club v. Fed. Energy Regulatory Comm'n*, 867 F.3d at 1371–75 (requiring quantification of indirect greenhouse gas emissions); *Ctr. for Biological Diversity v. Nat'l Highway Transp. Safety Admin.*, 538 F.3d 1172, 1215–16 (9th Cir 2008) (requiring assessment of the cumulative impacts of climate change); *WildEarth Guardians v. U.S. Bureau of Land Mgmt*., 870 F.3d 1222, 1236–38 (10th Cir. 2017); *Mid States Coal. for Progress v. Surface Transp. Bd*., 345 F.3d 520, 550 (8th Cir. 2003); *Wilderness Soc'y*, No. 22-cv-1871 (CRC), 2024 U.S. Dist. LEXIS 51011, at *83–92 (explaining that the BLM cannot "overlook[] what is widely regarded as the most pressing environmental threat facing the world today"); *WildEarth Guardians v. Zinke*, 368 F. Supp. 3d 41, 63, 67–77 (D.D.C. 2019) (invalidating nine BLM NEPA analyses in support of oil and gas lease sales because "BLM did not take a hard look at drilling-related and downstream [greenhouse gas] emissions from the leased parcels and, it failed to sufficiently compare those emissions to regional and national emissions"). The Supreme Court's recent decision in *Seven County Infrastructure Coalition v. Eagle County*, 605 U.S. at __, Slip Op. (May 29, 2025), does not alter the BLM's NEPA obligations to analyze GHG emissions and climate impacts for this lease sale. *Seven County* affirmed that agencies must still analyze indirect effects under NEPA. *See* Slip Op. at 16. The downstream GHG emissions that will result from this

wells drilled on the leases sold at this lease sale—and the climate change impacts of those GHG emissions—but also the impacts of other federal lease sales in the state, region, and nation, as well as impacts from GHG emissions from non-Federal sources. The BLM must consider GHG emissions in the aggregate along with other foreseeable emissions. Such analysis is necessary to meet the cumulative impacts demands of NEPA.

The indirect and cumulative impacts must be given meaningful context, including within carbon budgets, rather than simply dismissed as insignificant compared to national or global total GHG emissions. *See, e.g.*, *WildEarth Guardians*, 368 F. Supp. 3d at 77. "Without establishing the baseline conditions . . . there is simply no way to determine what effect the proposed [action] will have on the environment and, consequently, no way to comply with NEPA." *Half Moon Bay Fisherman's Marketing Ass'n v. Carlucci*, 857 F.2d 505, 510 (9th Cir. 1988). Excluding climate change effects from the environmental baseline ignores the reality that the impacts of proposed actions must be evaluated based on the already deteriorating, climate-impacted state of the resources, ecosystems, human communities, and structures that will be affected. The BLM's climate effects analysis "must give a realistic evaluation of the total impacts and cannot isolate a proposed project, viewing it in a vacuum." *Grand Canyon Trust v. Fed. Aviation Admin.*, 290 F.3d 339, 342 (D.C. Cir. 2002).[8]

In analyzing these impacts, the BLM must consider the full lifecycle of development activities and GHG emissions that are reasonably foreseeable under a BLM oil and gas lease. The social cost of greenhouse gases (SC-GHG) is a useful tool to aid in this analysis. While NEPA does not require a cost-benefit analysis, it is "nonetheless arbitrary and capricious to quantify the *benefits* of the lease modifications and then explain that a similar analysis of the *costs* was impossible when such an analysis was in fact possible and was included in an earlier draft EIS." *High Country Conservation Advocates v. United States Forest Serv.*, 52 F.

lease sale are indirect effects that require analysis. By controlling the oil and gas leasing process, the BLM possesses regulatory authority over managing the oil or gas subject to the prospective leasehold. *Cf. id.* at 4 ("[T]he Board possesses no authority or control over potential future oil and gas development in the Basin." (citation modified)) & 4 (Sotomayor, J., concurring in judgment) ("[T]he Board cannot control the products transported on the proposed rail line." (citation modified)). The oil or gas to be extracted is directly related to the leases at issue and thus not too proximately separate in time or place. *See id.* at 15–18. As such, under a rule of reason, the BLM must analyze the GHG emissions that would result because it manages and exerts authority over the oil or gas, which is directly related to this lease sale. *See id.* at 16 ("To be clear, the environmental *effects* of the project at issue may fall within NEPA even if those *effects* might extend outside the geographical territory of the project or might materialize later in time . . . ." (emphasis in original)).

[8] *See also Great Basin Mine Watch v. Hankins*, 456 F.3d 955, 973–74 (9th Cir. 2006) (holding agency's cumulative impacts analysis insufficient based on failure to discuss other mining projects in the region); *Kern v. BLM*, 284 F.3d 1062, 1078 (9th Cir. 2002) (holding that BLM arbitrarily failed to include cumulative impacts analysis of reasonably foreseeable future timber sales in the same district as the current sale); *Blue Mountains Biodiversity Project v. Blackwood*, 161 F.3d 1208, 1214-16 (9th Cir. 1998) (overturning Forest Service EA that analyzed impacts of only one of five concurrent logging projects in the same region); *San Juan Citizens All. v. United States BLM*, 326 F. Supp. 3d 1227, 1248 (D.N.M. 2018) (holding that BLM failed to take an hard look at the cumulative impact of GHG emissions (citing *Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin.*, 538 F.3d 1172, 1217 (9th Cir. 2008) (concluding that an agency "must provide the necessary contextual information about the cumulative and incremental environmental impacts" because even though the impact might be "individually minor," its impact together with the impacts of other actions would be "collectively significant"))).

Supp. 3d 1174, 1191 (D. Colo. 2014). Courts have rejected agency refusals to properly quantify the impact of GHG emissions.[9]

The Interior Department had "adopt[ed] . . . [the EPA's] new estimates of the social cost as the best available science." 90 Fed. Reg. 4779, 4779 (Jan. 16, 2025); *see* U.S. Dep't of the Interior, Informational Memorandum on DOI comparison of available estimates of social cost of greenhouse gases (SC-GHG), at 1, 8 (Oct. 16, 2024) [Ex. 4], https://eplanning.blm.gov/public_projects/2036015/200638053/20126874/251026854/20241016.DOI%20SC_GHG%20Info%20Memo.pdf (directing the BLM to "adopt the EPA's 2023 estimates of the Social Cost of Greenhouse Gases (SC-GHG) as the best available science (as of September 30, 2024)"). In a final Environmental Assessment (EA) for the Quarter 1 2025 New Mexico Oil and Gas Lease Sale, the BLM explicitly stated that it was rescinding its October 16, 2024, memorandum. *See* BLM, CARLSBAD FIELD OFFICE OIL AND GAS LEASE SALE ENVIRONMENTAL ASSESSMENT at 88, QUARTER 1 (2025) [hereinafter NM EA]. But the BLM failed to provide proper justification for changing its position. *See FCC v. Fox TV Stations, Inc.*, 556 U.S. 502, 515 (2009) (holding that an agency must provide "good reasons" for a change in position and must provide "a more detailed justification" when a "new policy rests upon factual findings that contradict those which underlay [an agency's] prior policy; or when its prior policy has engendered serious reliance interests that must be taken into account").

The Draft EAs eliminate reference to social cost estimates. For years and over multiple projects, the BLM has quantified climate impacts, primarily relying on the well-supported SC-GHG estimates. *See, e.g.*, BLM, ENVIRONMENTAL ASSESSMENT: WYOMING 2023 SECOND QUARTER COMPETITIVE LEASE SALE at 54–55 (2023). The BLM must provide such analysis for this lease sale.

The Draft EAs do quantify *benefits* of leasing. The BLM discusses various economic and other financial benefits of leasing, including increased employment opportunities. Draft EA at 46. Yet, the BLM is utterly silent on quantifying the monetary costs of moving forward with leasing, despite having quantified these costs for years in its leasing EAs using the widely accepted SC-GHG tool. The BLM must consider the full lifecycle of development activities and GHG emissions that are reasonably foreseeable under a BLM oil and gas lease. SC-GHG is a useful tool to aid in this analysis. While NEPA does not require a cost-benefit analysis, it is "nonetheless arbitrary and capricious to quantify the *benefits* of the lease modifications and then explain that a similar analysis of the *costs* was impossible when such an analysis was in fact

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[9] *See, e.g.*, *Montana Env't Info. Ctr. v. U.S. Office of Surface Mining*, 274 F. Supp. 3d 1074, 1094–99 (D. Mont. 2017) (rejecting agency's failure to incorporate the federal SCC estimates into its cost-benefit analysis of a proposed mine expansion); *see also Zero Zone, Inc. v. U.S. Dep't of Energy*, 832 F.3d 654, 679 (7th Cir. 2016) (holding estimates of the social cost of carbon (SCC) used to date by agencies were reasonable); *High Country Conservation Advocs. V. U.S. Forest Serv.*, 52 F. Supp. 3d 1174, 1190–93 (D. Colo. 2014) (holding the SCC was an available tool to quantify the significance of GHG impacts, and it was "arbitrary and capricious to quantify the *benefits* of the lease modifications and then explain that a similar analysis of the costs was impossible") (emphasis in original). An agency may not assert that the social cost of fossil fuel development is zero: "by deciding not to quantify the costs at all, the agencies effectively zeroed out the costs in its quantitative analysis." *High Country Conservation Advocates*, 52 F. Supp. 3d at 1192; *see Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin.*, 538 F.3d 1172, 1200 (9th Cir. 2008) (holding that while there is a range potential social cost figures, "the value of carbon emissions reduction is certainly not zero").

possible." *High Country Conservation Advocates v. United States Forest Serv.*, 52 F. Supp. 3d 1174, 1191 (D. Colo. 2014) (emphases in original). Courts have rejected agency refusals to properly quantify the impact of GHG emissions.[10] It is therefore arbitrary and capricious for the BLM to justify this sale based on economic "impacts" without even considering the societal costs from the GHG emissions and their adverse "impacts" on climate change and whether those costs outweigh the project's purported monetary benefits. *See, e.g.*, *High Country Conservation Advocates*, 52 F. Supp. 3d at 1191.

NEPA also requires agencies to "identify and develop methods and procedures . . . which will ensure that presently unquantified environmental amenities and values may be given appropriate consideration in decisionmaking along with economic and technical considerations." 42 U.S.C. § 4332(2)(B). A livable climate is a "presently unquantified environmental amenit[y]." Neglecting to use SC-GHG or replace it with a comparable tool to quantify climate impacts fails to "identify and develop methods and procedures" to ensure that this "presently unquantified environmental . . . value" is "given appropriate consideration in decisionmaking."

Therefore, the BLM must not only analyze GHG emissions. It must also address how GHG emissions inform its leasing decisions. "[T]he complexity of the task does not give the [BLM] a free pass to avoid making these tough decisions by asserting that GHG emissions did not factor into its decision-making." *Wilderness Soc'y*, No. 22-cv-1871 (CRC), 2024 U.S. Dist. LEXIS 51011, at *91. The BLM "must . . . explain how its GHG analysis inform[s] the decision to select" its preferred alternative. *Id.* at *91–92. If the BLM does "not consider GHG emissions when rendering its decision . . . it would . . . overlook[] what is widely regarded as the most pressing environmental threat facing the world today." *Id.*, No. 22-cv-1871 (CRC), 2024 U.S. Dist. LEXIS 51011, at *87–88. The BLM must quantify the projected monetary costs of moving forward with leasing in the state so that the BLM and the public can determine whether the asserted benefits of leasing outweigh the costs.

e. The Draft EAs fail to properly analyze methane emissions that would result from this lease sale.

The Draft EAs touch only briefly on methane emissions. The BLM must take the requisite hard look at the impacts of methane emissions that will result from development of and production on these lease parcels, including the economic, public health, and public welfare impacts of venting and flaring. *See, e.g.*, ENVIRONMENTAL DEFENSE FUND, FLARING AERIAL

[10] *See, e.g., Montana Env't Info. Ctr. v. U.S. Office of Surface Mining*, 274 F. Supp. 3d 1074, 1094–99 (D. Mont. 2017) (rejecting agency's failure to incorporate the federal SCC estimates into its cost-benefit analysis of a proposed mine expansion); *see also Zero Zone, Inc. v. U.S. Dep't of Energy*, 832 F.3d 654, 679 (7th Cir. 2016) (holding estimates of the social cost of carbon (SCC) used to date by agencies were reasonable); *High Country Conservation Advocs. V. U.S. Forest Serv.,* 52 F. Supp. 3d 1174, 1190–93 (D. Colo. 2014) (holding the SCC was an available tool to quantify the significance of GHG impacts, and it was "arbitrary and capricious to quantify the *benefits* of the lease modifications and then explain that a similar analysis of the costs was impossible") (emphasis in original). An agency may not assert that the social cost of fossil fuel development is zero: "by deciding not to quantify the costs at all, the agencies effectively zeroed out the costs in its quantitative analysis." *High Country Conservation Advocates*, 52 F. Supp. 3d at 1192; *see Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin.*, 538 F.3d 1172, 1200 (9th Cir. 2008) (holding that while there is a range potential social cost figures, "the value of carbon emissions reduction is certainly not zero").

SURVEY RESULTS (2021) [Ex. 5], https://www.permianmap.org/flaring-emissions/. In 2019 alone, venting or flaring accounted for roughly 150 billion cubic feet of methane, resulting in the loss of over $50 million in federal royalty revenue. This waste also means lost royalty revenues for taxpayers and Tribes. An analysis conducted by Synapse Energy Economics determined the value of lost gas in the form of: (1) lost royalties; (2) lost state revenue from taxes; and (3) lost revenue from wasted natural gas that could be used for other purposes. The study found that $63.3 million in royalties, $18.8 million in state revenue from taxes (from the top six states), and $509 million in gas value was lost due to venting, flaring, and leaks on federal and Tribal lands. OLIVIA GRIOT ET AL., ONSHORE NATURAL GAS OPERATIONS ON FEDERAL AND TRIBAL LANDS IN THE UNITED STATES: ANALYSIS OF EMISSIONS AND LOST REVENUE, SYNAPSE ENERGY ECONOMICS INC. at 3 (Jan. 20, 2023) [hereinafter GRIOT ET AL.] [EX. 6], https://blogs.edf.org/energyexchange/files/2023/01/EMBARGOED_EDF-TCS_Public_Lands_Analysis.pdf. The report found that, in 2019, leaks accounted for 46% and flaring for 54% of lost gas. *See id.* at 23.

Venting and flaring on Tribal and federal public lands has significant health impacts on frontline and fence line communities. *See e.g.*, Jeremy Proville et al., *The demographic characteristics of populations living near oil and gas wells in the USA*, 44 POPULATION AND ENV'T 1 (2022) [Ex. 7], https://doi.org/10.1007/s11111-022-00403-2. Proximity to oil and gas infrastructure creates disproportionate adverse health risks and impacts on Indigenous communities in particular. *See*, *e.g.*, *id.* at 2–5. Over 18 million people live within a mile of an oil and gas well. *Id.* at 10. A study links flaring to shorter gestation and reduced fetal growth. *See* Lara J. Cushing et al., *Flaring from Unconventional Oil and Gas Development and Birth Outcomes in the Eagle Ford Shale in South Texas*, 128 Envtl. Health Perspectives 077003-1, 077003-1 to 077003-8 (2020) [Ex. 8]. Reducing waste from flaring on federal and Tribal lands would lessen these harms. Therefore, the BLM should not issue additional oil and gas leases until the agency addresses waste on Tribal and federal public lands.

f. The Draft EAs fail to take a hard look at impacts to groundwater from well construction practices and hydraulic fracturing.

The Draft EAs fail to adequately address groundwater impacts. To isolate and protect usable water, those groundwater zones should be isolated with both casing and cementing. Rebecca Tisherman, et al., *Examination of Groundwater Resources in Areas of Wyoming Proposed for the June 2022 BLM Lease Sale* (May 12, 2022) [hereinafter Tisherman Report] [Ex. 9], https://eplanning.blm.gov/public_projects/2015538/200495187/20062621/250068803/Exhibit%20119-%20PSE%20WY%20Report%20May%202022%20Final.pdf; Dominic DiGiulio, *Dominic DiGiulio, Examination of Groundwater Resources in Areas of Montana Proposed for the March 2018 BLM Lease Sale* (Dec. 22, 2017) [hereinafter DiGiulio Report] [Ex.10], https://eplanning.blm.gov/public_projects/nepa/87551/136880/167234/Earthjustice_Protest_1-12-2018.pdf (Exhibit D to David Katz and Jack and Bonnie Martinell's protest of the March 13, 2018, BLM Montana-Dakotas oil and gas lease sales).

The Draft EAs ignore reasons the D.C. District Court in *Wilderness Society* found the BLM's groundwater analysis lacking: statements by industry trade associations explaining that only "economically viable" groundwater is considered usable, and (relatedly) that companies construct wells to protect groundwater only to a depth where there are already existing water wells nearby. *Wilderness Soc'y*, No. 22-cv-1871 (CRC), at *30–32.

The Draft EAs offer no reason to expect that the problems identified by the Tisherman report will not be repeated here in New Mexico. The BLM has offered no evidence showing that it made a reasoned decision when approving the wells in the Tisherman report that their casing and cementing comply with the agency's usable water regulations and protect **all** usable water zones.

For shallow fracturing, the Draft EAs also fall short. The BLM regulations require protecting usable waters regardless of whether they already have been tapped with a water well. The BLM fails to provide an explanation of the impacts to usable water zones where fracking is already occurring (even if those zones are not currently being used as a drinking water source) and how that fracking may degrade the quality of groundwater.

Indeed, an analysis of aquifers within the areas proposed for lease shows clear and significant overlaps with many of the parcels being offered. For the leases proposed by the Carlsbad Field Office, the following parcels are of significant concern:

Parcel ID	Aquifer Acreage Within Proposed Parcels	Parcel Overlap with Aquifers (%)
NM-2026-02-0510	269.21	100.00%
NM-2026-02-0555	109.55	100.00%
NM-2026-02-0481	3001.77	99.82%
NM-2026-02-0511	217.62	100.00%
NM-2026-02-0581	455.35	100.00%
NM-2026-02-6862	114.97	100.00%
NM-2026-02-0518	3320.91	100.00%
NM-2026-02-0550	2051.8	100.00%
NM-2026-02-0514	2791.98	100.00%
NM-2026-02-0548	173.24	100.00%
NM-2026-02-0561	113.92	100.00%
NM-2026-02-6878	107.56	100.00%
NM-2026-02-0528	2270.44	76.10%
NM-2026-02-6874	655.05	100.00%
NM-2026-02-0552	1546.55	100.00%
NM-2026-02-0542	343.41	100.00%
NM-2026-02-6875	2871.45	100.00%

For the Farmington Field Office, the following parcels are of concern:

Parcel ID	Aquifer Acreage Within Proposed Parcels	Parcel Overlap with Aquifers (%)
NM-2026-02-0558	1034.52	100.00%
NM-2026-02-0582	247.16	100.00%

Of the 30 New Mexico parcels offered, 19 are located almost completely over mapped aquifers. In a region with extremely limited water supplies, this fact, and the effect oil and gas development could have on these resources, must be analyzed prior to these areas being offered for lease. The BLM's failure to do so is a major deficiency of the Draft EAs. The agency cannot simply defer this analysis to the APD stage.

g. The Draft EAs fail to analyze the impacts of oil and gas leasing on environmental justice.

The BLM must take a hard look at environmental justice, and not only in relation to health. However, the Draft EAs do not analyze "environmental justice." Courts have repeatedly held that agencies must take a hard look at environmental justice pursuant to NEPA.[11] The BLM must explain this change in position from previous lease sale analyses that discussed the adverse effects of oil and gas activity on environmental justice communities.

At the most basic level, for example, the BLM has failed to disclose the potential risks—especially to vulnerable populations like pregnant women and children—of offering lease parcels in close proximity to homes and schools. Parcels proposed for sale by both the Carlsbad Field Office and Farmington Field Office present these risks, with 10 parcels lying within less than a half mile from either homes or schools. The BLM must revisit the analysis in these Draft EAs to ensure that these risks are fully explored in such a way that the communities located near proposed oil and gas development are aware of the risks the agency's decision may be presenting. The parcels of concern are: 0481, 6883, 6885, 0514, 0561, 6878, 6839, 0528, 0457, and 0582.

h. The BLM must evaluate the extent to which the proposed sale conflicts "solar application areas" designated under the recently finalized Solar Programmatic Environmental Impact Statement (Solar PEIS).

Choosing to offer these parcels for an oil and gas lease sale without simultaneously considering whether it is appropriate to offer lands recently proposed to be opened for possible solar energy development is a further oversight of the Draft EAs. The reason for this is emphasized in the Solar PEIS, which notes that areas leased for oil and gas production that are

[11] *See, e.g.*, *Friends of Buckingham v. State Air Pollution Control Bd.*, 947 F.3d 68, 87 (4th Cir. 2020); *Latin Ams. for Social & Econ. Dev. v. Fed. Highway Admin.*, 756 F.3d 447, 465 (6th Cir. 2014); *Coliseum Square Ass'n, Inc. v. Jackson*, 465 F.3d 215, 232 (5th Cir. 2006); *Cmtys. Against Runway Expansion, Inc. v. FAA*, 355 F.3d 678, 689 (D.C. Cir. 2004).

also appropriate for solar development create "Areas of Special Coordination"[12] that will generally prohibit solar development from taking place and favor oil and gas development. While this may be the logical result on lands already under lease for oil and gas development, creating new "Areas of Special Coordination" without consideration of the tradeoffs of doing so should be analyzed here. This is especially true where parcels considered for this sale have environmental conflicts—such as proximity or overlap with known aquifers—that should lead to their deferral from this and future oil and gas lease sales. Deferral would allow the BLM to more rationally consider the use of these lands for energy production, including consideration of leasing for alternative energy development that could enhance American energy production without risking long term degradation or destruction of critical resources like fresh water.

Different development scenarios and development modes (i.e., fossil fuels versus renewable energy sources) have differing levels and types of impacts, including impacts to the surface, groundwater, surface water, air quality, climate, and habitat. The BLM should have analyzed the impacts of both industries through its environmental analysis of these proposed sales. Ultimately, if the BLM chooses to offer parcels for oil and gas development that it has also opened to potential renewable energy development, it is making a choice that may undermine the country's energy security. Choosing such a course requires reasoned explanation and evaluation of tradeoffs.

The following parcels overlap lands identified as open or potentially open for solar development and the BLM has a duty to explain its decision to offer them for oil and gas development instead of renewable energy generation. This is especially true for parcels 0549, 0457, 6839, 6874, 6875, and 0558, all of which substantially overlap with areas the BLM has designated as open for solar energy development.

Carlsbad Field Office parcels:

Parcel ID	Solar PEIS Available Acreage Overlap	Solar PEIS Available Acreage Overlap (%)
NM-2026-02-0528	0.26	0.01%
NM-2026-02-0481	0.66	0.03%
NM-2026-02-0581	0.86	0.26%
NM-2026-02-0550	0.89	0.06%
NM-2026-02-0518	3.16	0.13%
NM-2026-02-0549	144.08	91.16%
NM-2026-02-0457	150.35	94.17%
NM-2026-02-6839	161.16	17.45%
NM-2026-02-6874	333.37	71.82%
NM-2026-02-6875	694.19	34.09%

[12] BLM, Final Programmatic Environmental Impact Statement and Proposed Resource Management Plan Amendments for Utility-Scale Solar Energy Development (Aug. 2024) (Final Solar PEIS), Appendix H-2.

Farmington Field Office parcels:

Parcel ID	Solar PEIS Available Acreage Overlap	Solar PEIS Available Acreage Overlap (%)
NM-2026-02-0558	444.09	66.14%

III. Conclusion.

We appreciate your consideration of these comments. Should you have any questions, please do not hesitate to contact us.

Respectfully submitted,

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Exhibit Index in Appendix to TWS et al. Comments on the Draft Environmental Assessments and Findings of No Significant Impact for the Bureau of Land Management New Mexico 2026 First Quarter Competitive Oil & Gas Lease Sale (DOI-BLM-NM-P020-2025-1005-EA & DOI-BLM-NM-F010-2025-0033-EA)

Exhibit No.	**Title/Description**
1	NAT'L PARK SERV., CARLSBAD CAVERNS NATIONAL PARK: GEOLOGIC RESOURCE EVALUATION REPORT (2007)
2	STANFORD UNIVERSITY, SEISMIC STRESS MAP DEVELOPED BY STANFORD RESEARCHERS PROFILES INDUCED EARTHQUAKE RISK FOR WEST TEXAS, NEW MEXICO (Feb. 8, 2018)
3	Durham University, *Human-made earthquake risk reduced if fracking is 895m from faults*, ScienceDaily (Feb. 27, 2018)
4	U.S. Dep't of the Interior, Informational Memorandum on DOI comparison of available estimates of social cost of greenhouse gases (SC-GHG) (Oct. 16, 2024)
5	ENVIRONMENTAL DEFENSE FUND, FLARING AERIAL SURVEY RESULTS (2021)
6	OLIVIA GRIOT ET AL., ONSHORE NATURAL GAS OPERATIONS ON FEDERAL AND TRIBAL LANDS IN THE UNITED STATES: ANALYSIS OF EMISSIONS AND LOST REVENUE, SYNAPSE ENERGY ECONOMICS INC. (Jan. 20, 2023)
7	Jeremy Proville et al., *The demographic characteristics of populations living near oil and gas wells in the USA*, 44 POPULATION AND ENV'T 1 (2022)
8	Lara J. Cushing et al., *Flaring from Unconventional Oil and Gas Development and Birth Outcomes in the Eagle Ford Shale in South Texas*, 128 ENVTL. HEALTH PERSPECTIVES 077003-1 (2020)
9	Rebecca Tisherman, et al., *Examination of Groundwater Resources in Areas of Wyoming Proposed for the June 2022 BLM Lease Sale* (May 12, 2022)
10	Dominic DiGiulio, *Examination of Groundwater Resources in Areas of Montana Proposed for the March 2018 BLM Lease Sale* (Dec. 22, 2017)

TWS et al. Comments on the Draft Environmental Assessments and Findings of No Significant Impact for the Bureau of Land Management New Mexico 2026 First Quarter Competitive Oil & Gas Lease Sale (DOI-BLM-NM-P020-2025-1005-EA & DOI-BLM-NM-F010-2025-0033-EA)

APPENDIX

EXHIBIT 1

National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Carlsbad Caverns National Park
Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2007/003

THIS PAGE:
The Big Room, Carlsbad Caverns NP.

ON THE COVER:
Stalactites and draperies decorate the Dome Room, Carlsbad Caverns NP

Photos by: Ronal Kerbo

Carlsbad Caverns National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2007/003

Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

June 2007

U.S. Department of the Interior
Washington, D.C.

The Natural Resource Publication series addresses natural resource topics that are of interest and applicability to a broad readership in the National Park Service and to others in the management of natural resources, including the scientific community, the public, and the NPS conservation and environmental constituencies. Manuscripts are peer- reviewed to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and is designed and published in a professional manner.

Natural Resource Reports are the designated medium for disseminating high priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability. Examples of the diverse array of reports published in this series include vital signs monitoring plans; "how to" resource management papers; proceedings of resource management workshops or conferences; annual reports of resource programs or divisions of the Natural Resource Program Center; resource action plans; fact sheets; and regularly- published newsletters.

Printed copies of reports in these series may be produced in a limited quantity and they are only available as long as the supply lasts. This report is also available from the Geologic Resource Evaluation Program website (http://www2.nature.nps.gov/geology/inventory/gre_publications) on the internet, or by sending a request to the address on the back cover. Please cite this publication as:

Graham, J. 2007. Carlsbad Caverns National Park Geologic Resource Evaluation Report. Natural Resource Report NPS/NRPC/GRD/NRR—2007/003. National Park Service, Denver, Colorado.

NPS D- 139, June 2007

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Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Carlsbad Caverns National Park. It contains information relevant to resource management and scientific research.

Established as a unit of the National Park System in 1923, Carlsbad Caverns National Park preserves Carlsbad Caverns and numerous other caves within an ancient fossil reef while protecting an extraordinary and unique ecological association of bats, cave climate, speleothems, hydrology, cave fauna, and microbes. In 1995, the United Nations recognized the worldwide significance of the spectacular natural resources at Carlsbad Caverns National Park by designating it as a World Heritage Site. Preservation and management of the geologic resources are important for enhancement of the visitor's experience and sustenance of the ecosystem.

Over 300 caves are known in the Guadalupe Mountains, and more than 100 caves have been surveyed inside the boundary of Carlsbad Caverns National Park. Decorations in these caves are arguably unsurpassed in the world and include dazzling gypsum chandeliers, sheet-like draperies, towering columns and domes, delicate soda-straw stalactites and other speleothems of great abundance and variation. The Big Room is the largest cave chamber in North America.

Carlsbad Caverns is also an extraordinary example of aggressive sulfuric acid dissolution. Most of the world's caves have developed through dissolution of limestone by weak carbonic acid, a by-product of meteoric groundwater and carbon dioxide. At Carlsbad Caverns, hydrogen sulfide migrated upward from deeply buried petroleum reservoirs and reacted with groundwater, forming sulfuric acid, dissolving the Capitan Limestone.

The dramatic landscape of the park is part of the Guadalupe Mountains, a mountain range recognized as the best-preserved Permian fossil reef in the world. Reef limestones form the prominent Guadalupe Escarpment and back-reef carbonates form the canyons and plateaus to the northwest. Geologists from all over the world come to the Guadalupe Mountains to study this Permian reef complex.

Carlsbad Caverns National Park lies just 5 miles (8 km) north of Guadalupe Mountains National Park along Guadalupe ridge. Each year over 500,000 visitors place increasing demands on the resources of Carlsbad Caverns.

The following issues, features, and processes were identified at scoping sessions as having critical management significance to the park:

- Water contamination: Infiltration of contaminated water from parking lots and sewer lines has the potential to impact the entire ecosystem, destroying cave features and the habitat of the world-famous colony of migratory Mexican free-tailed bats. This situation has resulted in the re-evaluation of infrastructure above the cave and measures to prevent contaminated water from entering the cave.
- Cave preservation: Caves contain delicate non-renewable resources and are a component of fragile karstic eco-systems. The continual use, development, and exploration of caves can have an extremely detrimental impact on those resources and eco-systems. Food, chewing gum, litter, lint, and urine are left behind by visitors to the developed caves as well as the undeveloped caves of the park. In the past, as many as 2,000 speleothems each year were vandalized or stolen from Carlsbad Cavern. Measures are being taken to reduce human impacts to park caves. One such measure has been the implementation of strict rules that cavers must follow to prevent the destruction of cave features and native microbes in Lechuguilla Cave.
- Water supply and Rattlesnake Springs: Rattlesnake Springs is the sole water supply source for the park and provides a vital wetland habitat for several species of threatened birds and fish. Contamination of the groundwater and groundwater flow paths continue to be management concerns.
- External mineral extraction and associated hazards: Carlsbad Caverns is surrounded by active hydrocarbon exploration that could have a negative impact on cave resources. The extraction of mineral commodities such as potash also occurs in the vicinity of the park.
- Paleontological resources: Marine invertebrate fossils are critical to the determination of Permian reef environments, and the identification of surface exposures at Carlsbad Caverns. These fossils provide a remarkable outdoor laboratory to study this ancient ecosystem. In addition, exemplary Pleistocene fossils are found in several of the caves at the park. Preservation and protection of paleontological resources from theft and destruction is critical to maintaining their scientific value and the visitor experience.
- Bat habitat: The survival of the park's population of migratory Mexican free-tailed bats depends upon understanding the relationship between geology and the environment.

Introduction

The following section briefly describes the regional geologic setting and the National Park Service Geologic Resource Evaluation Program.

Purpose of the Geologic Resources Evaluation Program

The Geologic Resource Evaluation (GRE) Program is one of 12 inventories funded under the NPS Natural Resource Challenge designed to enhance baseline information available to park managers. The program carries out the geologic component of the inventory effort from the development of digital geologic maps to providing park staff with a geologic report tailored to a park's specific geologic resource issues. The Geologic Resources Division of the Natural Resource Program Center administers this program. The GRE team relies heavily on partnerships with the U.S. Geological Survey, Colorado State University, state surveys, and others in developing GRE products.

The goal of the GRE Program is to increase understanding of the geologic processes at work in parks and provide sound geologic information for use in park decision making. Sound park stewardship relies on understanding natural resources and their role in the ecosystem. Geology is the foundation of park ecosystems. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize this goal, the GRE team is systematically working towards providing each of the identified 270 natural area parks with a geologic scoping meeting, a digital geologic map, and a geologic report. These products support the stewardship of park resources and are designed for non-geoscientists. During scoping meetings the GRE team brings together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes. Scoping meetings are usually held for individual parks and on occasion for an entire Vital Signs Monitoring Network. The GRE mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their innovative Geographic Information Systems (GIS) Data Model. These digital data sets bring an exciting interactive dimension to traditional paper maps by providing geologic data for use in park GIS and facilitating the incorporation of geologic considerations into a wide range of resource management applications. The newest maps come complete with interactive help files. As a companion to the digital geologic maps, the GRE team prepares a park-specific geologic report that aids in use of the maps and provides park managers with an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and up to date GRE contact information please refer to the Geologic Resource Evaluation web site (http://www2.nature.nps.gov/geology/inventory/).

Regional Description

Carlsbad Caverns National Park, was proclaimed a national monument in 1923 and established as a national park in 1930. The park preserves over 100 known caves formed within a Permian-age fossil reef in southeastern New Mexico. One of the major cave systems in the park, Lechuguilla Cave, is the nation's deepest limestone cave (1,593 feet [486 m]) and the third longest. Lechuguilla contains speleothems and microbes found nowhere else in the world. The Big Room in Carlsbad Cavern is the largest, most easily accessible chamber in North America. The United Nations recognized the worldwide significance of the natural resources at Carlsbad Caverns National Park by designating the park a World Heritage Site in 1995.

Located less than 5 miles (8 km) north of Guadalupe Mountains National Park and about 20 miles (32 km) southwest of Carlsbad, New Mexico, Carlsbad Caverns National Park incorporates 46,766 acres in two separate units (figure 1) (NPS 1996). The main unit extends for about 21 miles (34 km) southwestward along the Capitan Reef and varies from 3 to 6 miles (5 to 10 km) wide. This unit contains the cavern that gives the park its name and most of the park development, which was built on top of the reef escarpment. The backcountry stretches for miles to the west and southand includes the escarpment and several deeply cut canyons.

The separate Rattlesnake Springs unit contains about 80 acres and lies 7 miles (11 km) southwest of the park entrance. Rattlesnake Springs is the source of the park's water supply.

Elevations in the park range from 3,596 feet (1,096 m) in the lowlands to 6,368 feet (1,941 m) on the escarpment. About 71 percent of the park (33,125 acres) is designated wilderness and is managed according to the provisions of the Wilderness Act and NPS wilderness policies.

Carlsbad Caverns is rich not only in geologic history but also with cultural resources reflecting a long and varied history of human occupation. This history attests to the ability of humans to adapt to the harsh Chihuahuan Desert environment. About one million artifacts are preserved and protected in the park museum. These artifacts represent prehistoric and historic Native American occupations, European exploration and settlement, industrial exploitation, commercial and cavern accessibility development, and tourism, which have each left their mark on the area. Two historic districts, the Cavern Historic District and the Rattlesnake

Springs Historic District, are on the National Register of Historic Places.

General Geology

Carlsbad Caverns National Park is located within the Guadalupe Mountains, a limestone mountain range recognized as the best-preserved Permian-aged fossil reef in the world. The fossils here reveal a detailed picture of life along the coastline of a shallow inland sea 240 – 280 million years ago. Eventually, the coastline became a horseshoe-shaped limestone layer of rock over 1,800 ft (550 m) thick, 2 – 3 mi (3 – 5 km) wide and over 400 mi (640 km) long that bordered the Delaware Basin (figure 2). The Delaware and Midland basins are part of the Permian Basin, one of the most productive petroleum provinces in North America.

By the end of the Permian age sediments thousands of feet thick covered the Capitan reef burying it for tens of millions of years. Local faulting and stresses, especially over the past 20 million years, uplifted these reef sediments almost 10,000 feet (3,000 m) and tilted the uplifted block to the east. Wind, rain, and snow have since eroded away the overlying rock exposing the ancient reef to the surface once again. The reef limestones now form the prominent Guadalupe Escarpment, a physiographic feature oriented northeast-southwest. The deep canyons and caves of Carlsbad Caverns allow visitors to view this Permian reef from the inside.

The Permian stratigraphic section at the park records back-reef, reef, and fore-reef environments (figure 3). Fine-grained layers of siltstone in the back-reef strata are low permeability barriers to groundwater flow and provide a cap rock against further erosion (Van der Heijde et al. 1997). Along with brecciated fore-reef limestones, cavernous, fractured, massive reef limestones constitute the Capitan Formation.

The Guadalupe Mountains contain over 300 known caves and more than 100 have been surveyed inside Carlsbad Caverns National Park (NPS fact sheet 2005). Many of these caves exhibit the characteristically large rooms associated with sulfuric acid dissolution. The 370-ft (113 m)-high, 14-acre Big Room in Carlsbad Caverns, for example, is the largest cave chamber in North America (Kiver and Harris 1999).

At present, Carlsbad Cavern is relatively dry due to the arid nature of the surface climate. The dripping heard today inside the cavern is only an echo of what would have been heard during prior, wetter times. If in the future, the climate becomes wetter the growth of speleothems will accelerate, conversely a more arid environment will slow speleothem growth.

Park History

Stories have it that in the late 1800s James Larkin White, a local cowboy in southeastern New Mexico, investigated a column of “smoke” and found millions of bats emerging from a huge hole in the ground. This became known as “Bat Cave.” Bat Cave was later named Carlsbad Cave before becoming Carlsbad Cavern. Seeking a profit, miners staked claims and removed over 100,000 tons of bat guano, an extremely rich fertilizer, from Carlsbad and other Guadalupe Mountains caves from 1901 – 1921. The guano was shipped to the citrus groves in California. The floor of Bat Cave was lowered by as much as 50 feet (15 m), but none of the companies selling bat guano were profitable (Kiver and Harris 1999).

During the early 1900s, Jim White was working as a guano miner and began to explore the cave and guide interested people into the lower chambers. On one of these tours, Robert Halley of the General Land Office, Department of the Interior, was so impressed with the beauty of the caverns that his report led President Coolidge to establish Carlsbad Caverns as a national monument in 1923. In 1924, an article written by Willis T. Lee, a noted U.S. Geological Survey geologist who had led a 6-month National Geographic expedition to the cave, appeared in National Geographic magazine. Lee’s article led to increased public interest and the subsequent elevation to national park status in 1930.

Exploration of the caves at Carlsbad Caverns National Park continues to enrich the park’s history. Over a period of 2 years, a group of cave explorers slowly removed rubble from a blocked passage in a cave about 3 miles (4.8 km) from the entrance to Carlsbad Cavern. A strong flow of air indicated that more passages probably existed beyond the blocked passage. In 1986, explorers finished digging out the rubble and found the incredible depths of Lechuguilla Cave.

Jim White, the first explorer and unofficial guide to the cave, later became a park ranger and advanced to chief ranger. He devoted his life to opening up an underground wonderland that is now enjoyed by nearly one million visitors from all over the world each year.

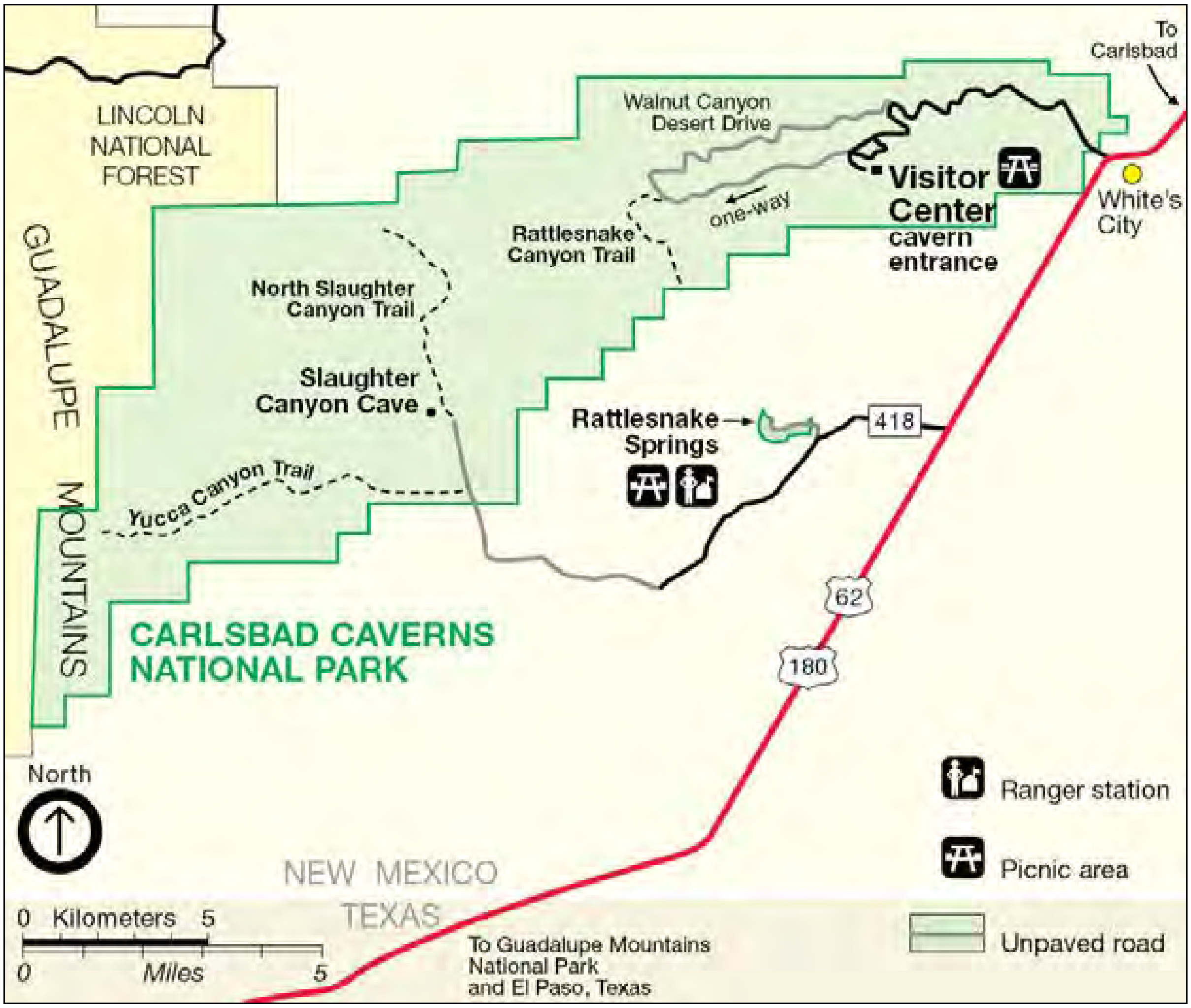


Figure 1. Location map of Carlsbad Caverns National Park.

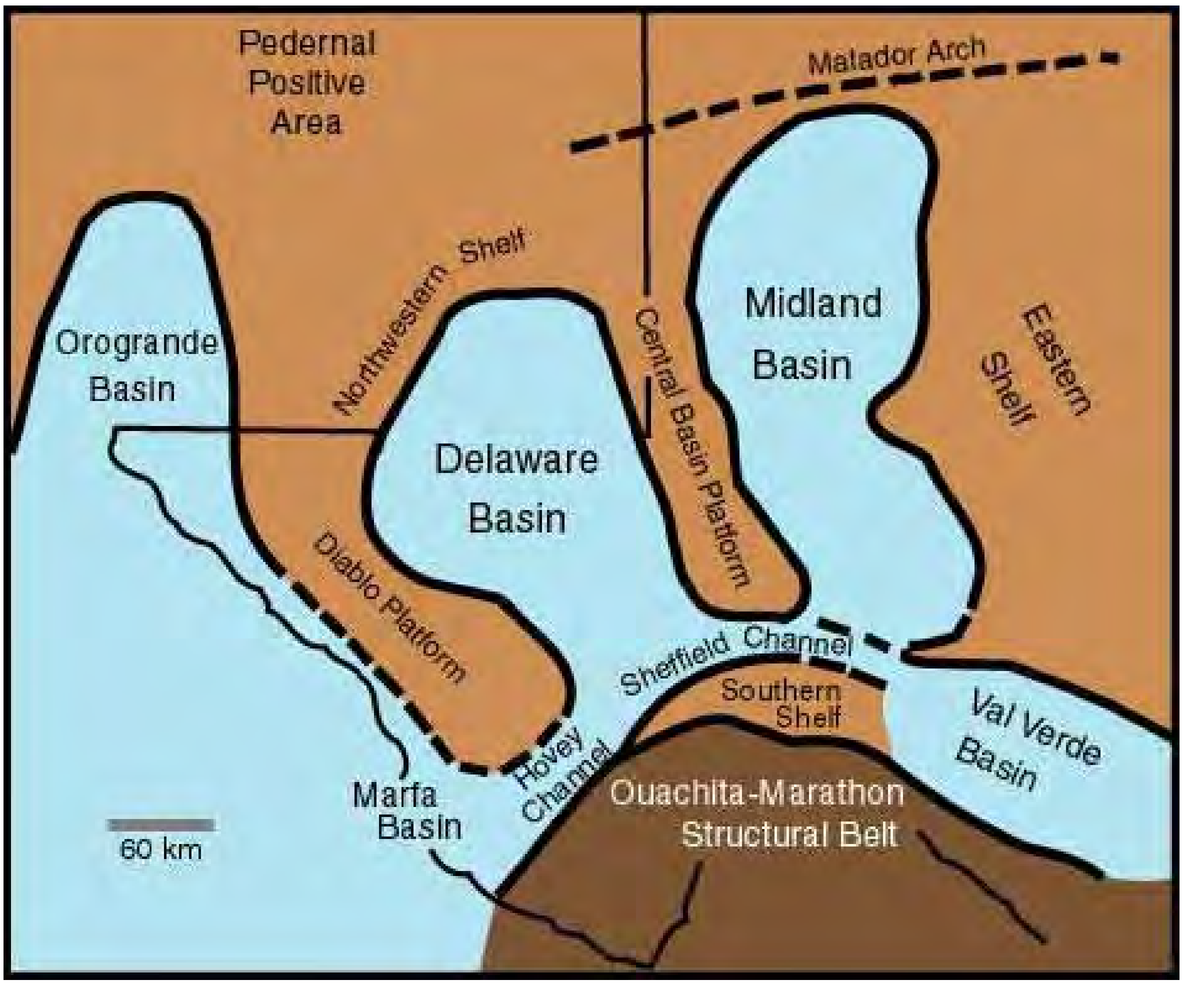
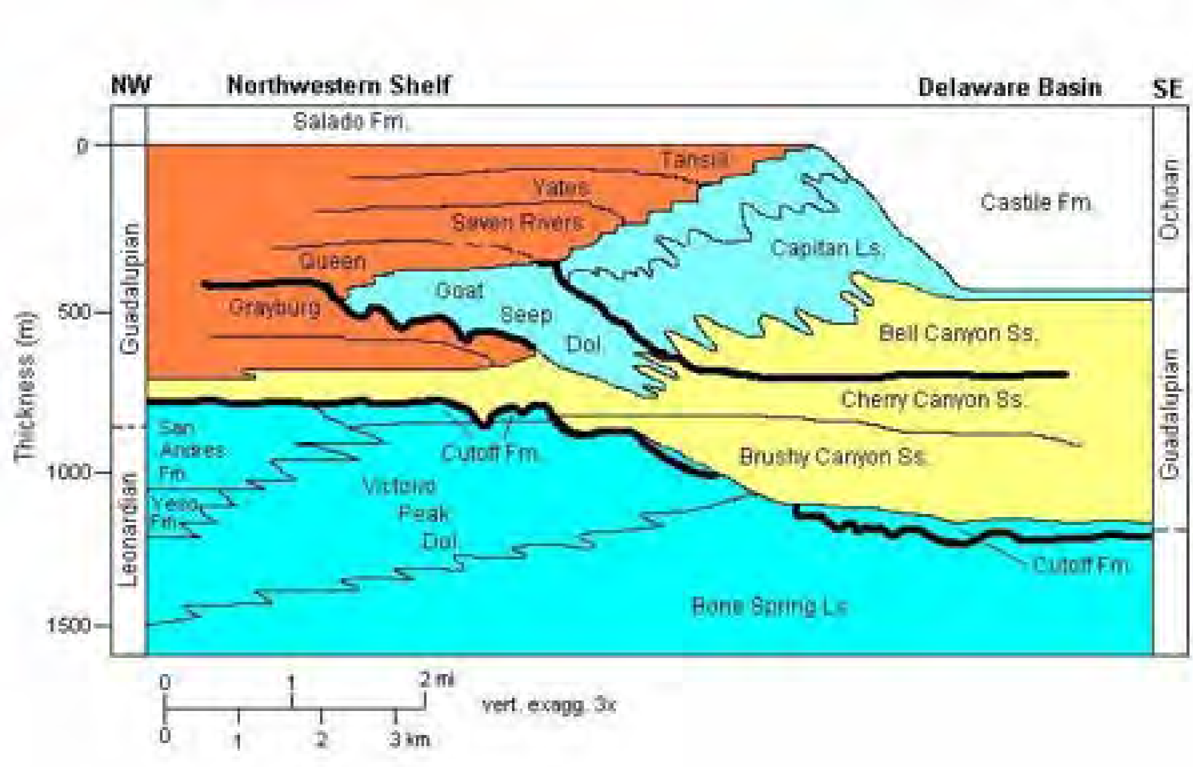


Figure 2. Major physiographic features of the Permian Basin during early Guadalupian time. Diagram from the New Mexico Institute of Mining and Geology, http://www.geoinfo.nmt.edu/staff/scholle/guadalupe.html#genset (access 2005).



A)

Period	Epoch	Back Reef Strata	Reef Strata	Fore Reef and Basin Strata
PERMIAN	Ochoa			Rustler Fm
				Castile Fm
	Guadalupe	Tansill Fm	Capitan Limestone	Bell Canyon Fm
		Yates Fm		
		Seven Rivers Fm		
		Queen Fm	Goat Seep Dolomite	Cherry Canyon Formation
		Grayburg Fm		
	Leonard	Sandstone tongue of Cherry Canyon Fm		
		San Andres Formation		

B)

Figure 3. Schematic cross-section (A) and stratigraphic column (B) for Carlsbad Cavern National Park showing back-reef, reef, and fore-reef formations. Colored formations in (B) are present within Carlsbad Caverns . Thick black lines in (A) are surfaces of erosion.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Carlsbad Caverns National Park on March 6-8, 2001, to discuss geologic resources, to address the status of geologic mapping, and to assess resource management issues and needs. The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

Significant geologic resources exposed both at the surface and in the caves pose geologic issues for the resource manager. Discussions during a one-day field trip, and the in-house scoping session, as well as from the *Final General Management Plan/Environmental Impact Statement* (GMP/EIS) identify the following geologic issues for Carlsbad Caverns National Park.

Water Contamination

Factors contributing to a relatively high vulnerability of Carlsbad Cavern National Park caves to contamination from the surface include: 1) the absence of a significant, continuous soil zone over the cave system, 2) the presence of localized but highly permeable fracture zones in the limestone, and 3) the presence of well developed karst. Most of the contaminants from parking lots are carried by the first 0.5 inch (13 mm) of rain. About 540,000 liters of contaminated water enters the groundwater system from parking lots in every 0.5 inch (13 mm) rainstorm. On average, there are 10 storms per year that produce more than 0.5 inch (13 mm) of rain (Bremer 1998). Therefore, at least 5.3 million liters of contaminated water enter the groundwater system every year (Burger and Pate 2001).

Studies by Brooke (1996) and van der Heijde and others (1997) identified three major potential sources that could threaten both water quality in the cavern and public health: 1) leaks in the sewer lines; 2) contaminated runoff from spills and vehicle fires on public parking lots and road segments; and 3) spills, leaking tanks, fires, and other accidental releases from the maintenance yard. The most threatened areas identified by the study in Carlsbad Cavern were: Quintessential Right, Left Hand Tunnel, New Section, the Main Corridor between Devil's Spring and Iceberg Rock, and locations in Chocolate High, the New Mexico Room, the Scenic Rooms, and the Big Room area (Van der Heijde et al. 1997). Infiltration in the vadose zone from the surface to the caves varies between 4 to 10 years in the Main Corridor and 14 to 35 years in the Big Room.

Infiltration research led to a re-evaluation of the infrastructure above the cave and proposals to change the management of cave and karst resources in the park (Burger and Pate 2001). Modifications of the developed area above Carlsbad Caverns were proposed in order to: 1) protect groundwater and cave resources from continuing chronic exposure to contamination, 2) protect cave resources from potential catastrophic contamination, and 3) protect visitors to Carlsbad Caverns from potential hazardous conditions due to contamination. The park prepared an Environmental Assessment (EA) designed to reduce the impacts from park facilities on the cave. Recommendations included the following proposals (Burger and Pate 2001; Pate personal communication 2006). Plans are currently in the works to replace the main outfall sewer line, remove most of the Bat Cave Draw Parking Lot, and install oil & grit separators on remaining lots. These changes are slated for implementation in the next 1 to 3 years (Pate personal communication 2006).

- Treat some of the runoff and eliminate some paved areas altogether.
- Resurface parking lots near the visitor center so that they drain southward, away from the cave.
- Install a storm water filtration system at drainage points for these parking lots
- Close the large parking lot in Bat Cave Draw to reduce the amount of vehicle fluid buildup. The EA recommends removing most of this parking lot and replacing it with a bus turnaround area and handicapped access path to the natural entrance
- Remove most of the paved surface and replace it with natural vegetation to help restore natural drainage and infiltration conditions.
- Replace the sewage collection system in the housing and office area north of Bat Cave Draw with new lines.
- Reroute the main sewage line southward to minimize the exposure of the caves to sewage leaks.

Sewage line repair and restructuring of the parking lots are funding priorities for the park. Implementation of a space reallocation plan would remove most residents from above the cave thus reducing the amount of sewage in the system and the number of vehicles parked above the cave on the north side of Bat Cave Draw.

Cave Preservation

Several anthropogenic structures located within the subsurface may affect the amount and distribution of water infiltrating into and through the subsurface. Water percolating into the subsurface is redistributed by the extensive underground trail system and virtually impervious lunchroom area about 750 feet (250 m) below the visitor's center (Van der Heijde et al. 1997). In the past, periodic cleaning of the trails released water into the surrounding caverns. Water lines along the trails are no longer in use but remain in the cave and could leak at an unknown rate at connection points and at spigots if use was resumed (Brooke 1996; Pate personal communication 2006). In the past, runoff from trails was thought to contain rock fragments, organic compounds, and nitrates from urine on the trail (Van der Heijde et al. 1997). However, trails in the cave are no longer washed so contaminated water is not released into the cave environment (Pate personal communication 2006).

The elevator and utility shafts underneath the visitor's center also provide major downward conduits for water infiltrating the upper formations (Brooke 1996). A sewage pump removes wastewater from the restroom facilities located within the lunchroom area through the utility shaft to the surface. Equipment failure or maintenance practices of these restroom and sewage transport facilities may result in contamination. Recognition of problems with the current pump and standpipe has prompted the park to request money for their replacement. However, the timeline for implementation of a new system remains uncertain (Pate personal communication 2006).

More than 500,000 visitors a year enter Carlsbad Caverns. Food, chewing gum, litter, and lint have been found throughout the cavern. Discoloration of speleothems in Carlsbad Caverns results from large accumulations of lint, clothing fibers, dead skin, and hair left behind each year by thousands of cave visitors. The buildup of lint makes the speleothems appear dull and gray. Investigations show that lint is a very good source of organic material for microbes, mites, and spiders and that the breakdown of the lint may generate organic acids that dissolve calcite speleothems (Burger and Pate 2001).

Researchers found that short rock walls along the sides of the trail contain much of the lint. To reduce lint accumulations, rock walls have been and are continuing to be, built along the five-kilometer-long trail (Pate personal communication 2006). The trail is vacuumed twice a year to remove lint and a volunteer group works in the cave during an annual week-long "Lint Camp" to remove lint and other litter from along the visitor trail system.

Formerly water was used to clean the floor in areas where there is a problem with visitors urinating in the cave and in places where the trail may become slick (Burger and Pate 2001). However, runoff from this cleaning method was problematic and as a result a new method of cleaning has been adopted. The new method of cleaning problem areas involves applying a bleach solution that is then covered with an absorbent material and removed from the cave. This has eliminated the presence of contaminated runoff from trail cleaning in the cave (Pate personal communication 2006).

Speleothem breakage monitoring between 1985 and 1991 revealed that as many as 2,000 speleothems annually were vandalized or stolen. Measures taken to correct this problem included the addition of stainless steel railings along both sides of the paved trail through the self-guided portions of the cave. During the installation of the railings from 1997 to 2000, monitoring showed that visitors leaving the trail system declined significantly. This monitoring also appeared to show a significant slow in vandalism to speleothems. Nevertheless, vandalism remains a concern and an ongoing problem for resource management (Pate personal communication 2006).

Lights in the cavern create an environment that allows algae, moss, and fungus to grow. The lights also draw animals farther into the cave than they would normally venture. These factors impact and change the cave environment.

Although entry to Lechuguilla Cave requires a permit, exploration and research have resulted in some adverse impacts to pristine cave resources. In 1996 it was documented that opening the lid to the airlock-culvert system allowed small dirt and debris particles to fall into the cave, and created a blast of air that was thought to affect cave conditions. The installation of a stainless steel access tube with an airlock system has corrected the problems associated with debris and airflow at the entrance (Pate personal communication 2006).

Expeditions requiring several days are necessary to explore and precisely document new areas, but exploration, recording expeditions, and careless travel have damaged numerous formations. Many delicate and once pristine formations adjacent to travel routes are covered by mud and dirt. The park has addressed this by implementing more stringent guidelines, including the requirement that minimum impact caving techniques be used when working in the cave. This action has led to better overall protection of cave resources. In addition restoration activities have also corrected some of the more serious impacts (Pate personal communication 2006).

Human urine also impacts the cave environment (NPS 1996). For safety and ultimately the protection of cave resources, urine is allowed to be placed in designated locations in the cave when expeditions require more than two days. This remains one of the more serious impacts to the cave environment despite various researchers' efforts to solve this difficult problem (Pate personal communication 2006).

As of 2006, 113 caves are known in the park. Although, cave resources in the backcountry are not being fully monitored, there is little evidence of vandalism and theft of cave resources.

Several caves outside the park boundary on U.S. Forest Service (USFS) and Bureau of Land Management (BLM) lands might connect to pristine park caves such as Lechuguilla and possibly other undiscovered caves (NPS 1996). Many water sources that are integral to the formation of the caves and ecosystem in the park also originate outside the park boundary.

Water Supply and Rattlesnake Springs

Rattlesnake Springs lies south of Guadalupe Ridge, about 5 miles (8 km) from the mouth of Slaughter Canyon, and is the sole water supply source for Carlsbad Caverns National Park. It also provides a vital wetland habitat that supports several species of threatened birds and fish.

In 1948, the National Park Service became concerned about aquifer contamination when agricultural development began. There is evidence showing that an aquifer adjacent to the one that supplies water to Rattlesnake Springs has been contaminated by oil and gas activities and that high flow conditions spill this contaminated water over into the Rattlesnake Springs drainage area (Pate personal communication 2006). A nearby gas field produces from the Morrow Formation (Pennsylvanian), the most important natural gas producer in the Delaware Basin of southeastern New Mexico (Mazzullo and Brister 2001). If there is a breach in the casing, a loss of circulation, or another drilling problem, the result could be contamination of one or more of the aquifers that supply water to the park and surrounding landowners. Because of these concerns, the National Park Service sponsored a study of the aquifer supplying Rattlesnake Springs (Bowen 1998).

Rattlesnake Springs is a high-discharge artesian spring that flows from a karstic, well-indurated limestone conglomerate located at the distal end of a small alluvial wedge between the Gypsum Plain of the Delaware Basin and the Guadalupe Reef Escarpment. The conglomerate is derived from the large alluvial fan emanating from Slaughter Canyon and is either Miocene-Pliocene or Pleistocene in age (Bowen 1998).

The limestone conglomerate lies above the Castile Formation, a regional confining layer, or aquitard. The low conductivity of the Castile is due to the presence of evaporites that have some of the lowest conductivity of any natural media ($2x10^{-8}$ to $4x10^{-13}$ m/sec).

Based on hydrologic data, Bowen (1998) hypothesized that flow within the Slaughter Canyon alluvial fan "is controlled by karst channels within the limestone conglomerate." The heterogeneity of the system localizes flow within channels and isolates the conglomerate between finer silt- and clay-dominated sediments. Karstic channels produce mostly isolated, discrete flow paths, and these flow paths need to be identified for the Slaughter Canyon area. An electrical survey (ground penetrating radar) could be used to identify the channels.

Bowen (1998) concluded that contamination of Rattlesnake Springs was not likely to occur from the nearby Washington Ranch natural gas injection facility. Furthermore, current agricultural withdrawals from the system appeared to have minimal impact on Rattlesnake Springs. Bowen cautioned, however, that future developments of the upper Black River Valley "could have significant impacts on the system due to the karstic nature of flow" (Bowen 1998).

The NPS has recently funded a group out of the University of Texas at El Paso to accurately determine the location of the discreet channel (or channels) that feed Rattlesnake Springs. Once determined, any future drilling for oil & gas can be directed away from this (or these) channels (Pate personal communication 2006).

Water flow in the park's backcountry springs and seeps has been monitored on an annual basis since the early 1960s. At that time 10 permanent springs, 12 permanent seeps, and 6 intermittent seeps were recorded. About half of these water sources were developed for early ranching and guano mining operations. Remnants of earthen and metal tanks, check dams, and catchment basins still exist. In 1993, 47 seeps and springs were inventoried in the park. About 20 of these are permanent water sources considered critical to wildlife.

Mineral Resources

Oil and Gas

Under federal law, no federal mineral or oil and gas leasing or the associated development is permissible in Carlsbad Caverns National Park. In addition, provisions in the Lechiguilla Cave Protection Act, the record of decision by the Bureau of Land Management with regard to the Bureau's *Dark Canyon Environmental Impact Statement* (establishing an 8,320-acre cave protection area north of Carlsbad Caverns National Park in the vicinity of Dark Canyon), and the USFS management action provide protection for many cave resources. However oil and gas are produced on state lands, and exploration and production on unrestricted state and private lands has the potential to irreparably alter or destroy cave resources in Carlsbad Caverns National Park.

The Lechuguilla Cave Protection Act (Public Law 103-169) gives additional protection to Lechuguilla Cave and other cave resources in and near the park by establishing a 9,720-acre cave protection area (NPS 1996). The act withdraws 6,280 acres of adjacent federal lands from mineral exploration and development and prohibits new drilling. However, the act does not apply to the 960 acres of adjacent private lands or 2,880 acres of state-owned lands within the cave protection area. Protective measures in the Lechuguilla Cave Protection Act include:

- Prohibiting occupancy on existing federal leases
- Canceling existing federal leases where necessary
- Prohibiting additional drilling on federal leases
- Limiting surface access to all federal leases in the cave protection area

During the summer of 2006 the State of New Mexico issued oil and gas leases on five sections of land approximately two miles north of the park boundary. These five sections of state land lie within the 9,720 acre cave protection area. No wells have been drilled in this state lease area at the time of this writing. Additional leasing on state and private lands north of the park remains a possibility. The NPS is trying to initiate a dialogue with the state of New Mexico to address park protection concerns.

Since the 1920's, hydrocarbon exploration has been active south of Carlsbad Caverns National Park in the Delaware Basin, a sub-basin of the larger Permian Basin. About 71 percent of Permian Basin oil (65 billion barrels) and 54 percent of Permian Basin associated and dissolved gas-in-place (0.93 trillion cu m; 32.7 trillion cu ft) have been produced from Permian-age strata. The remainder (mostly gas) is produced from Pennsylvanian or older Paleozoic rock, predominantly from the Ordovician Ellenburger Formation (Table 1) (Ward et al. 1986; Hill 1996).

TABLE 1: Producing units in the Delaware Basin

Period	Formation	Oil/Gas
Permian	Tansill Fm	Oil
	Yates Fm	Oil
	Seven Rivers Fm	Oil
	Queen Fm	Oil
	Grayburg Fm	Oil
	Bell Canyon Fm	Oil
	Cherry Creek Fm	Oil
	Brushy Canyon Fm	Oil
	San Andres Fm	Oil
	Abo-bone Spring	Oil
	Wolfcamp Fm	Oil
Pennsylvanian	Cisco Fm	Oil
	Canyon Fm	Oil
	Strawn Fm	Gas
	Atoka Fm	Gas
	Morrow Fm	Gas
Devonian	Woodford Fm	Gas
Silurian	Fusselman Fm	Gas
Ordovician	Montoya Fm	Gas
	Ellenburger Fm	Gas

(From Hill (1996) and the Texas Bureau of Economic Geology, access 2005)

The largest producers of oil in the Delaware (and Permian) Basin are the Guadalupian-age reservoirs of the Queen, Seven Rivers, Yates, and Tansill Formations (figure 3) (Ward et al. 1986; Hill 1996; New Mexico Institute of Mining and Technology 2005). Together, they account for 67 percent of all Permian oil found and 62 percent of all Permian gas found in the Delaware Basin. The second most prolific Permian reservoirs are found in Leonardian strata such as the open-shelf San Andreas Limestone (figure 4). Most of the production from Permian rocks comes from less than 5,000 feet (1,500 m) (Dolton et al. 1979).

Hydrocarbon traps in Permian rocks are mostly a combination of stratigraphic and structural traps with the hydrocarbons sealed in place by porosity and permeability barriers of carbonate, evaporite, or shale. Production is maximized in the near-back-reef or grainstone margin facies that was neither cemented like the reefs nor plugged with evaporite cement like back-reef strata closer to shore. Back-reef environments account for more than 90 percent of all hydrocarbon production in the Delaware Basin (figure 4).

No production comes from the Capitan, Victorio Peak, or Goat Seep reef or fore-reef facies. These rocks were tightly cemented on the sea floor shortly after deposition (New Mexico Institute of Mining and Technology 2005).

Basin sediments account for the rest of the production. Hydrocarbons are trapped in submarine channel sandstones and basinal limestones of the Delaware Mountain Group (Bell Canyon, Brushy Canyon, and Cherry Canyon Formations) (Berg 1979; Williamson 1979; Hill 1996; Texas Bureau of Economic Geology 2005). The submarine channel sandstones pinch out against the Capitan reef complex.

Most of the Permian oil is generated from the largely organic, carbon-rich, basinal sediments such as the Bone Spring Limestone. Oil in basinal facies has probably migrated only a short distance from source to reservoir. Oil in back-reef facies, however, moved up-section or laterally through fractured reef sediments to get from source to reservoir. Although cementation destroyed reef porosity, permeability through the reef zone was high due to fracturing of the reef.

Current estimates suggest that 1.0 to 6.0 billion barrels of oil in-place remains to be discovered in Permian rocks of the Permian Basin (New Mexico Institute of Mining and Technology 2005). This volume is 1.5 to 9.2 percent of the discovered Permian Basin crude oil.

Deeper, pre-Permian hydrocarbon (mostly gas) accumulations are found in the Delaware Basin and on the Central Basin Platform. Most of the gas is found in structural, stratigraphic, or combination traps that are sealed by shale and impermeable carbonate rocks (Hill 1996). Some Pennsylvanian reservoirs are found near Carlsbad, New Mexico, northeast of the park, but none extend past the northwest-southeast trending Huapache Monocline that intersects the Capitan reef between Rattlesnake Canyon and Carlsbad Caverns (Hill 1987, 1996). The lowermost Pennsylvanian gas reservoir is in the Morrow Formation, about 10,000 feet (3,050 m) beneath Carlsbad Caverns (NPS 1996).

Hundreds of producing gas and oil wells have been drilled north, east, and south of Carlsbad Caverns National Park (figure 4). Exploratory wells have been drilled within a few thousand feet of the north and east boundaries of Carlsbad Caverns, and some of these have encountered voids at the same depth as major passages in Lechuguilla Cave (NPS 1996). At least 61 wells drilled near the park have encountered lost circulation zones in the Capitan and Goat Seep Formations, suggesting that unexplored cave passages were intersected during drilling (NPS 1993, 1996).

Substantial hydrocarbon reserves and known cave resources exist immediately north of the park boundary. It is probable that exploratory drilling will intersect openings that connect with caves in the park. Resources inside the park could be at risk of contamination from toxic and flammable gases and other substances associated with the exploration production of oil and gas.

In 1993, the National Park Service convened a panel of geologists familiar with caves and geology in the Carlsbad region to consider the various risks of contamination to caves within the park from hydrocarbon exploration and production (NPS 1993). The principal conclusion of the panel was that there was no way to protect the cave resources of Carlsbad Caverns without establishing a cave protection zone along the northern boundary.

More detailed information about hydrocarbon reserves and oil and gas production potential in the Carlsbad Caverns area is given in the *Final Dark Canyon Environmental Impact Statement* (BLM 1993) and "Report of the Guadalupe Caverns Geology Panel to the National Park Service" (NPS 1993). More detailed information on the oil and gas resources of the Delaware Basin is available from the oil and gas atlases of the Texas Bureau of Economic Geology in Austin, Texas (http://www.beg.utexas.edu/, access 2005), and the New Mexico Bureau of Mines and Mineral Resources in Socorro, New Mexico (http://geoinfo.nmt.edu/, access 2005).

Sulfur

Sulfur deposits in the Delaware Basin formed in sedimentary rocks by the secondary oxidation of H_2S in groundwater. There are two primary sulfur producing areas in the Delaware Basin: the Rustler Springs sulfur district just south of Carlsbad Caverns National Park and the Fort Stockton sulfur district on the southeast edge of the Delaware Basin adjacent to the Central Basin Platform (Hill 1996). Sulfur also occurs on the Northwest Shelf and in the caves of the Guadalupe Mountains.

Sulfur has been reported in Carlsbad Cavern and Lechuguilla Cave (Hill 1987; Cunningham et al. 1993). Minute amounts of sulfur in Carlsbad Cavern were reported in the Big Room, Christmas Tree Room, and New Mexico Room. In the Big Room, sulfur occurs as an overgrowth crust lining a drip tube in a gypsum block. However, investigators found that some of the material thought to be sulfur was actually the yellow uranium minerals, tyuyamuite or metatyuyamunite (Cunningham et al. 1994; Hill 1996).

Lechuguilla Cave hosts more sulfur than all the other caves in the Guadalupe Mountains combined (Hill 1996). Multi-ton deposits exist in the North and South Ghost Town areas and in the Void. The sulfur has a massive, microcrystalline, conchoidal, or vuggy texture. Ghost Busters Hall, the Rift, the FLI Room, Hard Daze Night Hall, Chandelier Graveyard, and Southwest Branch and Far East sections of the cave are also reported to have sulfur deposits (Cunningham et al. 1993; Hill 1996).

Sulfide, Barite, and Fluorite deposits:

Deposits of various sulfides, barite ($BaSO_4$), and fluorite (CaF_2) are found around the margin of the Delaware Basin in the Guadalupe, Apache, and Glass Mountains and in the Fort Stockton area. The mineral deposits are small and of low economic potential. The mineral deposits in the Apache and Glass Mountains are more extensive than in the Guadalupe Mountains.

In Carlsbad Caverns, barite has been found at several locations within the entrance pit of Lechuguilla Cave (Hill 1996). The entrance lies along a flexure superimposed on the southeastern flank of the Guadalupe Ridge anticline. The barite occurs in the Seven Rivers Formation as an intergrowth with calcite.

Potash

Potash in an informal term usually meaning potassium oxide (K_2O) or potassium carbonate (K_2CO_3), but it may also include a variety of potassium minerals such as chlorides, sulfates, and nitrates with substitutions by magnesium, calcium, and sodium. Encompassing an area of approximately 1,160 square miles (3,000 square km) about 15-25 miles (25-40 km) east and northeast of Carlsbad in Eddy County, the Carlsbad Potash district contains some of the world's major potassium deposits (Hill 1996). At one time, the district supplied about 85 percent of domestic potash production.

Potash minerals occur entirely within the Salado Formation. The Salado Formation was deposited over the Capitan Limestone reef complex, but, in the park area, has since been removed by erosion (figure 3). Only a few deposits have been found outside of the district but are not economic.

Miscellaneous Deposits

Selenite, a clear, colorless variety of gypsum, has been found in the Castile Formation, especially along the small faults in the southwestern part of the East Quadrangle (Hayes 1974). Vast amounts of fine-grained gypsum occur in many areas. Limestone gravel suitable for road ballast has been quarried in the past. Limestone and dolomite from the Tansill, Yates, and Seven Rivers Formations have been used in the construction of the buildings at the park (Hayes 1974).

Paleontological Resources

For many years, geologists have visited an outcrop in Walnut Canyon for excellent exposures of the reef and near-back-reef facies of the upper Capitan Limestone and Tansill and Yates Formations (described in the "Geologic Features" section). Testing the limestone with hydrochloric acid has etched the outcrop and serendipitously exposed many of the marine organisms in the reef. Although fossils occur throughout the park, many geologists recognize the excellent reef exposure in Walnut Canyon as world-class and deserving of special protection. Preservation efforts could model those taken at Dinosaur National Monument to preserve and protect Jurassic dinosaur bones.

Bats and Bat Habitat Management

In summer evenings, about 5,000 bats per minute exit the entrance to Carlsbad Caverns. This evening exodus may last for up to 2 hours. In the early 1900s, an estimated 8 or more million bats were counted at Carlsbad Cavern, but today, only about 300,000 bats (mostly Mexican-freetail bats) use the cave.

There were several very large bat counts in the 1900s, however there are no records of the method by which these numbers were derived therefore they are of questionable scientific value. Although the exact numbers are unsure it is certain that bat populations have declined due to past mining activities, loss of habitat to the expanding human population, and the use of chemicals, especially DDT.

In the 1950s and 1960s. DDT was banned in the United States in 1972, but there is no such ban in Mexico, where the bats spend the winter. In 1994, a large quantity of illegal and improperly stored, DDT was discovered in a shed near the park. This may have contributed to the higher levels of DDT residue in the Carlsbad bats relative to bats in other parts of the country. Two shafts sunk by miners before 1923 also contributed to a bat population reduction. The shafts allowed warm air near the ceiling to escape so that the survival of bat pups in the maternity colony was made more difficult. The National Park Service plugged these shafts in 1981. Bat populations rose to 750,000 in the mid-1990s (Kiver and Harris 1999).

Bats are the only flying mammal in the world and one of the only night predators of insects. These gentle, insect eaters may consume up to 600 mosquitoes per hour and a lactating female can eat over half her weight in insects on her nightly forage. Bats from Carlsbad Cavern National Park are known to eat mostly moths, a significant portion of which are major pests on crops found along the Pecos and Black Rivers. Bats are at the top of the food chain and thus, are susceptible to increased levels of chemical pollutants that concentrate in lower plants and animals. The relationship between the bats, the geology of the caves, and the external environment is a delicate one and accentuates the need for ecosystem management beyond the borders of the park.

Microbes and Lechuguilla Cave

Previously unknown bacteria have been found living on rocks and in pools of Lechuguilla Cave. Surviving hundreds of meters below the ground with no light and no organic input from the surface, these bacteria line the walls, ceiling, and floors of many places in Lechuguilla Cave (Burger and Pate 2001). The pools in Lechuguilla Cave are also teeming with life competing for the few nutrients that exist. On the medical front, enzymes released by the bacteria have been found to attack leukemia cells.

Unfortunately, human exploration introduces foreign bacteria into the cave on skin, hair, and clothing fibers. These bacteria out compete native microbes for food and destroy their populations. To address this problem the park has instituted a policy requiring that everyone who enters Lechuguilla Cave has clean clothes and clean equipment, thus preventing the introduction of microbes from other caves into Lechuguilla. Cave explorers also are required to eat and sleep on drop cloths to catch food, skin, and hair. They are encouraged to wear bandanas to contain hair and are required to eat their food over plastic bags to catch falling crumbs.

In addition, cavers are restricted from getting near any pools found during exploration. When a pool is discovered, it is reported to the park and to scientists studying the microbes. Scientists approaching the pools wear Tyvek clean suits and set up slides that sit in the cave for up to five years. When the slides are collected, the bacteria are cultured in a lab and studied further (Burger and Pate 2001). Discoveries such as these are significant and demonstrate the need to protect similar natural areas for further research into the microbes and their environment.

Guides and Maps for Interpretation

Printed geologic trail guides are needed for the general public. The guides would also be an aid to the interpretive staff.

Springs associated with the Yates Formation-Tansill Formation contact are the most important water supply for animals in the park. Paul Burger, park geologist, expressed the need to map these springs for all 7.5 minute quadrangle maps (Appendix B). He also expressed a need for geo-habitat maps that associate wildlife habitat with geology, especially for endangered species (Appendix B). There has been no known interest in mapping the surface geology of the park since the 1960s.

Carlsbad Caverns National Park Planning Documents

The 1996 GMP, the 1995 *Cave Management Plan* (CMP), and the 1994 *Resources Management Plan and Environmental Assessment* (RMP) developed programs for the study, protection, exploration, surveying, and monitoring of cave resources. The major programs in these plans are summarized below. Details of each plan may be found in the appropriate document.

Subsurface Resources

The GMP proposes methods to reduce cave resource impacts, including ways to keep people from touching or breaking cave formations and spreading lint from their clothing. The 1993 Lechuguilla Cave Protection Act and the BLM *Final Dark Canyon Environmental Impact Statement* (1993) address cave resources north of the park boundary. The Park Service cooperates with the BLM and the State of New Mexico to mitigate impacts on cave resources within the park's boundary and outside of the park from drilling activities outside of the park boundaries.

The actions that are proposed in the GMP regarding subsurface resources include the following:

- No construction of new buildings or impervious areas (e.g., paved parking lots) above the cavern or other cave resources;
- Install catchment basins in parking lots to trap petroleum byproducts washed off pavement;
- Evaluate the infiltration hazard study;

- Continue to limit visitor access in the Green Lake Room, King's Palace, Queen's Chamber, and Papoose Room to protect the fragile cave resources;
- Increase NPS staff and deploy them more effectively to protect cave resources;
- Emphasize the significance of resources in interpretive messages;
- Implement actions to reduce the impacts of trails on Carlsbad Caverns, including surface material and trail cleaning methods;
- Redesign the trail lighting system to make it more efficient and easier to maintain and to minimize associated algal growth;
- Prioritize research, exploration and mapping needs for Lechuguilla Cave and ensure compatibility with NPS research guidelines and management needs and priorities;
- Evaluate possible improvements to the present Lechuguilla Cave airlock-culvert system;
- Develop a plan for the restoration and rehabilitation of Lechuguilla Cave resources;
- Provide funding and staffing to enforce existing guidelines for exploring and surveying all park caves;
- Protect paleontological resources during cave restoration projects; and,
- Develop a feasibility study to determine if Ogle Cave could be opened for guided tours similar to the tours given at Slaughter Canyon Cave.

The recommendations in the RMP and CMP are consistent with those in the GMP. They include:

- Preserve and perpetuate natural cave systems while providing opportunities for public education, recreation, and scientific study;
- Keep Lechuguilla Cave closed to the general public because of its hazardous nature, unique resources, research potential, and continuing exploration and survey;
- Inventory and monitor all caves designated for regulated public access;
- Provide information packet for visitors to wild caves;
- Photo-monitor caves designated for recreational visitor entry;
- Study water infiltration patterns to better understand and mitigate human-induced changes in the cave ecosystem; and,
- Implement a cave rehabilitation program to offset the alteration of the natural cave environment from over 50 years of intensive human use.

Surface Resources:

The GMP proposes a cooperative plan with Guadalupe Mountains National Park and the Waste Isolation Pilot Project (WIPP site) to monitor air quality in the vicinity of the park. The GMP also proposes to work cooperatively with the state of New Mexico to address water quality issues and to update the emergency flood response plan for flood-prone areas such as Walnut Canyon and Slaughter Canyon.

To protect fossil resources, the GMP proposes evening patrols of the park entrance road to discourage illegal collecting of fossils. Paleontological resources would be inventoried and analyzed. Old and new data is to be incorporated into the Smithsonian Institution's nationwide FAUN-MAP system.

The plan calls for a study of groundwater flow associated with Rattlesnake Springs and an inventory and monitoring of backcountry springs affected by human-made impoundments. The 1989 *Rattlesnake Springs Management Plan* and the 1982 *Water Resources Management Profile* also address water resource protection for the park.

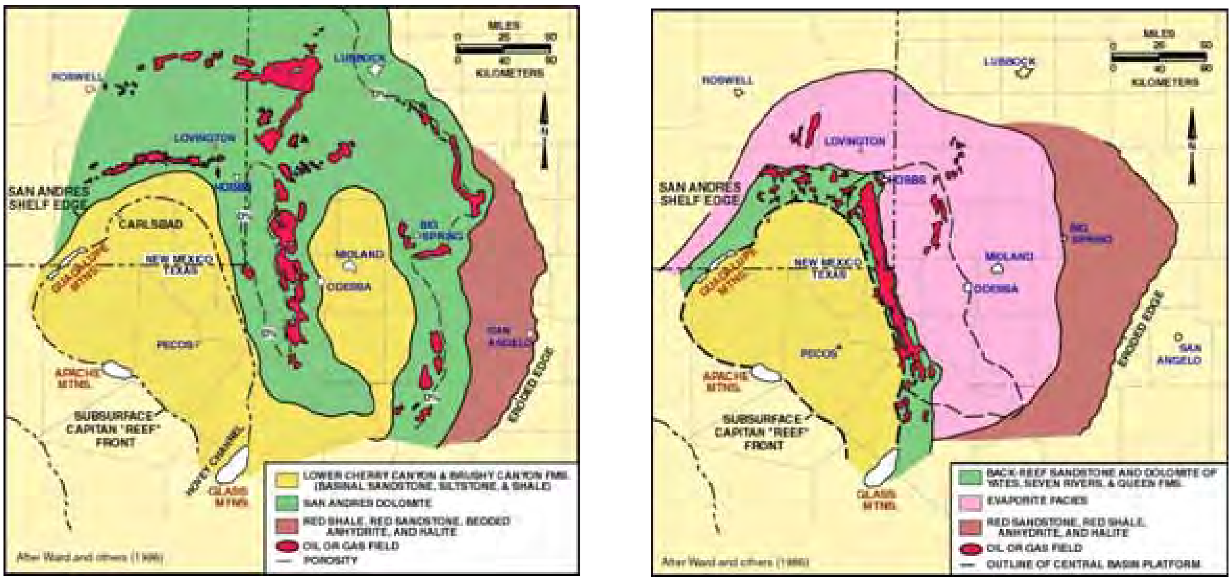


Figure 4. Inferred distribution of depositional facies in the lower Guadalupian strata (A) and upper Guadalupian strata (B) of the Permian Basin. Oil and gas fields producing from those intervals are also shown. Dashed line in (A) represents line of zero net porosity. Diagrams from the New Mexico Institute of Mining and Geology, http://www.geoinfo.nmt.edu/staff/scholle/guadalupe.html#genset (access 2005) and Ward and others (1986).

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Carlsbad Caverns National Park.

The surface and cave features in the Guadalupe Mountains are the result of geologic forces, climate changes, and the action of water over a vast span of time. The caves in Carlsbad Caverns and in Guadalupe Mountains National Park are the result of a process of dissolution involving sulfuric acid. Decorations in these caves are arguably unsurpassed in the world. On the surface, Carlsbad Caverns NP and the surrounding Guadalupe Mountains provide a unique window to the world's best outcrops of a preserved ancient reef where a 250-million-year geologic story is exceptionally exposed in the desert landscape. The Capitan Reef continues to offer exceptional potential for additional cave discovery, exploration, and research (NPS 1996).

Formation of Carlsbad Cavern

There are 113 known caves within Carlsbad Caverns National Park and most of them reveal the unusual mode of origin by sulfuric acid (H_2SO_4). Most of the world's limestone caves are created when surface water flows down through cracks in limestone and slowly enlarges passageways. Surface (meteoric) water contains dissolved carbon dioxide forming a weak acid called carbonic acid. This acid slowly dissolved the rock in more than 90 percent of the world's limestone caves. These types of caves are typically very wet and have streams, rivers, and sometimes lakes or large waterfalls. They are part of the local or regional drainage system that transports surface water to the sea. This process formed the caves in Mammoth Cave National Park and Buffalo National River in the Ozarks, but not Carlsbad Caverns National Park. There are no flowing streams in any of the hundreds of caves in the Guadalupe Mountains.

About 60 million years ago, during a major episode of mountain building known as the Laramide Orogeny, the central part of New Mexico and Colorado was uplifted, forming a major, north-trending arch known as the Alvarado Ridge. This ridge extended from Wyoming to west Texas and had a maximum elevation in central and southern New Mexico of about 12,000 ft (3,650m). Water in limestone aquifers moved down the east slope of the Alvarado ridge toward Texas, and some of that water flowed through limestones of the Capitan Reef. This water had significant hydrostatic head (pressure) which forced it upward along fractures in the Capitan Limestone to spring outlets scattered through the ancestral Guadalupe Mountains. As water moved upward through the fractures, it dissolved limestone and formed vertically oriented fissure caves. About 30 million years ago, in Late Oligocene to Early Miocene time, uplift culminated in faulting associated with the opening of the Rio Grande Rift along the axis of the Alvarado Ridge. Erosion gradually exhumed the Capitan Reef, and coupled with faulting along the rift, caused the water table to fall. As the water table dropped, fracture caves became partly air-filled, allowing space for hydrogen sulfide to degas into the atmosphere. Hydrogen sulfide was derived from the microbially assisted alteration of oil and gas and gypsum in oil fields adjacent to the Guadalupe Mountains and is widely distributed in deep groundwater. Once in the cave atmosphere, hydrogen sulfide was rapidly reabsorbed into oxygen-rich water percolating downward from the surface. Mixing of hydrogen sulfide and oxygen in an aqueous environment produced in the sulfuric acid that dissolved limestone and formed the immense passages and galleries characteristic of Guadalupe Mountain caves. Because the Guadalupe Mountains are tilted eastward, the locus of sulfuric acid dissolution migrated eastward with time (DuChene and Cunningham 2006). Consequently, the oldest caves (about 12.5 million years) in the Guadalupes are in the west, and they become progressively younger to the east (3.8 million years at Carlsbad Cavern) (Polyak et al. 1998) (figure 5).

One of the clues, which led geologists to the sulfuric acid hypothesis, is the presence of gypsum ($CaSO_4.2H_2O$) in many caves. Gypsum is produced by the reaction of sulfuric acid with limestone ($CaCO_3$). Gypsum is a soft white mineral that coats walls, and forms crystals in some of the caves. Massive deposits of gypsum in the Big Room past the Bottomless Pit and at numerous locations in Lechuguilla cave attest to the large amount of sulfuric acid required to dissolve the immense rooms of Carlsbad Caverns and other caves in the Guadalupe Mountains.

As dissolution of limestone progressed, support for the cave ceilings was reduced so that ceiling blocks tumbled to the floors of caves. Boulder-size blocks are common, but the largest of them is the massive Iceberg Rock in Carlsbad Cavern that weighs over 200,000 tons (Kiver and Harris 1999). Ceiling breakdown and roof collapse is one hypothesis for the creation of the entrance to the surface (Kiver and Harris 1999). An alternative hypothesis, however, suggests that the entrance to Carlsbad Caverns is a former spring outlet that was fed by water ascending through a tube developed along fractures that extended deep into the Capitan Limestone (Palmer and Palmer 2000).

Speleothems

Many of the speleothems (cave formations) that continue to grow and decorate Carlsbad Cavern are a result of rain and snowmelt percolating through the Capitan Limestone. Surface water contains dissolved carbon dioxide, which makes it slightly acidic and capable of dissolving limestone. Eventually, water saturated with calcium carbonate seeps and drips into the cave where loss of carbon dioxide causes calcite to precipitate as speleothems.

Many cave parks contain the stalactites, stalagmites, columns, flowstone, and helictites that are common in Carlsbad Caverns. However, the park is world famous because of the abundance and variety of common speleothems, and the presence of rare and exotic speleothems, especially in Lechuguilla Cave. Hanging from the ceiling in Lechuguilla Cave are glittering white gypsum chandeliers 15 to 20ft (4.5 – 6m) long, walls encrusted with aragonite 'bushes', and rippling strands of delicate 'angel hair' crystals that may reach 30 feet (9 m) long (Cahill and Nichols 1991).

In the Kings Bell Cord in the Kings Chamber in Carlsbad Caverns, extremely delicate soda-straw stalactites that usually grow to a few inches in length, grow to 6 feet (1.8 m) in length. In Lechuguilla, soda-straw stalactites reach 18 feet (5.5 m) in length.

Stalagmites that grow to immense size are called domes. Giant Dome in the Hall of Giants is 50 feet (15 m) tall. Crystal Springs Dome is one of the few speleothems still growing in Carlsbad Cavern. A thin film of new calcite forms on the surface of the dome as groundwater, saturated with dissolved calcium, drips onto the dome and carbon dioxide escapes into the cave atmosphere. The growth rate for Crystal Springs Dome is estimated to be equal to the thickness of a coat of paint added every 90 years. The size of these speleothems is even more remarkable considering that many grow in a stop and start process rather than a continuous process.

Caves in Carlsbad Caverns National Park also contains subaqueous minerals and speleothems. Elongate calcite crystals ('dogtooth spar') coat some cave walls and one pool in Lechuguilla has clear crystals of selenite (gypsum). Cave pools, many now mostly or completely dry, contain calcite crystals and "pool fingers" that formed under water. Large rounded forms called mammilaries, or "cave clouds" record a time when water filled the cave.

Helictites, distorted twig-like lateral projections of calcium carbonate, remained a mystery to speleologists for many years. Mineralogists discovered a microscopic opening in the center of the helictites that allowed water to move upward by capillary action. Excellent examples of helictites can be seen in the Queen's Chamber of Carlsbad Cavern.

In Lechuguilla Cave, formations similar to conventional helictites were discovered in pools where they are developing under water. Rather than capillary forces, another process known as the "common ion effect" probably formed these features. The pool contains water saturated with calcium carbonate, and it is constantly resupplied with water percolating downward from the surface. Some of this water passes through deposits of gypsum located near the pool, dissolving calcium sulfate in the process. This water, which is saturated with calcium sulfate, flows into the pool. This results in the pool water near the point of influx becoming supersaturated with calcium, which then precipitates to form the worm-shaped speleothems known as subaqueous helictites (Davis et al. 1992; Kiver and Harris 1999).

Park Caves

Carlsbad Cavern

Carlsbad Cavern is one of the world's largest caverns by volume. It also is considered to be one of the most adorned with speleothems. The paved trail drops about 830 feet (250 m) from the natural entrance through the Main Corridor into the King's Palace area, which includes the Green Lake Room, the King's Palace, the Queen's Chamber, and the Papoose Room. Approximately 750 feet (225 m) below the visitor center, the trail inclines upward to the elevator area (NPS 1996).

The cross-shaped Big Room measures 1,800 feet (550 m) in length, up to 1,100 feet (336 m) wide, and 255 feet (69 m) at its highest point. Various world-renowned speleothems include the Whale's Mouth, the Temple of the Sun, Giant and Twin Domes in the Hall of Giants, the Lion's Tail, Painted Grotto, and Green and Mirror Lakes (figure 6).

Lechuguilla Cave

Lechuguilla Cave is about 4 miles (6.5 km) north of the Carlsbad visitors center. It is the deepest known limestone cave in the United States and contains some of the most spectacular formations in the world. Some of these include subaqueous helictites found nowhere else, rare hydromagnesite (magnesium carbonate) balloons, 20-foot-long (6 m) gypsum chandeliers and gypsum hairs, 15-foot-long (4.5 m) soda straws, and unusual gypsum crystals, flowers, and crusts. The volumes of air entering and leaving the cave during periods of barometric change outside indicate that much of the cave is still unexplored.

Rare chemosynthetic bacteria and obligate fungi, which derive energy from gypsum, magnesium, and iron deposits, have been discovered in Lechuguilla. These organisms are believed to have a role in cave formation, and the pristine conditions of Lechuguilla Cave provide an unprecedented opportunity to study natural cave processes and cave climate. Lechuguilla is within a designated wilderness area and has no human developments above it to alter cave processes.

Over 89 miles (143 km) of passages have been discovered and mapped in Lechuguilla Cave, which may be connected to other known caves outside the park boundary, such as Big Manhole Cave (NPS 1996). Surveyed passages extend within about 600 feet (183 m) of the north boundary of the park. Closed to recreational caving, Lechuguilla is open by permit only for exploration and mapping, limited documentational photography, and research in such fields as cave mineralogy, microbiology, biology, and paleoclimatology.

Slaughter Canyon Cave

Formerly called New Cave or New Slaughter Cave, Slaughter Canyon Cave is one of the larger caves in the park. Located just within the mouth of Slaughter Canyon about 8.5 miles (9.5 km) southwest of the visitors center, Slaughter Canyon Cave is about 1.75 miles (2.6 km) long. The main corridor is approximately 1,170 feet (357 m) long with cross sections up to 220 feet (67 m) wide. The cave is characterized by large rooms with arched ceilings. Parts of the cave are highly decorated with speleothems, including an 89-foot (27 m) column. The hillside above the site contains fore-reef and related fossils.

Ogle Cave

Ogle Cave is connected to Rainbow Cave. The two caves formed independently and are connected by a tight joint passage called Blood Fissure. Ogle Cave is located high on the east side of Slaughter Canyon, across from Slaughter Canyon Cave.

Ogle Cave is one large linear passage about 1,500 feet (488 m) long and averages about 100 feet (30 m) in height and width. The cave is one of the larger chambers in the park. Entry into the cave requires a 180-foot (59 m) technical descent on ropes through a naturally occurring vertical passage.

The cave is decorated with large speleothems. Some of the larger speleothems include massive stalactites, stalagmites, draperies, flowstone, bell canopies, and The Bicentennial column (one of the world's tallest at 106 feet). Smaller speleothems include shields, rimstone dams, cave pearls, helictites, popcorn, and rafts.

Backcountry Caves

Ten of the 84 known backcountry caves are open to cavers with NPS permits. The volume and length of these cave passages vary. Several of the park caves may be interconnected and some may be connected with caves outside the park (NPS 1996).

Caves Outside the Park

The Guadalupe district of Lincoln National Forest contains more than 120 known caves. Most of these are along Guadalupe Ridge just west of Carlsbad Caverns NP. Cottonwood Cave is one of the most prominent with a massive entrance, large formations, almost 3 miles (5 km) of passages, and gypsum deposits in the form of flowers and hanging chandeliers. Other caves include Virgin Cave, Black Cave, Hell Below Cave, Three Fingers Cave, and Madonna Cave.

Several well-known caves are within the Lechuguilla Cave protection area just north of the park. The BLM Dark Canyon special management area is contiguous with the northern boundary of the park. Big Manhole Cave is about 1.25 surface miles (2 km) from the entrance to Lechuguilla and contains deposits of paleontological materials. Big Manhole Cave may be connected with Lechuguilla Cave. Mudgetts Cave and Snake Trap Cave are two other significant caves on BLM land and are close to the park's northern boundary.

Permian Reef Features

The semiarid plateau that surrounds the park is composed of reef limestones deposited between 240 and 280 million years ago during the Permian Period. The Guadalupe Mountains offer a remarkable record of environments associated with this ancient reef complex.

The massive, unstratified limestone reef deposits of the Capitan Limestone form the escarpment seen to the southwest of the visitors center. Unlike modern reefs, which are composed mainly of coral, the primary framework of this Permian reef was made up of calcareous sponges, algae, and bryozoans (figure 7). Skeletal deposits of dead organisms were bound by encrusting organisms and natural calcite cement that filled pore spaces. Today, the preserved reef is approximately 750 feet (230 m) thick. The 1,000-foot cliff, El Capitan, in Guadalupe National Park is composed primarily of the massive Capitan Limestone and most of Carlsbad Caverns lies within this same formation. The ancient reef now preserved in the Capitan Limestone once resembled modern reefs that fringe the coastline of modern Belize in Central America today.

Outcrops in Bat Cave Canyon and Walnut Canyon expose the reef fabric and four significant elements of the reef facies: 1) an *in situ* framework of oriented organisms; 2) encrusting and binding organisms that added stability to the framework; 3) internal sediment of skeletal fragments, pellets, or other grains lodged in open pores in the framework; and 4) submarine cement crusts filling virtually all remnant porosity. (New Mexico Institute of Mining and Geology, access 2005).

The plateaus and canyons that today form the landscape northwest of the Guadalupe escarpment contain the back-reef environments of the Permian reef complex. Features that record the transition from reef to back-reef are exposed in Walnut Canyon. Immediately landward of the reef is the back-reef grainstone facies (figure 8). Strata show signs of open marine circulation, with normal or only slightly hypersaline conditions. Marine fossils are abundant, especially fusulinids and other foraminifers, gastropods, pelecypods, green algae (especially *Mizzia* and *Macroporella*), blue green algal boundstones, oncoids, and other skeletal grains. The carbonates change from massive reef limestone to bedded grainstones and packstones.

Aggregates of round carbonate-coated particles, called pisolites, distinctive features of Grayburg, Queen, Seven Rivers, Yates, and Tansill rocks are found landward of the grainstone facies (figure 8). The back-reef pisolite facies is an elongate feature, parallel to the reef trend exposed in Walnut Canyon and in outcrops along the old guano trail by the cave entrance. As in the Permian, pisolites form today in warm, high calcium carbonate water landward of the reef. They range from a few millimeters to 5 centimeters in diameter).

The Permian pisolitic deposits are associated with large (3-10 ft [1-3 m] high; 30-80 ft [10-25 m] diameter) polygonal features termed "teepee structures" (figure 9) (Dunham 1969; Kendall 1969). Teepee structures are polygonal expansion features marked by buckled and deformed sediments, crusts of precipitated (originally aragonite) cement, and pockets of pisolitic sediment beneath and between the polygonal bulges. They are usually stacked in a series of inverted 'V's. Good examples of teepee structures are found near the bottom of the bat flight amphitheater, and are also exposed in Walnut Canyon.

The pisolites may be the most controversial facies in the Permian of the Texas-New Mexico area (New Mexico Institute of Mining and Geology, access 2005). The origin of pisoliths and tepee structures have been the subject of numerous studies and considerable controversy. Pisolite formation is attributed to one of the following three hypotheses: 1) marine inorganic precipitation in a subtidal setting; 2) caliche formation in continental areas or coastal spray-zones where carbonate sediment is brought in by storms or other episodic processes; and 3) back-barrier, marine or groundwater seepage through permeable barriers into sub-sea level salinas. Adding to the quandary is the lack any modern analog that comes close to modeling the breadth and abundance of pisoliths preserved in the Permian reef complex (Scholle and Kinsman 1974; Esteban and Pray 1977, 1983; New Mexico Institute of Mining and Geology, access 2005).

The persistence of the pisolite facies in space and time, its elongate geometry parallel to the reef trend, and its consistent juxtaposition between open marine and restricted environments indicate that the pisolite facies formed a subaerial barrier between the inner and outer back-reef environments. This scenario would favor either the caliche or salina seep interpretations. Further support for the salina seepage model comes from a number of studies of modern coastal salinas, lakes, and sabkhas in southern and western Australia. Conceivably, an elongate, irregular ridge of low-relief islands, tidal flats, and dunes formed just seaward of the pisolites which allowed marine water seepage into the back barrier lagoon. Exposures in the park allow further testing of all three hypotheses.

Dolomitic mudstones and thin sandstone beds formed in shallow, quiet, and relatively still waters of back-reef lagoons landward of the pisolite facies (figure 8). Dry periods produced mudcracks formed by the buckling of sediments as they partially dried. Mudcracks typically form polygonal structures in a honeycomb pattern. Mudcracks are exposed on the flat ceiling in Carlsbad Cavern near the Bat Cave sign. Modern back-reef lagoons similar to those in the Permian exist today off the coast of Florida.

Back-reef deposits that formed farthest landward from the reef were subject to periodic drying, which concentrated minerals in the water creating extremely saline conditions. Consequently, most marine organisms could not survive in this harsh environment. Most of the fossils seen in back-reef outcrops are gastropods and some types of algae.

Today, semi-permeable clay layers in the Tansill Formation prevent rainwater and snowmelt from easily percolating downward to lower layers. The groundwater accumulates above the clay layers and then moves horizontally until it emerges in springs or seeps along canyon walls. Big Hill Seep, which can be viewed from a pull-out along the Walnut Canyon drive, is one example of this lateral groundwater flow.

The fore-reef environment formed on the ocean side of the reef. As the reef grew upward in the Permian, large house-sized blocks of the reef collapsed or were broken off by waves and fell into deeper water. This process created a poorly sorted debris pile at the base of the reef composed of lime mud, fossils, and reef fragments.

Carlsbad Caverns is developed primarily in the fractured reef and fore-reef Capitan Limestone, but the entrance and all of the upper level are in the back-reef dolomites of the Tansill and Yates Formations. The deep parts of the cave are cut in the lower part of the reef as well as steeply-dipping fore-reef talus of the Capitan Formation. Fore-reef bedding is visible near the Bottomless Pit.

Fossils

Many invertebrate, Permian marine fossils from the Capitan reef system are abundant in Carlsbad Caverns NP. Exposed along Walnut Canyon are, calcareous sponges (e.g., *Guadalupia*, *Amblysyphonella*, *Cystaulete*, and *Cystothalamia), Tubiphytes*, stromatolitic blue-green algae, phylloid (leaf-shaped) algae, and bryozoans that form the dominant framework organisms of the reef. Encrusting *Archaeolithoporella* (a possible alga), *Tubiphytes* (found as both framework and encrusting forms), *Solenopora* (a probable red alga), *Collenella* (an algal form) and other, less common, organisms are also seen in the reef facies. Ancillary fauna that lived on the reef and that can be found in the park include foraminifers, ostracods, echinoids, brachiopods, and pelecypods.

Fossil fauna in Walnut Canyon illustrate the change from reef to back-reef environments. These include cephalopods, foraminifers, pelecypods, gastropods, and dasycladacean green algae (particularly *Mizzia* and *Macroporella*). Most notably, sponges and encrusting bryozoans are missing.

Modern reefs are commonly formed by large communities of coral, but in the Permian reefs, coral was rare. Solitary horn coral were present but are relatively uncommon in outcrop. Brachiopods were abundant and exhibit a wide variety of shapes. Nautiloids, swimming predators related to the modern chambered nautilus, squid and octopus, are also present. Most nautiloids were extinct at the end of the Permian. Crinoids attached themselves to the seafloor and were common inhabitants in well-circulated Permian reef environments although most species died out at the end of the Permian period.

Two species of trilobites along with the largest fossil sponge yet known from the Permian of North America have been discovered at Carlsbad Caverns (Santucci et al. 2001). Trilobites were among the dominant life forms in the Paleozoic Era but were in decline in the Permian Period and were extinct by the end of the period.

Carlsbad Caverns, Lechuguilla Cave, Slaughter Canyon Cave, and Musk Ox Cave have yielded Pleistocene to Holocene vertebrate fossils. Thirty-six species have been identified from the park caves, and among these species are Pleistocene shrub oxen, pronghorn, an extinct cheetah-like cat, mountain goat, dire wolf, shrew, marmot, horse, and an extinct vulture.

In the Lower Cave and the Big Room within Carlsbad Caverns, fossilized bats, a Pleistocene jaguar, and recent mountain lion bones have been discovered in a location that indicates the animals must have entered the cave by a different route than the present-day entrance (Santucci et al. 2001). In 1947, remains of a juvenile Shasta ground sloth (*Nothrotheriops shastensis*) were discovered in Lower Devil's Den. Additional bones were found in 1959. Dated at 111,900 years B.P., these bones provided the oldest absolute date for any sloth material and the oldest absolute date for any vertebrate remains from the Guadalupe Mountains.

Ringtail cat (*Bassariscus astutus*) fossils are reported from Lechuguilla Cave along with fifteen complete or partial bat skulls. The bat fossils date to less than 10,000 years B.P. and include a hoary bat (*Lasiurus cinereus*) not commonly found in caves, a western big eared bat (*Plecotus townsendii*) that prefers shallow gypsum caves or entrances of caves or mines, a long-legged bat (*Myotis volans*) that prefers rock crevices or trees, and a small-footed myotis (*Myotis leibii*) that was the most abundant inhabitant of Lechuguilla Cave. *Myotis leibii* has not been found at Carlsbad Cavern which is only three miles southeast of Lechuguilla Cave.

Slaughter Canyon Cave (New Cave) is the only cave that has yielded the extinct Constantine's free-tailed bat (*Tadarida constantinei*). Mountain deer (*Navahoceros fricki*) and other vertebrate fossils also have been found in Slaughter Canyon Cave.

Vertebrate fossils discovered in Musk Ox Cave represent an assemblage of Late Pleistocene fauna that died after being trapped in a large sinkhole. A horse, a small artiodactyl, a bovid, a large dog, a bobcat-like feline, a shrub ox, and a small antelope have been identified among the remains. Further exploration of the cave in 1975 led to the discovery of two skulls and a skeleton that were identified as bush ox (*Euceratherium* cf. *sinclairi*) and dire wolf. A follow-up trip discovered remains of Harrington's Mountain Goat (*Oreamnos harringtoni*) in the cave.

Structural Features

Guadalupe Ridge is a large anticline that dips gently to the northeast. Walnut Canyon occupies a complementary syncline to the north. Bat Cave Draw, situated between the two main east-west passages of the cavern, is a smaller synclinal structure within the large Guadalupe Ridge. Associated with these structures are NW-SE and NE-SW stress-strain trends that influence the distribution and orientation of open versus closed fractures defining the hydrology of the cave system.

Brooke (1996) observed two primary joint orientations: a major orientation of joints between N70°E and N90°E and a second significant orientation between due north and N30°W. Brooke's results corresponded to those found by Tallman (1993) in a regional study of the area, also. Local joints have the same orientation as the major caves. Both joint and cave orientations follow regional structural trends. The dominant joint and cave orientation is parallel to the ridge axis. The second major orientation is perpendicular to the ridge axis (Van der Heijde et al. 1997).

Uplift and folding of the Guadalupe block in Cenozoic time resulted in the preferential joint orientation present today at the park. The continuity, frequency, and hydraulic effectiveness of the joints are controlled and dependent upon the competence of the rock layers and the magnitude of the stresses and strains to which these layers have been subjected. Joints within the massive Capitan Limestone are relatively continuous with some reaching 100 feet (33 m) or more. Fractures in the dolomite and limestone layers of the Tansill Formation, however, are less continuous due to the presence of local siltstone layers.

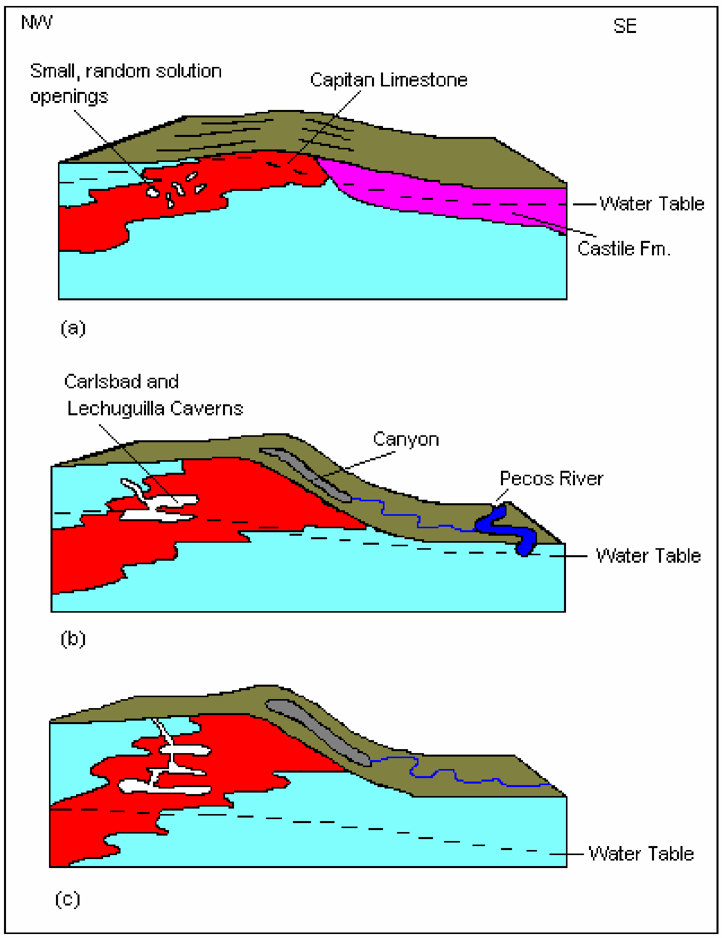


Figure 5. Schematic diagram illustrating the evolution of the cave system at Carlsbad Caverns National Park. A) Small, random solutional openings form in the zone of saturation. B) The water table lowers as the Guadalupe block is uplifted, producing sulfuric acid that dissolves limestone. Caves begin to form. C) Downcutting and cave formation continues as the water table is lowered with continued uplift. Modified from Kiver and Harris (1999).

Figure 6. Speleothems in The Big Room: The Hall of Giants (top) and the Chandelier (bottom). Photos used with the permission of Finley-Holiday Film Corp.

Figure 7. More speleothems in the Big Room, Temple of the Sun. Photo used with the permission of Finley-Holiday Film Corp.

Figure 8. A portion of the diorama of the Capitan reef produced by Terry L.Chase and displayed at the Permian Basin Petroleum Museum in Midland, Texas. This artist's conception emphasizes the framework sponges and the abundant encrusting fauna. Photograph by Peter Scholle, New Mexico Institute of Mining and Geology 1999.

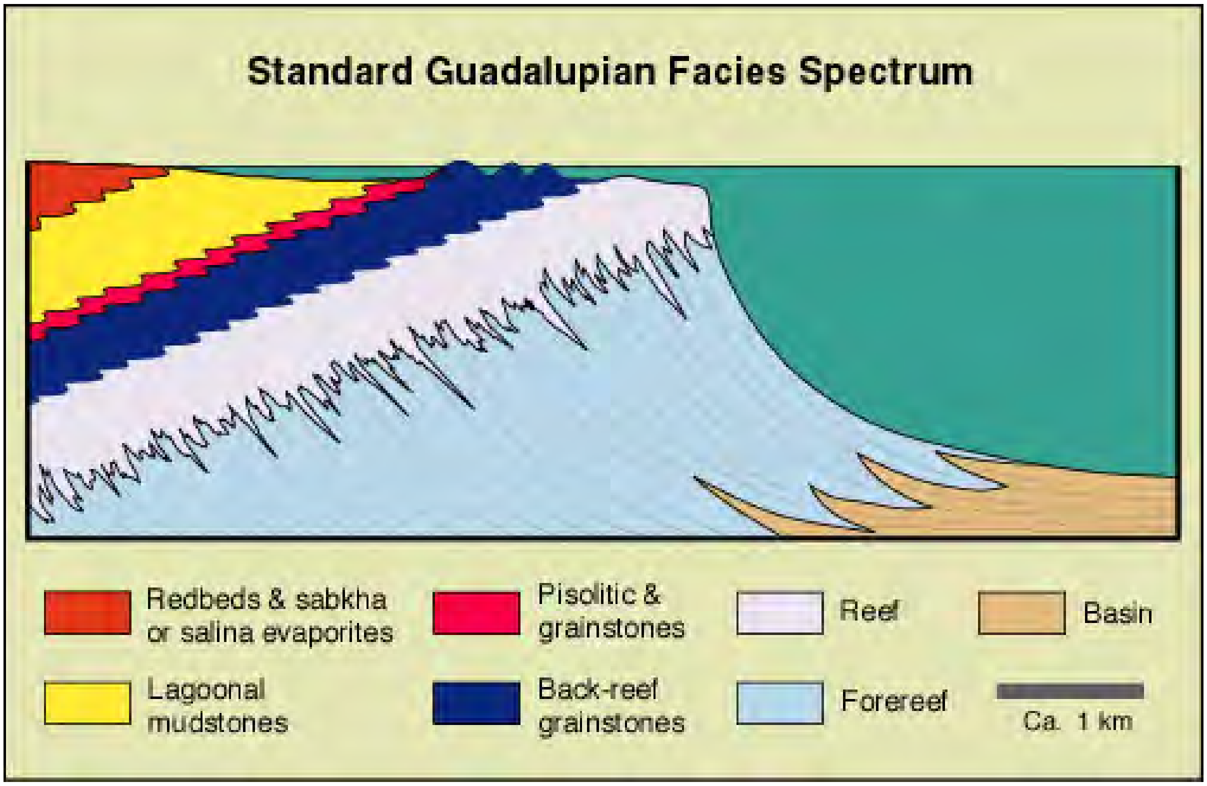


Figure 9. Shelf-to-basin spectrum of depositional environments for Capitan and Capitan-equivalent strata of the Guadalupe Mountains. Vertical axis is approximately 0.5 km; horizontal axis is roughly 35 km. Diagram from the New Mexico Institute of Mining and Geology, http://www.geoinfo.nmt.edu/staff/scholle/graphics/permdiagr/GuadPaleogeog.html (access 2005).

Figure 10. Tepee structure in Tansill Formation. Light yellow layers are dolomitized pisolitic and fenestral sediment; darker, gray layers are zones of sheet spar (aragonitic cement crusts). Outcrop at southwest end of parking lot at Carlsbad Caverns visitor's center. Photograph by Peter Scholle, New Mexico Institute of Mining and Geology 1999.

Map Unit Properties

This section provides a description for and identifies many characteristics of the map units that appear on the digital geologic map of Carlsbad Caverns National Park. The table is highly generalized and is provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in this table. More detailed unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the NPS Geologic Resources Division.

The sedimentary rocks exposed at Carlsbad Caverns National Park are primarily limestone and dolomite that formed in back-reef and reef settings. The following Map Unit Properties Table presents a view of the stratigraphic column and an itemized list of features for each rock unit. Some of the units in the table are correlative so that the geologic column does not represent consistent younger-to-older strata within the Permian Epochs. For example, the Tansill Formation, Capitan Limestone, and Bell Canyon Formation, although geographically distinct, are correlative as are the Yates, Capitan Limestone, and Bell Canyon Formations (figure 3).

Specific properties of the different formations are included in the table that may be significant with regard to management decisions. The properties in the table include the formation name, a lithologic description of the unit, its resistance to erosion, suitability for development, hazards, paleontologic resources, cultural and mineral resources, karst issues, and a miscellaneous category. The units in the table are the same that are on the accompanying digitized geologic map.

Map Unit Properties Table

Period	Map Unit (symbol)	Unit Description	Erosion Resistance	Paleontology Resources	Cultural Resources	Karst Issues	Hazards	Mineral Occurrence	Suitability for Development	Other
QUATERNARY	Alluvium (Qal)	Gypsiferous and calcareous sand & silt. Mapped only in Black River Valley & Dark Canyon.	Low	None	None documented	None	None	None	Groundwater issues?	None
	Gravel (Qg)	Poorly sorted uncemented limestone pebbles and cobbles from Capitan Limestone and Carlsbad Group; associated silt & clay; some cemented by caliche or travertine; covers much of Castile Fm, esp. north and west of Black River; 200+ ft (61+ m) thick south of Rattlesnake Canyon and west of Black River; 300+ ft (91+ m) thick in wells north of Carlsbad Caverns NP	Low	None	None documented	None	Potential contamination and disruption of groundwater to Rattlesnake Springs	Gravel	Future developments of upper Black River V. could impact flow to Rattlesnake Sp	None
TERTIARY	Dikes (Ti)	Three fine- grained, vesicular, alkali trachyte dikes cut the Castile Fm in secs. 11, 14, & 15, T26S., R24E (south of Capitan Ls escarpment; west of Hwy 62); strike about 60 degrees NE; dip about 80 degrees N; 1,000 to 4,000 ft (305 to 1,200 m) long;	Appear as weathered linear zones of brownish soil	None	None	None	None	None	Not exposed in park; limited exposures	None
PERMIAN	Rustler Formation (Pr)	Grayish- pink cryptocrystalline porous dolomite exposed in scattered outcrops south of Capitan Limestone escarpment	Scattered outcrops south of Carlsbad Caverns NP	Dolomite contains mollusks, brachs, normal- marine fossils. Anhydritic parts contain molluscan fauna only	Not in Carlsbad Caverns NP	N/A	None	Halite; gypsum, other sulfates	N/A	May contain the youngest Permian fauna in North America
	Castile Formation (Pcs)	White massive gypsum in the East Quad with some interlaminated white gypsum & dark- gray limestone in the lower part; may include residual gypsum & clastics of the Salado and Rustler Formations in the upper 150 ft; thinly laminated light- to dark- gray granular limestone near the southwest corner and alternating very thin laminae of dark- gray limestone & gypsum in southeast corner of the West Quad; massive white gypsum near mouth of Rattlesnake Canyon	Exposed south of Capitan Limestone escarpment	Non- fossiliferous		Aquitard to groundwater flow	None	Selenite gypsum	Not exposed in park	Springs and seeps
	Tansill Formation (Carlsbad Gp) (Pt)	Light olive gray to very pale orange fine- grained laminated occasionally pisolitic dolomite, mostly in beds 0.5 to 5 ft (0.2 to 1.5 m) thick, & rare thin beds of very pale orange very fine grained quartz sandstone or siltstone; at least 300 ft (90 m) thick near mouth of Slaughter Canyon, normally between 100 and 150 ft (30 to 46 m) thick	High; caps summit of Guadalupe Mtns and over Capitan reef	Gastropods, fusulinids, crinoids, algae near reef		Few karst features	Rockfall potential in canyons	High uranium content (54 ppm); Oil reservoir in Delaware Basin	Local building stone; overlies Capitan Ls caves; exposed in wilderness west of visitors center	World class exposures of backreef features
	Yates Formation (Carlsbad Gp) (Pya)	Very pale orange to yellowish- gray fine- grained laminated frequently pisolitic dolomite, mostly in beds 0.3 to 2 ft (0.1 to 0.6 m) thick, alternating with grayish- orange to pale yellowish orange calcareous quartz siltstone or very fine grained sandstone, mostly in beds 1 to 6 in (2.54 to 15 cm) thick; 270 ft (82 m) thick in North Slaughter Canyon to 375 ft (125 m) thick closer to Capitan Limestone	Slope- forming siltstone & sandstone beds alternating with dolomite ledges	Fusulinids, pelecypods, gastropods, scaphlopods near reef		Low permeable siltstone inhibits groundwater infiltration; some karst	None documented	Oil reservoir in Delaware Basin	Local building stone; exposed in wilderness west of visitors center	World class exposures of backreef features; springs and seeps
	Seven Rivers Formation (Carlsbad Groupp) (Ps)	<u>Carbonate facies (Psc):</u> yellowish- gray fine- grained laminated frequently pisolitic dolomite mostly in beds 1 to 3 feet (0.3 to 0.9 m) thick with rare thin beds of very pale orange quartz siltstone. <u>Evaporite facies (Pse):</u> white gypsum with associated light olive gray to pale- red aphanitic dolomite & pale reddish brown siltstone; formation thickness: 335- 600 ft (110- 200 m)	High; Resistant dolomite (overlies Queen Fm)	Fusulinids, pelecypods, gastropods, scaphlopods near reef; fossils rare in evaporite facies		Some karst	None documented	Barite in Lechuguilla Cave; Oil reservoir in Delaware Basin	Local building stone; exposed in wilderness west of visitor's center	Classic example of carbonate to evaporite facies change; springs and seeps

Period	Map Unit (symbol)	Unit Description	Erosion Resistance	Paleontology Resources	Cultural Resources	Karst Issues	Hazards	Mineral Occurrence	Suitability for Development	Other
PERMIAN	Capitan Limestone (Pc)	Massive (reef) Member (Pcm): very light gray to light olive gray, may contain irregularly branching dikes of grayish- orange calcareous quartz siltstone; thickness: 750 to 1000 ft (250- 335 m). Breccia (reef- talus) Member (Pcb): foreslope facies; very light gray to light olive gray fine- grained locally brecciated limestone with widely spaced indistinct bedding planes inclined 20 to 30 degrees to the southeast; thickness: 750 to 1000 ft (250- 335 m)	High; cliff former	Reef framework species: calcareous sponges (*Guadalupia, Amblysyphonell, Cystaulete, Cystothalamia*), *Tubiphytes*, algae (blue- green, phylloid, red *Solenopora*), bryozoans; Others: fusulinids, coral, crinoids, brachiopods, cephalopods, pelecypods, echinoderms, ammonoids, mollusks, trilobites; Pleistocene/Holocene vertebrate remains in caves: shrub oxen, pronghorn, mountain goat, dire wolf, shrew, marmot, horse, vulture, cheetah- like cat, ground sloth, free- tailed bat, deer,artiodactyls, bovid, dog	Cultural resources in caves; home to bats	Cavernous, massive, high fracture permeability; speleothems; massive limestone inhibits groundwater flow	Cave collapse; groundwater infiltration may occur along fractures; trails may be slick in caves	Sulfur deposits; uranium minerals (tyuyamuite or metatyuyamunite); gypsum	Development may disrupt bat habitat & impact cave features; exposed in wilderness west of visitors center	World class caves and cave features; unusual mode of origin; most extensive fossil reef on record
	Bell Canyon Formation (Pbc)	Dark- gray fine- grained fetid limestone in beds 1 to 12 in (2.54 to 30 cm) thick & brown- weathering very thin bedded quartz siltstone 3 to 5 feet (0.9 to 1.5 m) thick at top; limestone locally contains abundant silicified fossils; becomes sandstone- rich towards the basin	Not exposed in park; exposed SW of Carlsbad & in GUMO	Bryozoans fusulinids, corals, brachiopods, echinoderms, conodonts, radiolaria, sponges, ammonoids	Not exposed in park	Forereef deposits – no caves in map area	N/A	Oil reservoir in Delaware Basin	N/A	Named for Bell Canyon, a gorge that drains eastward from Rader Ridge to Hwy 62, SW of Carlsbad Caverns NP
	Queen Formation (Pq)	Very pale orange to yellowish- gray fine- grained laminated dolomite mostly in beds 0.3 to 4 ft (0.1 to 1.2 m) thick interbedded with very pale orange silty dolomite, calcareous quartz siltstone, & very fine- grained sandstone in beds 0.3 to 3 ft thick (0.1 to 0.9 m); sandstone is largely confined to the basal part and siltstone is predominant in the upper 100 ft (30 m) (Shattuck Member); ripple marks, cross- bedding, channel cuts in many beds; thickness at type locality is 421 ft (128 m)	Shattuck Member siltstone is relatively nonresistant	Crinoids, echinoids, bryozoans, pelecypods, gastropods, scapholopods, algae near reef; fossils rare in evaporite facies	None documented	None documented	Potential rock fall in canyons west of visitors center	Oil reservoir in Delaware Basin	Exposed on the surface of plateaus in wilderness and NFS land NW of visitors center; upper 1/3rd is unstable siltstone	Type section is in Dark Canyon, just below mouth of Payne Canyon (west of visitors center); Springs and seeps
	Goat Seep Dolomite (Pgs)	Thickly- bedded to massive, finely- crystalline to saccharoidal, cream to light- gray dolomite; shelf margin reef dolomite underling younger Capitan Ls; exposed in extreme SW corner of map area and perhaps Lechuguilla Cave; exposures along Western Escarpment of Guadalupe Mtns from Last Chance Canyon southward; up to 1,300 ft (400 m) thick	High; exposed west of Carlsbad Caverns NP	Sponges, brachiopods, pelecypods, bryozoans, coral, crinoids, echinoderms; (rare) gastropods & ammonoids	None documented	If exposed in Lechuguilla Cave, it is one of only a few caves developed in Pgs	None documented	None documented	Limited surface exposures	Underlies Capitan Limestone
	Grayburg Formation (Pg)	Yellowish- gray to very pale orange laminated fine- grained generally oolitic dolomite mostly in beds 3 to 18 in (7.6 to 46 cm) thick interbedded with yellowish- gray cross- laminated fine- grained oolitic limestone in beds 6 to 18 in (15 to 46 cm) thick, with very pale orange cross- laminated calcareous or dolomitic quartz siltstone or very fine- grained sandstone in beds 4 to 30 in (10 to 76 cm) thick; overlies San Andres Ls along a karstic unconformity; underlies Queen Fm.; basal white sandstone beds form a conspicuous ledge in Last Chance Canyon; about 435 ft (133 m) thick	High; dolomites and sandstones form cliffs	Fusulinid molds (*Parafusulina dunbari*), gastropods, crinoids, brachiopods, pelecypods, nautiloids, algae near reef; fossils rare in evaporite facies	None documented	None documented in Carlsbad Caverns NP	None documented	Oil reservoir in Delaware Basin	Bentonite layers; exposed west of visitors center in wilderness and NFS land	Type section in Sitting Bull and Gilson Canyons, NW of Carlsbad Caverns NP; Springs and seeps

Period	Map Unit (symbol)	Unit Description	Erosion Resistance	Paleontology Resources	Cultural Resources	Karst Issues	Hazards	Mineral Occurrence	Suitability for Development	Other
PERMIAN	Cherry Canyon Fm. – sandstone tongue (Pcc)	Grayish- orange to pale yellowish orange cross- bedded dolomitic or calcareous very fine- grained quartz sandstone containing abundant silicified fossils; large- scale cross- bedding and channel fillings exposed in Last Chance Canyon; underlies thin San Andres Fm in northwestern part of park; 260 ft (80 m) thick at mouth of Sitting Bull Canyon	Moderately resistant in map area; generally forms slopes	Lower part: fusulinids, echinoid spines, sponges, brachiopods	None documented	None in Carlsbad Caverns NP	None	Oil reservoir in Delaware Basin	Limited exposures in wilderness and on NFS land	None
PERMIAN	San Andres Limestone (Psa)	Very pale orange fine- grained generally cherty fetid dolomite and limestone in even to irregular beds a few inches to several ft thick; mapped in Last Chance and Sitting Bull Canyons Upper Member (Psau): non- cherty, dark, slabby limestone; 100 ft (30 m) thick in Last Chance Canyon, NW corner of map area Lower cherty Member (Psal): cherty limestone; 200 ft (60 m) thick in Last Chance Canyon, NW corner of map area	Resistant to erosion	Common fossils: gastropods, brachiopods, fusulinids, sponges, corals, bryozoans, chitons, scaphopods, pelecypods, nautiloids, ammonoids, trilobites, shark's tooth	None documented	Limited exposures in park – no karst issues	None documented;	Oil reservoir in Delaware Basin, Northwest Shelf, & Central Basin Platform; sulfur deposits in Eddy Co, NM	Exposed NW of visitors center in wilderness and on NFS land	Springs and seeps
PERMIAN	Yeso Formation (Py)	Dolomite, some limestone, red, yellow, & gray siltstone, yellowish fine- grained sandstone, & gray- to- white bedded and nodular gypsum; basal unit thin- bedded, nodular, cherty ls interbedded with gypsum; limited exposures in NW part of map	Low	Rare fossils in evaporite sections; poorly preserved brachiopods, bryozoans, crinoids, gastropods, fusulinids in non- evaporite sections		Thin limestone beds: no karst issues		Sulfur deposits in Eddy Co, NM.	Exposed NW of visitors center in wilderness and on NFS land	

Unit descriptions are from Hayes (1974), Hayes and Koogle (1958), and Hill (1996).

Geologic History

This section highlights the map units (i.e., rocks and unconsolidated deposits) that occur in Carlsbad Caverns National Park and puts them in a geologic context in terms of the environment in which they were deposited and the timing of geologic events that created the present landscape.

During the Permian Period (286-245 Ma) (figure 10), the Carlsbad Caverns region was near the equator. Western North America was submerged beneath a shallow tropical ocean while a broad alluvial plain spread across eastern North America. The Appalachian Mountains formed as plate tectonic activity closed the proto-Atlantic Ocean and lithospheric plates collided. As the supercontinent, Pangaea, formed in the late Permian and early Triassic, the proto-Gulf of Mexico also closed as South America collided with what would become the North American continent (figure 11). This collision was responsible for uplift of the Ancestral Rocky Mountains in Colorado.

Active plate convergence caused a rise in sea level, which, combined with regional subsidence, led to the encroachment of a shallow Permian sea into the southwestern region of the North American continent. An arid climate prevailed in the western part of Pangaea restricting marine evaporitic conditions over much of the continental shelf seaway (Peterson 1980).

An arm of this Permian sea flooded into New Mexico and west Texas occupying the Delaware Basin, which had a connection to the open ocean through the Hovey Channel, a narrow channel to the south (figure 2) (King 1948; Hill 1996; New Mexico Institute of Mining and Geology 2005). The Delaware Basin was a relatively deep cratonic basin with depths on the order of 2,000 feet (600 m). The Hovey Channel restricted water flow into the basin much like the Strait of Gibraltar restricts the connection of the Mediterranean Sea with the Atlantic Ocean. Consequently, circulation in the basin was poor and an anoxic environment at depth allowed for the thick accumulation of organic material that later, with burial and maturation, transformed into hydrocarbons.

In the warm, shallow, tropical sea, organic reefs thrived and ringed the Delaware Basin. Depositional environments landward of the reef included redbeds, sabkha evaporites, lagoonal mudstones, pisolitic grainstones, and back-reef grainstones while fore-reef and basin deposits were seaward of the reef (figure 8).

Redbeds, composed of clastic terrigenous detritus, were closest to shore and derived their fine-grained sediments from the north, northeast, and perhaps also the northwest. Sabkha environments formed on the seaward margin of the redbeds and consisted of nodular and mosaic gypsum (sometimes halite) interbedded with some dolomite and red siltstone. This association also is found on modern coastal sabkhas.

Seaward of the main evaporite deposits are fine-grained, thin-bedded dolomicrites deposited in a shallow subtidal or lacustrine setting or a hypersaline marine lagoon (Sarg 1981; Hill 1996; New Mexico Institute of Mining and Geology 2005). Fossils are rare in the tidal flat. Interbedded lagoonal sandstones may represent both fluvial and eolian processes, but probably most are subaqueous deposits. Back-reef lagoons probably were less than 100 feet (30 m) deep and may have been emergent at times, but likely they were never deeper than 3oo feet (100 m) (Hill 1996). Low porosity is characteristic of these strata since pore spaces were plugged with evaporite minerals, especially anhydrite ($CaSO_4$).

Thin (20 cm to 2 m; 8 in to 7 ft) beds of sandstone are interbedded with the dolomicrites. These clastic beds have few sedimentary structures and essentially no fossils or trace fossils. They may represent small progradational advances of sabkha-type sedimentation across the back-reef lagoonal area.

Seaward of the lagoonal mudstones lies the pisolitic grainstone facies. This facies is about 1 mi (1.6 km) wide and about 1 mi (1.6 km) thick (it persists throughout the Grayburg to Tansill section). Irregularly bedded deposits of laminated, fenestral carbonate and beds of skeletal debris are interbedded with abundant lenticular zones of pisolitic dolomite. The pisoids range in size from 0.04 inches to 2 inches (a few millimeters to greater than 5 cm), and although very porous on outcrop, this facies shows extensive filling by evaporite minerals in the subsurface. Associated with the pisolites are teepee structures.

The pisolite facies is always found as a transitional zone between fossiliferous marine grainstones, packstones, and wackestones on the seaward side and the largely barren, evaporitic dolomicrites on the landward side (figure 8) (Scholle and Kinsman 1974; Esteban and Pray 1977, 1983). The consistent geometry and restricted environments of the pisolite facies indicate that at least part of this facies formed a narrow strip of land that was subaerially exposed (except for tidal channels). As such, this facies represents a long-lived barrier to water movement between open shelf and lagoonal settings.

The back-reef grainstone facies lies seaward of the pisolite facies (figure 8). Strata show signs of open marine circulation, with normal or only slightly hypersaline conditions. Marine fossils are abundant, especially fusulinids and other foraminifers, gastropods, pelecypods, green algae (especially *Mizzia* and

Macroporella), blue green algal boundstones, oncoids, and other skeletal grains. The lithology is mostly grainstones and packstones.

The back-reef grainstone facies was a topographically elevated area. Small, coalescing sand waves and islands, perhaps with intervening tidal passes, formed on the seaward edge of this facies and acted as an overall deterrent to water movement farther landward. Unlike the other back-reef facies, the grainstone-island belt underwent only partial dolomite replacement and relatively minor evaporite pore-filling cementation. As a result of their porosity and their proximity to updip, overlying evaporites that plug the pores and prevent the upward movement of liquids, rocks of this facies are often prolific hydrocarbon reservoirs.

Seaward of the back-reef grainstone facies was the main carbonate-producing facies of the area, the reef (figure 8). The Capitan reef was the zone of maximum faunal diversity. Calcareous sponges and phylloid algae formed the major framework organisms of the reef (figure 7). They were encrusted by possible red or blue-green algae. The reef also contained a wide variety of ancillary organisms such as echinoderms (both crinoids and echinoids), bryozoans, brachiopods, mollusks, ostracods, scarce solitary corals, trilobites, and others.

Massive amounts of contemporaneous marine cementation played a major factor in the formation of the Guadalupian reefs. Large and small cavities alike were rapidly filled with carbonate cement precipitated directly from ambient seawater. This cementation reduced porosity to such a degree that the reef facies is not a significant hydrocarbon reservoir despite the fact that locally extensive fracturing has created zones of high permeability.

Unlike today's modern reefs (like the Great Barrier Reef off the Australian coast), the Permian reef probably did not extend into the surf zone. Careful reconstruction of the reef complex suggests that the Capitan Reef, the youngest Permian reef, probably lay a few meters to perhaps several tens of meters below sea level with a more gradual slope into the basin than the sharp reef break of today's reefs (figure 8) (Garber et al. 1989; Hill 1996; New Mexico Institute of Mining and Geology, access 2005).

The rapid rate of marine cementation of the reef facies, coupled with the very high rate of biological productivity, produced more material in the reef margin zone than could be accommodated, given limited rates of subsidence. This excess material was transported into back-reef and fore-reef environments. The Capitan reef of the Guadalupe Mountains prograded seaward between 3 to 6 miles (5 to 10 km) despite sitting at the margin of a nearly 1,800-foot (600 m) deep basin. Such progradation required a very large volume and a high rate of sediment production.

The intense contemporaneous cementation of the Capitan reef, coupled with rapid progradation of largely unconsolidated and compactable debris, led to extensive fracturing of the cemented reef slab during the depositional process. The fractures formed parallel to the shelf edge and filled with internal sediment, encrusting organisms, carbonate cement, and sand grains.

The fore-reef talus apron is one of the most volumetrically important carbonate facies in the Permian reef complex. Material from the reef, near-back-reef, and upper slope was transported by rock fall, grain flow, debris flow, and turbidity currents and deposited in a relatively uniform apron of steeply dipping rubble. This poorly sorted or unsorted reef detritus varies in size from small fragments and individual constituent grains to larger blocks of lithified reef framework. Bedding angles exceed 35 degrees on the upper slope and gradually flatten to only a few degrees near the basin floor.

Isolated sand-filled channels up to 30 feet (10 m) thick can be found in some areas of the upper and middle slope. Carbonate debris beds interfinger with sandstone beds. The carbonate beds thin into the basin while the sandstone beds, derived from the continent, thicken basinward.

Basinal carbonates are very fine-grained and are generally finely laminated and dark-colored, although organic carbon content rarely exceeds one percent. Basin strata are mostly devoid of fauna except for a few radiolarians. Carbonates are not major constituents of the basin facies but rather, terrigenous sandstones and siltstones provide greater than 90 percent of the basin fill. They have very high porosities in the subsurface and make excellent hydrocarbon reservoirs.

The basin clastics are very fine-grained, subarkosic sandstones and coarse siltstones that are compositionally very similar to the thin clastic units found on the shelf. The presence of abundant detrital sandstone and siltstone in a basin rimmed by a carbonate-producing system posed a significant problem in Permian basin stratigraphy. How were sands deposited in a basin yet leaving so little record in the surrounding shelf-margin facies? The answer was found in stratigraphic features that recorded episodic rise and fall of sea level. Sea level can change due a variety of causes such as regional subsidence, local tectonic effects, eustatic (global) sea level stands, and continent-wide vertical movements.

In the Permian Basin, reefs and/or grainstone shoals flourished during high sea level stands. The platform margins acted as carbonate "factories" and broad carbonate-evaporite lagoons occupied much of the shelf area (figure 12). Thin, but widespread, carbonate turbidite units were deposited in the basins. Clastic sediments were either trapped in vegetated dunes or interdune flats, on sabkhas, or in shoreline deposits well up on the shelf.

When sea level lowered, fluvial and eolian sands and silts spread across the shelf area, accumulating on the margins and eventually transported into the basins to form thick sandstone sequences (figure 12). Some of these sands and silts may also have moved through channels or tidal passes in the barrier reef during times of carbonate sedimentation. This would account for some lenticular sandstone beds, but the cyclic distribution of both shelf and basin carbonate-clastic packages indicates that some form of sedimentation with sea level change is required to explain the overall sediment distribution (Sarg 1985, 1986; New Mexico Institute of Mining and Geology, access 2005).

In very late Permian time, as the final suturing of Pangaea took place, the connection to the open ocean became restricted. Evaporation exceeded the inflow of normal marine water so that salinity increased. With increased salinity, life on the reef ceased. Eventually, thick deposits of gypsum that make up the Castile Formation filled the Delaware Basin and covered the reef core.

Water depths continued to decrease and conditions became even more hypersaline as anhydrite, halite (NaCl), sylvite (KCl), and other evaporitic minerals of the Salado Formation were deposited. Commercial deposits of potash minerals have been exploited in these thick, last-stage fillings of the Delaware Basin.

For most of the Mesozoic Era (figure 10), the Permian Basin region was part of a stable, largely non-depositional province. During the late Cretaceous to mid-Tertiary Laramide Orogeny, the Guadalupe Mountains were locally uplifted accompanied by faulting and southeastward tilting. Karst development may have begun at higher elevations. Sediment eroded from the higher regions may have filled any remaining karst features of Permian age at lower elevations. Tectonic activity may have mobilized hydrogen sulfide gas and sulfide-rich brines in mid-Tertiary time, producing sulfuric acid by mixing with oxygenated water infiltrating from the surface. Carlsbad Cavern began to form within the phreatic (saturated) zone although the extent of its development at this time is not yet known.

During the late Cenozoic (1-3 Ma), the region was uplifted and the Guadalupe Mountains tilted to the east-northeast. The caves were further enlarged, and extensive gypsum was deposited as a result of carbonate dissolution by sulfuric acid. Joints (fractures without significant displacement) reopened parallel to the reef front and a lesser set of joints formed perpendicular to this first set.

Uplift and erosion continued to dissect the region during the Pleistocene Epoch, and the major Guadalupe caves gradually emerged into the vadose (unsaturated) zone. Erosion removed the younger rocks and part of the Castile Formation and exhumed the buried reef front that forms the Guadalupe Escarpment today. Meteoric, carbon dioxide-rich water from the surface deposited travertine speleothems, particularly during times of humid climate in the Pleistocene. Age dates from the Big Room indicate that Carlsbad Cavern was drained at that level more than 500,000 to 600,000 years ago.

Eventually, erosion exposed the upper cave level and formed the entrance of Carlsbad Cavern. With drying of the cave and a decrease in infiltrating water in the semiarid climate, the rate of speleothem growth decreased. Today, Quaternary-age gravel and alluvial deposits continue to be deposited in the canyons along Guadalupe Ridge

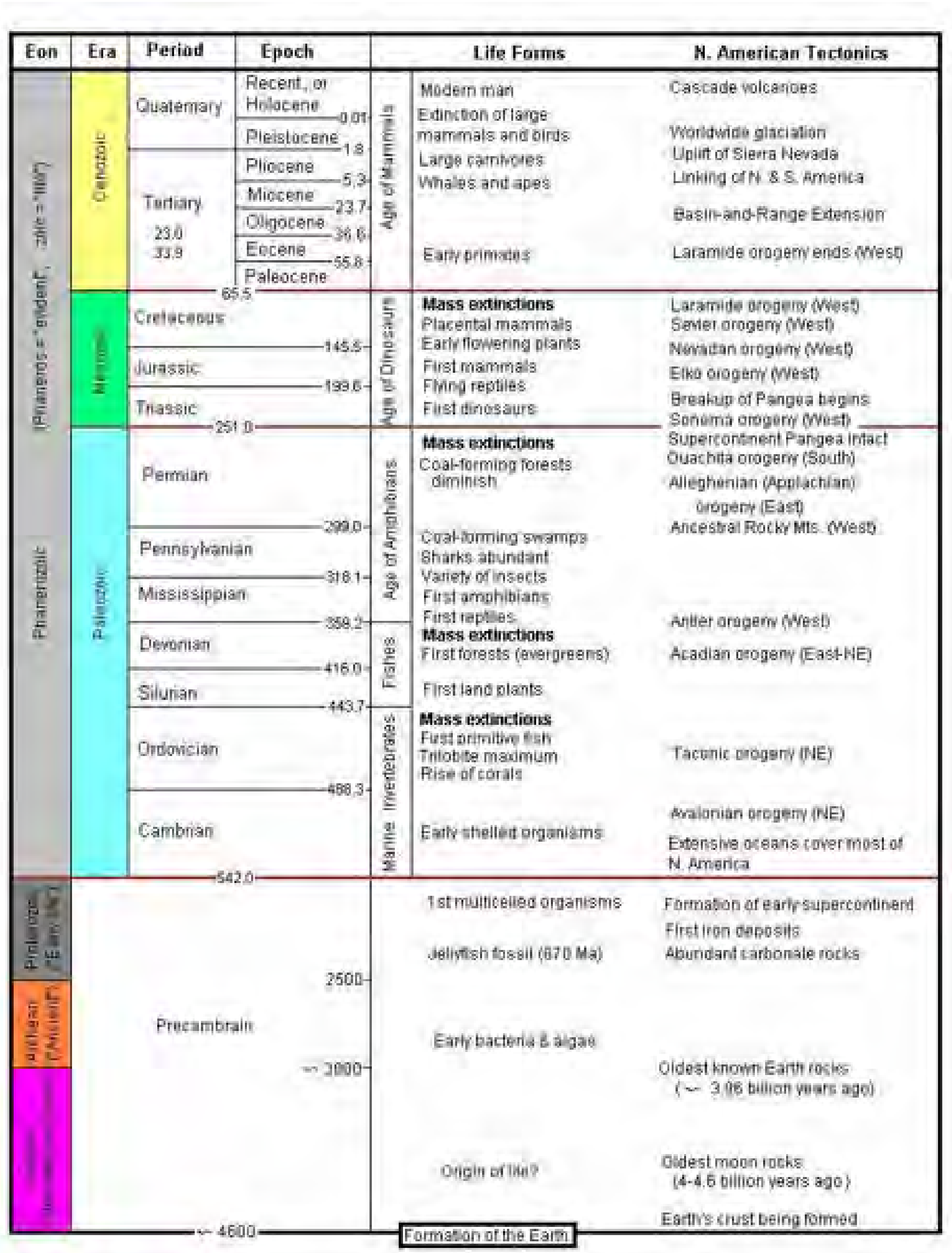


Figure 11. Geologic time scale showing the various life forms and major tectonic events in North America. Ages are based on the 2004 geologic time scale from the International Commission on Stratigraphy.

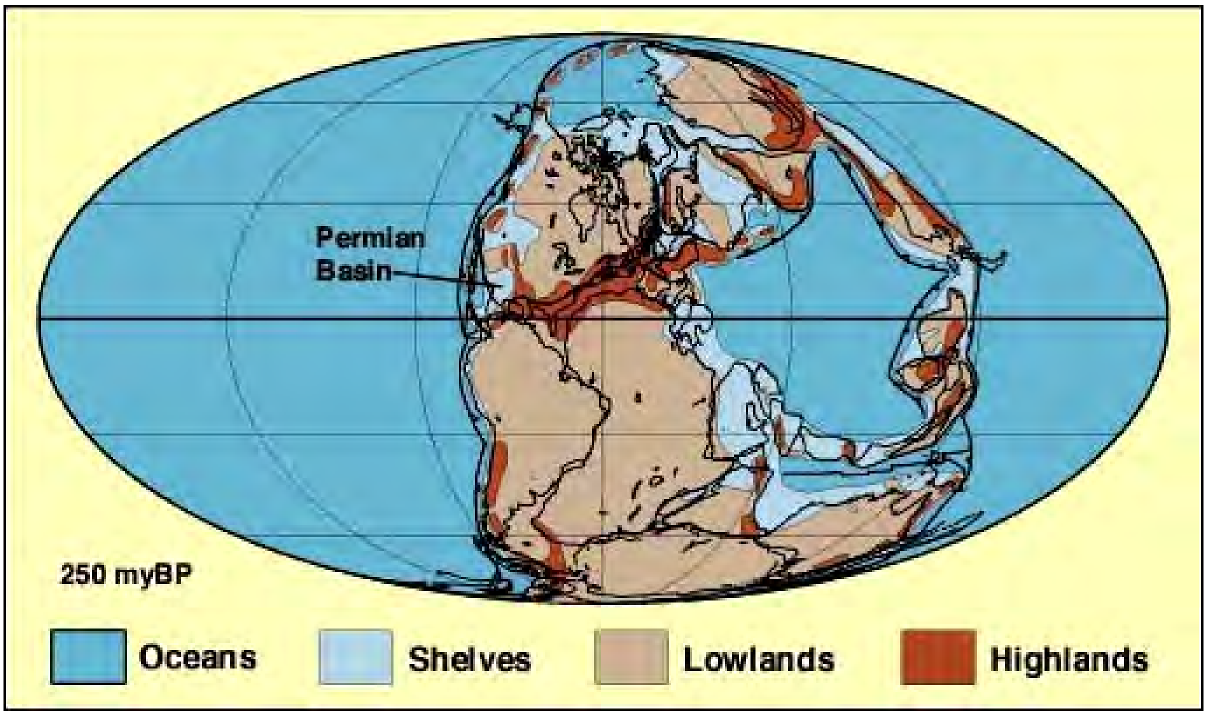


Figure 12. Continental reconstruction during Late Permian (Kazanian) time. In this model, the Permian Basin lies just south of the equator and close to the western margin of the supercontinent Pangaea. Approximate present-day continental outlines shown for reference. From the New Mexico Institute of Mining and Geology, http://www.geoinfo.nmt.edu/staff/scholle/graphics/permdiagr/GuadPaleogeog.html (access 2005) and Scotese and others (1979).

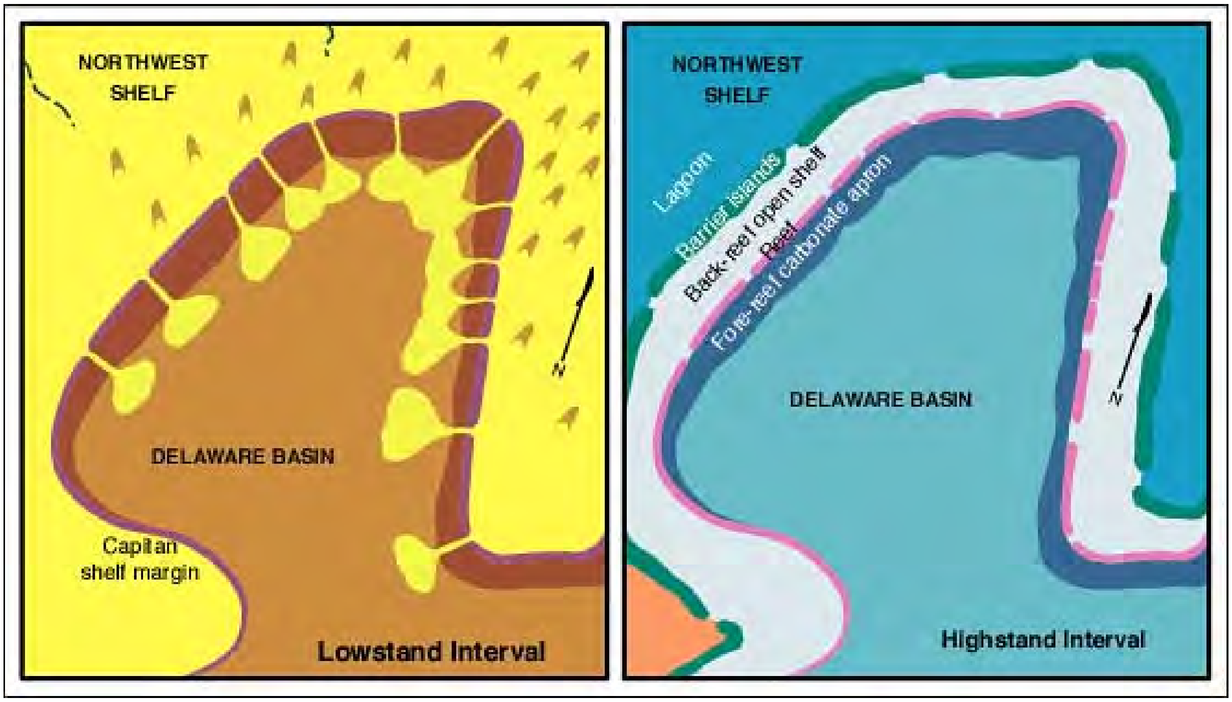


Figure 13. Hypothetical views of the Delaware Basin and surrounding platform areas during sea-level low- and highstands. Lowstand intervals were periods of terrigenous sand transport across shelves, mainly by eolian processes, and sand deposition occurred mainly in the basin. Highstand intervals saw development of shelf-margin reefs with associated back-reef carbonate-evaporite-redbed deposits and thick carbonate fore reef talus deposits. Basins of this time had only thin calcareous shale deposition. From the New Mexico Institute of Mining and Geology, http://www.geoinfo.nmt.edu/staff/scholle/graphics/permdiagr/GuadPaleogeog.html (access 2005).

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit http://wrgis.wr.usgs.gov/docs/parks/misc/glossarya.html.

allochthonous. Formed far from its present place.
alluvial fan. A fan-shaped deposit of sediment that accumulates where a high gradient stream flows out of a mountain front into an area of lesser gradient.
back-reef. The landward side of a reef; the area and deposits between the reef and the mainland.
basin (structural). A doubly-plunging syncline in which rocks dip inward from all sides.
basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.
block (fault). A crustal unit bounded by faults, either completely or in part.
boundstone. A sedimentary carbonate rock whose original components (e.g., skeletal matter, algae, foraminifera, etc.) were bound together during deposition.
breccia. A coarse-grained, generally unsorted, sedimentary rock made up of cemented angular clasts.
calcareous. A rock or sediment containing calcium carbonate.
carbonaceous. A rock or sediment with considerable carbon, esp. organics, hydrocarbons, or coal.
chemical weathering. The dissolution or chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances.
clastic. Rock or sediment made of fragments or pre-existing rocks.
craton. The relatively old and geologically stable interior of a continent.
cross-bedding. Uniform to highly-varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions.
dip. The angle between a structural surface and a horizontal reference plane measured normal to their line of intersection.
dolomicrite. A sedimentary rock consisting of clay sized dolomite crystals
dune. A low mound or ridge of sediment, usually sand, deposited by wind.
eolian. Formed, eroded, or deposited by or related to the action of the wind.
evaporite. Chemically precipitated mineral(s) formed by the evaporation of solute-rich.
facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, mineralogy, fossils, etc. of a sedimentary rock.
fault. A subplanar break in rock along which relative movement occurs between the two sides.
fore-reef. The seaward side of a reef.
grainstone. A mud-free (<1%), grain-supported, carbonate sedimentary rock.
karst topography. Topography formed by the dissolution of calcareous rocks.
monocline. A one-limbed flexure in strata, which are usually flat-lying except in the flexure itself.
mud cracks. Cracks formed in clay, silt, or mud by shrinkage during subaerial dehydration.
oncolite. A small concentrically laminated calcareous sedimentary structure formed by the accretion of successive layered masses of gelatinous sheaths of blue green algae, generally less than 10 cm in diameter.
orogeny. A mountain-building event, particularly a well-recognized event in the geological past (e.g. the Laramide orogeny).
packstone. Sedimentary carbonate rock whose granular material is arranged in a self-supporting frame work, yet also contains some matrix of calcareous mud
Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic Periods (also see Laurasia and Gondwana).
pisolite. A round or ellipsoidal accretionary body commonly formed of calcium carbonate.
permeability. A measure of the ease or rate that fluids move through rocks or sediments.
porosity. The proportion of void space (cracks, interstices) in a volume of a rock or sediment.
prodelta. portion of a delta below the level of wave erosion.
progradation. The seaward building of land area due to sedimentary deposition.
red beds. Sedimentary strata that are predominantly red due to the presence of ferric oxide (hematite) coating individual grains.
sabkha. A coastal environment in an arid climate where evaporation rates are high.
salina. A place where crystalline salt deposits are formed or found, such as a salt flat or pan.
subarkose. A sandstone that does not contain enough feldspar to be classed as an arkose
tectonic. Relating to large-scale movement and deformation of Earth's crust.
terrigenous. Derived from the land or continent.
trace fossils. Sedimentary structures, such as tracks, burrows, etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.
travertine. A limestone deposit or crust formed from precipitation of calcium carbonate from saturated waters, especially near hot springs and in caves.
uplift. A structurally high area in the crust, produced by movement that raises the rocks.
wackestones. Sedimentary carbonate rock whose granular material is arranged in a self-supporting frame work, yet also contains some matrix of calcareous mud.

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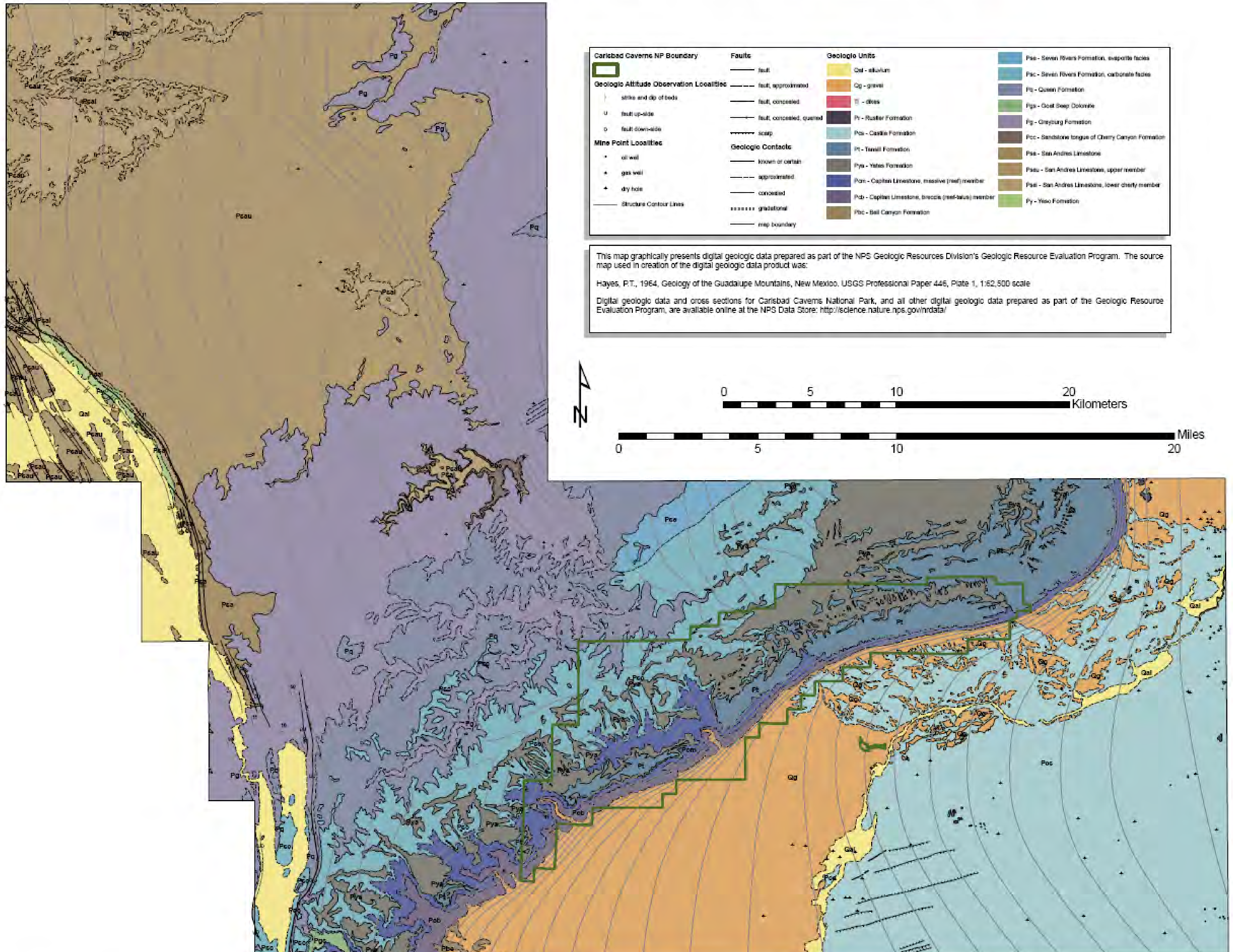
Appendix A: Geologic Map Graphic

The following page provides a preview or "snapshot" of the geologic map for Voyageurs National Park. For a poster size PDF of this map or for digital geologic map data, please see the included CD or visit the GRE publications webpage: http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm.

Geologic Map of Carlsbad Caverns NP



This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resource Evaluation Program. The source map used in creation of the digital geologic data product was:

Hayes, P.T., 1964, Geology of the Guadalupe Mountains, New Mexico. USGS Professional Paper 446, Plate 1, 1:62,500 scale

Digital geologic data and cross sections for Carlsbad Caverns National Park, and all other digital geologic data prepared as part of the Geologic Resource Evaluation Program, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/

Appendix B: Scoping Summary

The following excerpts are from the GRE scoping summary for Carlsbad Caverns National Park. The scoping meeting occurred on March 6-8, 2001; therefore, the contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

A Geologic Resources Inventory (GRI) workshop was held for both Carlsbad Caverns (CAVE) and Guadalupe Mountains (GUMO) National Parks March 6-8, 2001. The purpose was to view and discuss the park's geologic resources, to address the status of geologic mapping for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), Natural Resources Information Division (NRID), Carlsbad Caverns, Guadalupe Mountains, as well as academics from the Colorado School of Mines, the New Mexico Bureau of Mines and Mineral Resources and the Texas Bureau of Economic Geology were present for the workshop.

This involved single-day field trips to view the geology of both GUMO (led by Gorden Bell, Mike Gardner, and Charlie Kerans) and CAVE (led by Paul Burger), as well as another full-day scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the GRD, and the on-going GRI. Round table discussions involving geologic issues for both GUMO and CAVE included the status of geologic mapping efforts, interpretation, paleontologic resources, sources of available data, and action items generated from this meeting.

Overview of Geologic Resources Inventory (GRI)

The NPS GRI has the following goals:

1. to assemble a bibliography of associated geological resources for NPS units with significant natural resources; "GRBIB",
2. to compile and evaluate a list of existing geologic maps for each unit,
3. to develop digital geologic map products, and
4. to complete a geological report that synthesizes much of the existing geologic knowledge about each park.

It is stressed that the emphasis of the inventory is not to routinely initiate new geologic mapping projects, but to aggregate existing "baseline" information and identify where serious geologic data needs and issues exist in the National Park System. In cases where map coverage is nearly complete (ex. 4 of 5 quadrangles for Park "X") or maps simply do not exist, then funding may be available for geologic mapping.

After introductions by the participants, Tim Connors presented overviews of the Geologic Resources Division, the NPS I&M Program, the status of the natural resource inventories, and the GRI in particular. He also presented a demonstration of some of the main features of the digital geologic database.

Geologic Mapping

The USGS has published Professional Papers (PP) on both the Texas and New Mexico portions of the Guadalupe Mountains. PP-215 (by Phil King, circa 1948) covers the Texas portion of the Guadalupes (GUMO) and contains a geologic map at 1:48,000 scale that ends at the Texas state line. PP-446 (by Phil Hayes 1964) covers the New Mexico portion of the Guadalupe Mountains (CAVE) and contains a geologic map at 1:62,500 scale. CAVE staff have supplied GRI staff with a preliminary digitized version of this map that needs some additional attribution. Both were excellent, very comprehensive publications for their day and still are quite useful even though interpretations have been refined since their publication.

The USGS has also published a few other maps that cover the CAVE area. MF-1560-a ("Mineral Resource Potential and Geologic Map of the Guadalupe Escarpment Wilderness Study Area, Eddy County, New Mexico") is mapped at 1:24,000 scale. GQ-112 and GQ-98 are also published as separate maps that predate PP-446 and are both at 1:62,500 scale. Of note, however, is that MF-1560-a only covers the southwestern-most portion of CAVE.

All of these maps were considered worthy of digitizing as they represent some of the best sources of existing "baseline" data. GRI staff will incorporate the digitization of these maps into their future workplan.

Also, the Colorado School of Mines (under the direction of Mike Gardner), has been concentrating their efforts on large-scale mapping of the Permian Reef at GUMO, specifically the Brushy Canyon unit. They have digital versions of this mapping in ArcView format and are willing to share it with the NPS.

Desired Enhancements to the Existing Maps

CAVE 1:24,000 scale mapping: Paul Burger would like to see the six main "quadrangles of interest" for CAVE (Queen, Serpentine Bends, Carlsbad Caverns, Gunsight Canyon, Grapevine Draw, and Rattlesnake Spring) mapped at 1:24,000 scale. At this time, it is not known if Hayes compilation map at 1:62,500 scale was compiled from original 1:24,000 scale maps. If they were, then the data is essentially already there. GRD will attempt to discern if this is true for the Hayes map.

Peter Scholle mentioned that the New Mexico GS will be producing a geologic map of the Carlsbad West quadrangle at 1:24,000 scale, but this is not one of the parks quadrangles of interest, as it lies directly west of the actual town of Carlsbad, which is northeast of CAVE proper. He also thought that the Hayes maps need refinement in the CAVE area.

Paul would also like to see more detailed mapping of the Yates-Tansill contact because it is the location from which water emanates to become the parks water supply.

Suggested improvements to the existing maps

- Refinements to King's maps would involve splitting out the Carlsbad Group into three formations (Yates, Tansill, Seven Rivers formations) to seamlessly edge-match that of Hayes map (and hence eliminate the New Mexico/Texas "boundary fault"). Gorden Bell thought that aerial photography and satellite photos could be used to do this with minimal field checking.
- Integrate Mike Gardner's large scale mapping of the Western escarpment with the King map for better detail for the Brushy Canyon unit members which also include some minor faults that are not shown on King's maps
- Work out the subdivision of the Bone Spring versus the Cutoff formations where the units are shown but the interpretations have changed over time
- Work out the Victorio Peak-San Andres problem which relates to Goat Seep (which is really now known as the Grayburg and Queen);
- Resurveying of roadcuts is desired in and around both parks
- Hazard and rockfall assessments should be conducted, although most susceptible areas don't seem to affect facilities
- Essentially re-map approximately one quadrangle worth of mapping on Carlsbad Group in GUMO (not quad specific); New Mexico Bureau estimates ~$100,000 to do that work

Use of LIDAR technology for higher resolution

Charlie Kerans and Mike Gardner would see the use of LIDAR technology as a great asset to refining any mapping and future research, and would like to have this data available for the Guadalupe Mountains and Delaware Basin in the very near future.

They "rough" estimated the data acquisition at between $60,000 for a "poor-man's DEM" to $100,000 for full LIDAR coverage.

Various ideas were proposed on how to go about accomplishing this task and need to be followed up on by the cooperators. Joe Gregson told the group of the Department of the Interior (DOI) high priority program to obtain funds through regions to obtain such LIDAR information. He mentioned that leveraging with adjacent land managing agencies (Forest Service, BLM, etc) often is the most successful way to acquire funding for obtaining this technology

Mike Gardner made the suggestion that the Colorado School of Mines, NPS, and Texas and New Mexico Geologic Bureaus cost share to acquire the LIDAR data for the region.

The NPS could not guarantee such funding allocations for FY-2001, but Joe said he would talk to Ingrid Langraf (USGS) about any available funding and would report back to the group at a later time on what he finds out.

Here is what Joe was able to find out as of March 14, 2001:
"At the GUMO/CAVE geologic resources inventory scoping workshop, the group expressed interest in obtaining LIDAR data for the parks and adjacent area to support geologic mapping, research, and resource management. Here is what I found out about getting high resolution LIDAR elevation data for the parks and Delaware Mtns. via the NPS/USGS agreement.

"The USGS does not do a direct 50/50 cost share on LIDAR as with other base cartography but does have contractors available that can fly the area and supply the data. Right now, the ball park cost is about $10K per quadrangle. Contiguous GUMO and CAVE coverage would require about 15-16 quads plus 6-8? quads (guessing) for the Colo. School of Mines (CSM) study area. That puts the project costs in the $200K-$250K range. The best avenue for funding the project (at least for the NPS part) appears to be the Dept. of Interior High Priority Program which annually funds data projects for DOI bureaus. Through the NPS Intermountain Region, CAVE and GUMO park staff can request high resolution elevation data with requirements for LIDAR. If the parks can get other DOI bureaus (BLM, BOR, BIA, USGS, etc.) to also request the data, it has a very good chance of being funded. Unfortunately, the DOI Program call is past for this year, and it runs a year in advance (i.e., a request next year would get put into work in FY 2003 at the earliest).

"I know this does not address the immediate needs of CSM that were discussed at the workshop, but it is the best that I could come up with at the moment. If anyone has other ideas for data sources or funding and wishes to pursue this further, let me know."

Digital Geologic Map Coverage

As stated earlier, it was agreed upon by the consensus of the group that the King and Hayes maps were worthy of digitization with the caveat of the "Desired Enhancements" listed above. Once the maps exist in a digital format they are easier to refine both in the field and electronically.

GRI staff in Denver will attempt to accomplish this digitization in their workplan in FY-2002. Of note, is the existence of digital linework for the Hayes 1964 map in PP-446, but there is no accompanying metadata. GRI staff would also like to get it attributed as per their NPS digital geologic map model. Dave Roemer (CAVE-GIS) will need to be consulted for more specifics on metadata for this coverage.

Charlie Kerans thought that another additional piece of information that should be tied to any digital geologic database would be measured stratigraphic sections that could be georeferenced and brought up in a GIS. This should be easy to add in to the NPS Digital Geologic Database Model.

Other desired GIS data

General needs: Paul Burger would like to see a GIS coverage for linear features for CAVE (Kim Cunningham and Dave Yagnow) for the Dark Canyon Environmental Impact Statement (EIS). Additionally, he is interested in a delineated watershed for Rattlesnake Springs, which is the sole water supply for city of Carlsbad. Ground Penetrating Radar (GPR) or an electromagnetic survey could be used to delineate this.

Soils: Pete Biggam (GRD Soil Scientist) supplied the following information in reference to soils for both parks:

"We currently have in place an Interagency Agreement with the TX - NRCS to map all NPS units in Texas, based upon an estimated completion by 2005 (as funding allows)

“We are estimating that we might initiate soils mapping at GUMO in 2003, and would be utilizing the NRCS soil survey crew that is currently located in El Paso, TX. This, of course, is dependent on funding being provided by NPS I&M for this effort. We would also be looking at initiating soils mapping at CAVE and WHSA in a similar timeframe.

“We operate similar to the GRI, we would schedule a soil scoping session, look at soils research that was already performed at GUMO, map it to National Cooperative Soil Survey Standards with local input from GUMO in regards to their soil resource management concerns.

“Products would be a digital soils map, digital soil attributes, metadata, soil report, as well as potentially some soil information/education products which could be incorporated into GUMO's interpretive program. There would be data that would be utilized within the NPD GIS Theme manager as well, similar to what is being done with GRI.

“We would also have a ‘last acre mapped session’, where we would have a soils field tour of the park."

Geologic Hazards

GUMO has a published hazards map from R.R. Railsback (University of Texas at Dallas) that was done in 1976. It has been digitized by Parsons Engineering. It is titled *Geologic Hazards in the Pine Springs Canyon area, Guadalupe Mountains National Park*. Vicky Magnis (NPS-IMR GIS) apparently has this data in digital format from Parsons Engineering and it is currently being tracked down by Tim Connors. It is unknown what format the data is in (AutoCAD, ArcView etc.). Vicki will be working with GUMO staff on the GIS portion of their General Management Plan (GMP).

Paleontology

Greg McDonald (GRD Paleontologist) would like to see an encompassing, systematic Paleontological inventory for both GUMO and CAVE describing the known resources in both parks with suggestions on how to best manage these resources.

Other Sources of Data

- Charley Kerans did a presentation on “Hierarchical Stratigraphic Analysis of a Carbonate Platform, Permian of the Guadalupe Mountains”. He mentioned that much of this data will be out in CD-ROM in the near future. It will likely be available from the Texas Bureau of Economic Geology website (http://www.beg.utexas.edu). GRI staff are interested in obtaining a copy of this once it is available to the public.
- The Colorado School of Mines has a website for research on the slope and basin consortium at http://www.mines.edu/Academic/geology/sbc/.

Interpretation

Numerous topics regarding interpretation of geologic resources were discussed. Among these included:

- ·The Permian Reef complex should be better utilized in both parks as the major interpretive focus, and the tie of the Guadalupe Escarpment between both parks should be made to illustrate the importance of the Capitan Reef as a world-class feature that is unique to this area alone. This should also serve to illustrate the GUMO-CAVE story to the regional picture for Permian time.
- Make better use of park trails to showcase and interpret the park geology for visitors
- A Reef diorama in each visitor center showing modern analogs and the process of reef building
- Mike Gardner has offered to assemble a Bone Springs-Shumard trail guide trail for GUMO (for free)
- Make better use of the story of P.B. King’s "interpretations" of the reef as a major contribution to the science of geology in general.

Geologic Report

An encompassing report on each parks geology is a major focus of the GRI. To date both the King and Hayes Professional Papers fulfill a major role in describing the regional geology, but are highly technical and not written for the average NPS Resource Manager.

To this end, it was generally agreed that simpler, toned down reports will need to be written for both CAVE and GUMO. The next task is to find enthusiastic report writers to tackle this chore. Both states geologic bureaus (Texas and New Mexico) have offered their assistance in reviewing such reports in final format, supplying maps and graphics on the local geology in their existing publications, and offering their general assistance to the NPS. Peter Scholle says his agency is already doing a publication on the geology of New Mexico's State Parks.

Paul Burger was enthusiastic about writing such a report for CAVE, and thought this would be a good use of his time as the parks geologist.

Jan Wobbenhorst suggested GUMO geologist Gorden Bell as the logical choice to write such a report for GUMO, as he is the local NPS expert on the geology.

Scoping Session Attendees:

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Carlsbad Caverns National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2007/003
NPS D-139, June 2007

National Park Service

Director • Mary A. Bomar

Natural Resource Stewardship and Science

Associate Director • Michael A. Soukup

Natural Resource Program Center

The Natural Resource Program Center (NRPC) is the core of the NPS Natural Resource Stewardship and Science Directorate. The Center Director is located in Fort Collins, with staff located principally in Lakewood and Fort Collins, Colorado and in Washington, D.C. The NRPC has five divisions: Air Resources Division, Biological Resource Management Division, Environmental Quality Division, Geologic Resources Division, and Water Resources Division. NRPC also includes three offices: The Office of Education and Outreach, the Office of Inventory, Monitoring and Evaluation, and the Office of Natural Resource Information Systems. In addition, Natural Resource Web Management and Partnership Coordination are cross- cutting disciplines under the Center Director. The multidisciplinary staff of NRPC is dedicated to resolving park resource management challenges originating in and outside units of the national park system.

Geologic Resources Division

Chief • David B. Shaver
Planning Evaluation and Permits Branch Chief • Carol McCoy

Credits

Author • Dr. John Graham
Editing • Sid Covington, Ron Kerbo, and Melanie Ransmeier
Digital Map Production • Anne Poole and T. T. Hayes
Map Layout Design • Andrea Croskrey

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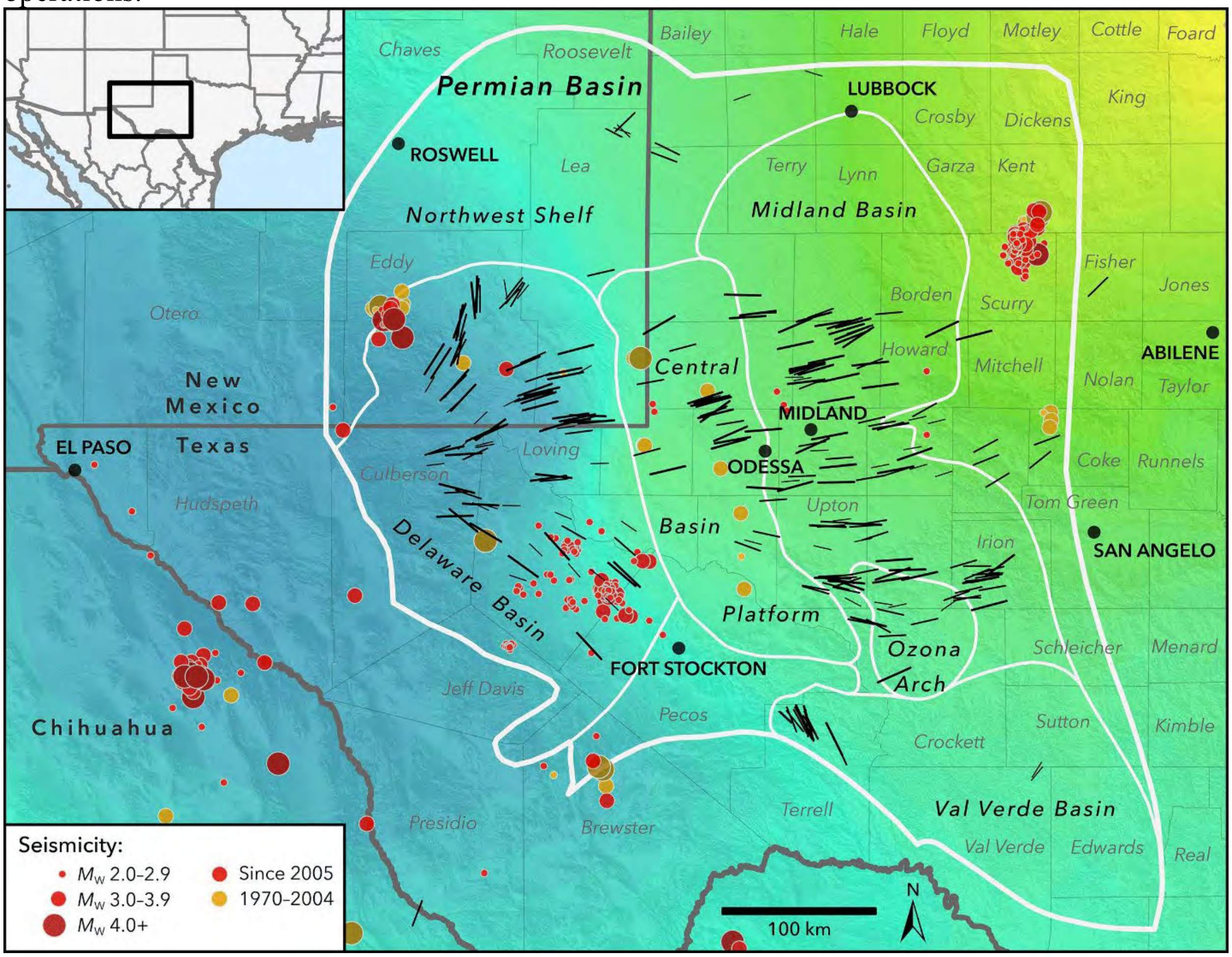
EXHIBIT 2

Seismic stress map developed by Stanford researchers profiles induced earthquake risk for West Texas, New Mexico

A map created by Stanford geophysicists can help predict which parts of West Texas and New Mexico may be at risk of fracking-induced earthquakes. The map could guide oil discovery efforts in the region.

Stanford geophysicists have developed a detailed map of the stresses that act in the Earth throughout the Permian Basin in West Texas and southeastern New Mexico, highlighting areas of the oil-rich region that could be at greater risk for future earthquakes induced by production operations.



This new map of Earth's stress field in the Permian Basin of West Texas and southeastern New Mexico could help energy companies avoid causing earthquakes associated with oil extraction. (Image credit: Jens-Erik Lund Snee)

The new study, published this month in the journal ***The Leading Edge***, provides a color-coded map of the 75,000-square mile region that identifies those potential oil and gas development sites that would be most likely to trigger an earthquake associated with fluid injection.

Previous Stanford research has shown that wastewater injected as a step in hydraulic fracturing (fracking) underlies an increase in seismic activity in parts of the central and eastern U.S., particularly in Oklahoma, starting in 2005. While none of these small-to-moderate earthquakes has yet caused significant property damage or injury, they represent an increased probability of larger earthquakes.

Now, Texas is poised to take center stage as the Permian Basin is becoming the country's most important oil- and gas-producing region. In the 1920s, energy companies began extracting the basin's bountiful petroleum deposits during a boom that lasted decades. More recently, the advance of hydraulic fracturing techniques has spurred a new development frenzy. Hundreds of thousands of wells could be drilled in the region in the next few decades.

"We want to get out ahead of the problem in Texas," said study co-author **Mark Zoback**, the Benjamin M. Page Professor of Geophysics in Stanford's **School of Earth, Energy & Environmental Sciences** (Stanford Earth), who led a number of the Stanford studies in Oklahoma. "We want to stop fluid injection from triggering even small earthquakes in Texas so that the probability of larger earthquakes is significantly reduced."

High-stress environment

To gauge the risk of future quakes, researchers must first understand the direction of the stresses in a region and their approximate magnitude. When the stress field aligns with a pre-existing fault in a certain manner, the fault can slip, potentially producing an earthquake. In regions such as the central and eastern U.S., far from tectonic plate boundaries such as the San Andreas Fault, this slippage occurs as a natural process, but very rarely. But increasing fluid pressure at depth reduces the friction along the fault, sometimes triggering an earthquake.

"Fluid injection can cause a quake on a fault that might not produce a natural earthquake for thousands of years from now," said study lead author Jens-Erik Lund Snee, a PhD student in the **Department of Geophysics** at Stanford Earth.

In a previous study, Zoback and postdoctoral scholar Cornelius Langenbruch found that in Oklahoma, fluid injection caused about 6,000 years of natural earthquakes to occur in about five years.

Creating a next-generation stress map

Building on **previous efforts** to create maps of stress and seismic potential in the Permian Basin, the Stanford researchers added hundreds of new data points from West Texas and southeastern New Mexico, much of the data being provided by the oil and gas industry. Their findings paint a complicated picture of the Permian Basin, which features some relatively consistent horizontal stress areas along with others that show dramatic directional rotations. "We were surprised to see such high variability," said Lund Snee. "It raises a lot of questions about how you can have rotations like that in the middle of a continental plate, far from a plate boundary."

"This is the one of the most interesting stress fields I've ever seen," Zoback said. "While the stress field in this region is surprisingly complex, the data is excellent and having documented what it is, we can now take action on this information and try to prevent the Permian Basin from becoming Oklahoma 2.0."

A tool for safer, more efficient drilling

The Stanford researchers said the new stress map provides oil companies with detailed quantitative data to inform decisions on more effective drilling operations in the Permian Basin.

"This is the most complete picture of stress orientation and relative magnitude that they've ever had," Zoback said. "They can use these data every day in deciding the best direction to drill and how to carry out optimal hydraulic fracturing operations."

Future studies will focus on improving knowledge of fault lines in the region and gaining a better understanding of fluid pressure, specifically how the amount of water injection (both now and in the past) has impacted the geological mechanisms at work in the area.

"There is the potential for a lot of earthquakes in this area," said Lund Snee. "We want to understand what's causing them and provide companies with the tools to avoid triggering them."

Zoback is also a senior fellow at the ***Stanford Precourt Institute for Energy****, co-director of the* ***Stanford Center for Induced and Triggered Seismicity*** *and director of the* ***Stanford Natural Gas Initiative****.*

The study was supported by the Stanford Center for Induced and Triggered Seismicity, an industrial affiliates program that studies scientific and operational issues associated with triggered and induced earthquakes.

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EXHIBIT 3

Human-made earthquake risk reduced if fracking is 895m from faults

Date: February 27, 2018

Source: Durham University

Summary: The risk of human-made earthquakes due to fracking is greatly reduced if high-pressure fluid injection used to crack underground rocks is 895m away from faults in the Earth's crust, according to new research.

FULL STORY

The risk of human-made earthquakes due to fracking is greatly reduced if high-pressure fluid injection used to crack underground rocks is 895m away from faults in the Earth's crust, according to new research.

The recommendation, from the ReFINE (Researching Fracking) consortium, is based on published microseismic data from 109 fracking operations carried out predominantly in the USA.

Jointly led by Durham and Newcastle Universities, UK, the research looked at reducing the risk of reactivating geological faults by fluid injection in boreholes.

Researchers used microseismic data to estimate how far fracking-induced fractures in rock extended horizontally from borehole injection points.

The results indicated there was a one per cent chance that fractures from fracking activity could extend horizontally beyond 895m in shale rocks.

There was also a 32 per cent chance of fractures extending horizontally beyond 433m, which had been previously suggested as a horizontal separation distance between fluid injection points and faults in an earlier study.

The research is published in the journal *Geomechanics and Geophysics* for Geo-Energy and Geo-Resources.

Fracking -- or hydraulic fracturing -- is a process in which rocks are deliberately fractured to release oil or gas by injecting highly pressurised fluid into a borehole. This fluid is usually a mixture of water, chemicals and sand.

In 2011 tremors in Blackpool, UK, were caused when injected fluid used in the fracking process reached a previously unknown geological fault at the Preese Hall fracking site.

Fracking is now recommencing onshore in the UK after it was halted because of fracking-induced earthquakes.

Research lead author Miles Wilson, a PhD student in Durham University's Department of Earth Sciences, said: "Induced earthquakes can sometimes occur if fracking fluids reach geological faults. Induced earthquakes can be a problem and, if they are large enough, could damage buildings and put the public's safety at risk.

"Furthermore, because some faults allow fluids to flow along them, there are also concerns that if injected fluids reach a geological fault there is an increased risk they could travel upwards and potentially contaminate shallow groundwater resources such as drinking water.

"Our research shows that this risk is greatly reduced if injection points in fracking boreholes are situated at least 895m away from geological faults."

The latest findings go further than a 2017 ReFINE study which recommended a maximum distance of 433m between horizontal boreholes and geological faults. That research was based upon numerical modelling in which a number of factors, including fluid injection volume and rate, and fracture orientation and depth, were kept constant.

Researchers behind the latest study said that changing these parameters might lead to different horizontal extents of fractures from fluid injection points.

The researchers added that this did not mean the modelling results of the previous study were wrong. Instead they said the previous study was approaching the same problem using a different method and the new study provided further context.

In the latest research the researchers used data from previous fracking operations to measure the distance between the furthest detected microseismic event -- a small earthquake caused by hydraulic fracturing of the rock or fault reactivation -- and the injection point in the fracking borehole.

From the 109 fracking operations analysed, the researchers found that the horizontal extent reached by hydraulic fractures ranged from 59m to 720m.

There were 12 examples of fracking operations where hydraulic fractures extended beyond the 433m proposed in the 2017 study.

According to the new study, the chance of a hydraulic fracture extending beyond 433m in shale was 32 per cent and beyond 895m was one per cent.

The research also found that fracking operations in shale rock generally had their furthest detected microseismic events at greater distances than those in coal and sandstone rocks.

Microseismic data was used in previous Durham University research from 2012. This suggested a minimum vertical distance of 600m between the depth of fracking and aquifers used for drinking water, which now forms the basis of hydraulic fracturing regulation in the UK's Infrastructure Act 2015.

Professor Richard Davies, Newcastle University, who leads the ReFINE project, said: "We strongly recommend that for the time being, fracking is not carried out where faults are within 895m of the fracked borehole to avoid the risk of fracking causing earthquakes and that this guideline is adopted world-wide."

ReFINE is led jointly by Durham and Newcastle Universities and has been funded by the Natural Environment Research Council (UK), Total, Shell, Chevron, GDF Suez, Centrica and Ineos.

Working closely with a global network of leading scientists and institutions, ReFINE focuses on researching the potential environmental risks of hydraulic fracturing for shale gas and oil exploitation.

Story Source:

Materials provided by **Durham University**. *Note: Content may be edited for style and length.*

Journal Reference:

1. M. P. Wilson, F. Worrall, R. J. Davies, S. Almond. **Fracking: How far from faults?** *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, 2018; DOI: 10.1007/s40948-018-0081-y

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EXHIBIT 4

United States Department of the Interior

OFFICE OF THE SECRETARY
Washington, DC 20240

INFORMATIONAL MEMORANDUM

DATE: October 16, 2024

FROM: Jacob Malcom, Director, Office of Policy Analysis
Kawa Ng, DOI Chief Economist

SUBJECT: DOI comparison of available estimates of social cost of greenhouse gases (SC-GHG)

SUMMARY

PPA recommends that Bureaus adopt the EPA's 2023 estimates of the Social Cost of Greenhouse Gases (SC-GHG) as the best available science (as of September 30, 2024).

COMPARISON OF SC-GHG ESTIMATES

As described in the PPA memo "Applying the social cost of greenhouse gases (SC-GHG) at DOI" (October 7, 2024), the Interagency Working Group on Social Cost of Greenhouse Gases (IWG, 2021) and the U.S. Environmental Protection Agency (EPA, 2023a) reported SC-GHG estimates for a range of years and for several discount rates. To facilitate a comparison between these two reports, Table 1 shows the cost estimates of an additional metric ton (t) emitted in 2020 and a ton emitted in 2050 for three GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In summary:

- The EPA 2023 estimates for CO_2 and N_2O are higher than the IWG 2021 estimates.
- The EPA 2023 estimate for CH_4 is lower than the IWG 2021 estimates.[1]

This memo compares the estimates under the 2.5% discounting scenario, the only discounting scenario common to both reports: IWG 2021 used 2.5%, 3%, and 5%; while EPA (2023a) used 2.5%, 2%, and 1.5%. The emission years 2020 and 2050 are the earliest and latest years included in both reports. All cost estimates are in 2020 dollars.

[1] Although not directly comparable, the EPA 2023 estimate for 2050 emissions of CH_4 under 2.0% discounting is higher than the IWG 2021 estimate at 2.5% discounting.

Table 1.Comparing Estimates in IWG (2021) and EPA (2023): SC-GHG/t (2020-$)

Year of emission		2020			2050		
Source of estimates		IWG (2021)	EPA (2023)	EPA (2023)	IWG (2021)	EPA (2023)	EPA (2023)
Discount rate		2.5%	2.5%	2.0%	2.5%	2.5%	2.0%
Carbon dioxide	CO_2	$76	$117	$193	$116	$205	$308
Methane	CH_4	$2,000	$1,257	$1,648	$3,800	$3,547	$4,231
Nitrous oxide	N_2O	$27,000	$35,232	$54,139	$45,000	$65,635	$92,996

As part of this review, PPA compared several SC-GHG estimates:

- The Interagency Working Group on Social Cost of Greenhouse Gases (IWG) (2021),
- Resources For the Future (RFF) (2022),
- U.S. Environmental Protection Agency (USEPA) (2023), and
- Barrage & Nordhaus (DICE-2023).

PPA considered several criteria when comparing these different SC-GHG estimates. The primary considerations are whether the estimates met the 2017 short-term recommendations from the National Academies of Sciences, Engineering, and Medicine (NASEM)[2] and how the estimates align with current Federal guidance (e.g. OMB circulars, NEPA, Executive Orders). The NASEM's short-term recommendations encompass more specific criteria, such as utilizing the most current, peer-reviewed science and literature to support the estimates. Federal guidance (specifically OMB Circular A-4) provides criteria for discounting. Summaries of the different SC-GHG estimates and how they assessed against these criteria appear below.

BACKGROUND ON SC-GHG GUIDANCE

Prior to EPA's November 2023 update, IWG's February 2021 interim values constituted the official, Government-wide estimates of the SC-GHG. The IWG noted that these interim values had not been updated to account for recommendations by NASEM. The IWG reported plans to publish updated, final estimates by January 2022, though as of the time of writing, the IWG has not published final values. However, the IWG's 2023 memo stating that agencies should use their professional judgment to determine which estimates of the SC-GHG to use for analysis was published roughly three weeks after EPA's November 2023 updated SC-GHG report.

The IWG declared their 2021 estimates to be interim values because (among other reasons) the estimates had not addressed NASEM's recommendations regarding the 2016 IWG estimates of SC-GHG. The IWG's stated goal in 2021 was to update the 2021 values by addressing the NASEM recommendations. EPA's November 2023 SC-GHG estimates address most of NASEM's recommendations. Although none of the current estimates (including EPA's) meet the

[2] National Academies of Sciences, Engineering, and Medicine (U.S.), ed. *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Washington, DC: The National Academies Press, 2017.

NASEM's long-term recommendations,[3] PPA finds that as of the time of writing EPA's 2023 estimates are the only SC-GHG estimates produced by a Federal agency to address NASEM's short-term recommendations, and as such best reflect the available evidence, as called for in IWG's December 2023 guidance memo.

In addition to best meeting IWG's December 2023 guidance memo, the discount rates and methodology used in EPA's 2023 SC-GHG estimates align with the updated OMB Circulars A-4 and A-94 (OMB 2023a, OMB 2023b). Thus, PPA finds that it would be appropriate for DOI to adopt EPA's 2023 SC-GHG estimates for analyses that include estimates of GHG emissions, while acknowledging that flexibility is needed for projects already underway.

BRIEF OVERVIEW OF THE CURRENTLY AVAILABLE SC-GHG ESTIMATES

PPA reviewed four estimates of the SC-GHG from four different Integrated Assessment Models (IAMs): IWG's 2021 estimates, RFF's 2022 estimates, USEPA's 2023 updated estimates, and those estimates by Barrage and Nordhaus using DICE-2023. Several of the IAMs used to generate these estimates use components from other IAMs that have produced their own SC-GHG estimates. In particular, Climate Impact Lab's DSCIM and work by Howard and Sterner figure in developing and testing damages meta-analysis. PPA did not evaluate these estimates on their own because they are, in part, captured within the work by USEPA, RFF, and DICE-2023.

2021 Estimates by the Interagency Working Group on Social Cost of Greenhouse Gas

The estimates published in 2021 by the IWG were explicitly characterized as interim values. These were a restatement of the estimates the IWG previously published in 2016, adjusted for inflation. The IWG stated an intention to publish final estimates in 2022 to address the 2017 NASEM recommendations. The efforts to address the 2017 NASEM recommendations informed the work of Climate Impact Lab, Resources for the Future, and USEPA, with many of the researchers at those organizations having been part of the IWG effort.

The 2021 IWG estimates included three sets of SC-GHG estimates based on an average set of damages and at constant discount rates of 5%, 3%, and 2.5%. A fourth set was included at the 95th percentile of damages under 3% discounting. The estimates for the SC-CO_2 per metric ton emitted in 2020 dollars are $14.48, $51, $76, and $151.61 respectively.

[3] EPA (2023a) notes that "modeling in this report omits most of the consequences of changes in precipitation, damages from extreme weather events, the potential for nongradual damages from passing critical thresholds (e.g., tipping elements) in natural or socioeconomic systems, and non-climate mediated effects of GHG emissions other than CO_2 fertilization (e.g., ocean acidification due to CO_2 emissions, tropospheric ozone formation due to CH_4 emissions). Importantly, this update does not yet reflect interaction effects and feedback effects within, and across, natural and human systems. For example, it does not explicitly reflect potential interactions among damage categories, such as those stemming from the interdependencies of energy, water, and land use." EPA (2023a) further notes that given "the numerous categories of damages that are currently unrepresented, the resulting SC-GHG estimates presented in this report likely underestimate the marginal damages from GHG pollution."

2022 Estimates by Resources for the Future

The 2022 estimates, a collaborative effort spearheaded by RFF and UC Berkeley, "incorporate updated scientific understanding throughout all components of SC-CO2 estimation in the new open-source Greenhouse Gas Impact Value Estimator (GIVE) model, in a manner fully responsive to the near-term NASEM recommendations." (Rennert et al., 2022). GIVE is made up of four distinct modules designed to capture the most recent peer-reviewed scientific research in socioeconomic projections, climate-impact modeling, damage functions, and discounting methodology. GIVE models risk using a Monte Carlo approach to establish a probability distribution of potential discounted stream of damages. Uncertainties are assigned to the components within each module and then compounded through each module at each step of the calculation. The resulting probability distribution of social cost estimates helps to describe the uncertainty of the risk associated with an incremental volume of GHG emissions.

2023 Estimates by United States Environmental Protection Agency

Like RFF's 2022 estimates of the SC-GHG, the estimates published by EPA in November 2023 fully address NASEM's 2017 short-term recommendations. Similar to the GIVE model, EPA's estimates are based on a model constructed of four distinct modules as recommended by NASEM: one each for socioeconomic projections, climate impact modeling, damage functions, and discounting. However, EPA's estimates synthesize components and modules from several different IAMs within the four modules. For the socioeconomic module, EPA uses the projections by RFF in their Social Cost of Carbon Initiative (EPA 2023a). For the climate impact module, EPA uses the Finite Amplitude Impulse Response (FAIR) model. EPA's damages module uses three separate damage functions, which produce three distinct streams of damages: 1) the Data-driven Spatial Climate Impact Model (DSCIM) by Climate Impact Lab, 2) the damage function module from RFF's Greenhouse Gas Impact Value Estimator (GIVE) model, and 3) a meta-analysis-based damage function from work by Peter Howard and Thomas Sterner. The streams of damages are fed into a discounting module that is based on the discounting module used in the GIVE model.

2023 Estimates by Barrage and Nordhaus

A version of the Dynamic Integrated Model of Climate and the Economy (DICE) was one of the original IAMs used to estimate the social cost of carbon, and later the SC-GHG (by IWG), and was one of the three available IAMs when IWG published their 2021 interim estimates. DICE-2023 is the most recent version of DICE and is described in a working paper by Lint Barrage and William Nordhaus (Barrage & Nordhaus 2023). In contrast to the IAMs used to estimate the other evaluated SC-GHG estimates, which Barrage and Nordhaus describe as "policy evaluation models", DICE-2023 is a policy *optimization* model. It contains a welfare function that the model seeks to maximize.

The companion paper to the DICE-2023 compares several different estimates of the social cost of carbon (SCC) under different modeling assumptions, primarily the discount rate and global mean temperature-change target.

Nordhaus and Barrage defend the use of a higher, risk-adjusted, discount rate. The Cost-Benefit Optimal scenario starts with a roughly 4.5% discount rate. However, another DICE-2023 scenario using a roughly 2% discount rate (similar to OMB's current recommended social discount rate) results in a SCC in 2020 of $170/tCO2 (2019 $) (Barrage and Nordhaus, 2023). This is similar to the SCC estimates from RFF and USEPA.

DICE-2023 updates the previous DICE version's damage function using an alternative damage function derived from Howard and Sterner. The updated model also includes a version of the FAIR model (used by RFF and USEPA) to represent carbon cycle dynamics within DICE-2023.

Comparison of the SC-GHG Estimates

Interestingly, while the various updated approaches (RFF, DICE-2023, and USEPA) rely on different model designs and underlying research, they arrive at similar values (after adjusting for discount rates). Table 2 below compares the different estimates of the social cost of a metric ton of CO_2 emitted in 2020 across the different sets of estimates.

Table 2: Social Cost of Metric Ton of CO_2 Emitted in 2020 (2020 $)

Report/Organization (Near-Term Discount Rate):	IWG 2021 Interim (2.5%)[1]	IWG 2021 (3% @ 95th Percentile)[2]	RFF (2%)	DICE 2023 Cost-Benefit Optimal (4.5%)[3]	DICE 2023 Cost-Benefit Optimal (2%)[3]	USEPA (2.5%)	USEPA (2.0%)
SC-CO_2/mt	76	152	185	54	172	117	193

Notes: 1: The lowest discount rate used in the 2021 Interim Report by IWG was the constant discount rate of 2.5%.
2: In addition to IWG's published SC-GHG estimates that assumed mean statistical damages, they published a single set of SC-GHG values for the 95th percentile of damages at a 3% constant discount rate.
3: DICE-2023: this model version uses the preferred parameters of the study's authors. Values in the original study were presented in 2019 dollars at $53 and $170 at the near-term discount rates of 4.5% and 2% respectively. PPA has inflated those to 2020 dollars for comparison with the other SC-CO2 estimates. PPA used an inflation rate of 1.32% derived from BEA's GDP chain type deflator (Line 1 of Table 1.1.9). https://apps.bea.gov/iTable/?reqid=19&step=3&isuri=1&1921=survey&1903=13

EVALUATION CRITERIA AND COMPARISONS

NASEM published their 2017 recommendations in a 281-page report. The recommendations can be summarized as saying that Integrated Assessment Models (IAMs), which estimate the SC-GHG, should update their approach such that "each step in SC-CO_2 estimation is developed as a module – socioeconomic, climate, damages, and discounting – that reflects the state of scientific knowledge in the current, peer-reviewed literature." (NASEM 2017) This modular framework, NASEM suggests, makes review and updating of the underlying components of an IAM easier as new research and science become available.

Federal guidance relevant to applying the SC-GHG can be found in OMB circulars, NEPA guidance, and Executive Orders. DOI guidance on applying the SC-GHG has been provided through Secretary Order 3399 and via the Office of the Solicitor. OMB Circular A-4, covering rulemaking, and recent CEQ guidance, covering analyses subject to NEPA, together provide the best summary of criteria and scope related to selecting and applying the SC-GHG in DOI analyses. The guidance within OMB Circular A-4 is most relevant to selecting discounting methodology when applying the SC-GHG within analyses.

This section discusses each of these criteria: 1) modularity of the underlying IAM's components, 2) current, peer-reviewed science and literature, and 3) discounting alignment. These criteria form the basis for comparison across the four sets of SC-GHG estimates as DOI considers adopting the USEPA estimates.

Modularity of Underlying IAM's Components

Apart from IWG's 2021 estimates, all evaluated sets of SC-GHG address the NASEM recommendation for modularity of the socioeconomic, climate, damages, and discounting components. Many modules are shared in some capacity between the RFF, USEPA, and DICE-2023 model platforms. The IWG's 2021 estimates are simply a restatement of their 2016 results, adjusted for inflation, and thus do not address any of the NASEM recommendations.

Current Peer-Reviewed Science and Literature

The USEPA and RFF use nearly identical sources for the underlying science and literature. However, USEPA does use some sources that are not as recent as those used by RFF. USEPA has suggested that these sources were preferred because the sources chosen by RFF had not been fully peer-reviewed to EPA's standards and thus did not meet the criteria EPA had set out in designing their modeling framework. DICE-2023 has undergone peer-review and uses some of the same underlying sources as USEPA's and RFF's models. The IWG's 2021 estimates are simply a restatement of their 2016 results, adjusted for inflation, and thus do not address any of the NASEM recommendations.

Discounting Alignment

The 2023 update to OMB Circular A-4 provides the most current Federal guidance on discounting of social costs and benefits. The prior guidance had a consumptive discount rate of 3% and recommended a 7% rate when there was incidence on investment. The new guidance recommends a single 2% discount rate and the use of a shadow price of capital methodology to capture incidence on capital. OMB further recommends that, where feasible, for periods of analysis over many years, agencies use OMB's long-term discount rates provided in the appendix, or consider whether alternative discounting methodologies (e.g. Ramsey or generational discounting) are appropriate. It is important to note that use of OMB's recommended long-term rates will not align with the discount rates of any of the reviewed SC-

GHG estimates. All three of the SC-GHG estimates PPA reviewed use a form of Ramsey-style generational discounting. While DICE-2023 proposes an optimal SC-GHG based on a near-term discount rate of 4.5%, it does provide an alternate set of SC-GHG values based on a near-term discount rate of 2%. Both RFF and USEPA each offer a set of SC-GHG based on a near-term discount rate of 2%. The 2021 IWG estimates of SC-GHG do not offer a set based on a 2% discount rate, nor do they use a form of generational discounting.

Considerations for Discounting Methodology:

The discounting methodology and guidance found in EPA's 2023 companion report to the updated SC-GHG values is a significant change from prior SC-GHG estimates and reflects the latest peer-reviewed research and the recommendations from NASEM. This update presents potential implementation challenges that must be considered for individual applications.

EPA's 2023 SC-GHG estimates *for a given emissions year* are the net present values (NPV) of future effects of those emissions. To calculate NPV, EPA (2023a) uses a dynamic, Ramsey-like discount model that accounts for generational concerns. To apply SC-GHG, the analyst must apply a second step and discount the SC-GHG from all future emissions years back to a common year of analysis; that is, the analyst must calculate NPV for Year 0 of the analysis. The most rigorous approach would adopt the same discounting approach for both steps, though this may be computationally difficult and beyond the scope of a particular analysis. For a more tractable option in the second step, EPA (2023a) provides a near-term (constant) discount rate to approximate the NPV. This approximation gives a smaller total than the dynamic, Ramsey-like discount rates specific to each year. The difference is greater for emissions occurring farther from the year of analysis. EPA considers the underestimate to be acceptable for projects with timelines of 30 years or less.

As an additional consideration, when incorporating SC-GHG into a larger benefit-cost analysis, this discounting approach may not align with the discount rates, methodology, and guidance found in OMB Circulars A-4 and A-94. While these circulars allow for generational discounting, EPA's dynamic discount rates are not currently available for analysts to apply to other benefits and costs within an analysis. PPA recommends that analysts balance analytical rigor with the needs of the application. In particular, PPA recommends that analysts consider the option of using EPA's constant near-term discount rate to estimate NPV in Year 0, even for projects with timelines longer than 30 years. In these cases, the analysis should include a discussion of the potential impact this choice has on the resulting estimates. PPA will continue to investigate ways to address this issue.

CONCLUSION

After analyzing the relevant criteria, PPA recommends that Bureaus adopt the EPA's 2023 estimates of the Social Cost of Greenhouse Gases (SC-GHG) as the best available science (as of September 30, 2024).

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EXHIBIT 5

FLARING

AERIAL SURVEY RESULTS

EXPLORE THE DATA

The wasteful practice of burning away gas has long been a problem in the oilfield. Data shows that companies in the Permian Basin burned away roughly 1 trillion cubic feet of gas since 2013.

While this waste problem has been well documented, much less has been known about methane emissions from flares.

EDF has now conducted four surveys of over a thousand flare stacks across the basin, from February to November 2020, which reveal methane emissions from flaring are a significant and widespread problem.

In each survey, we found that 10% of flares were either unlit—venting completely uncombusted methane directly to the atmosphere—or burning only part of the gas they were releasing.

menu

Although there was a large decrease in the volume of gas flared in late spring, due to the drop in production, there was no change in observed flare performance. We estimate at least 7% of Permian gas sent to flares is escaping directly into the atmosphere. This means companies are emitting 3.5 times more methane than what EPA assumes.

AT THIS RATE, FLARING CAN NOW BE CONSIDERED ONE OF THE LARGEST SOURCES OF METHANE EMISSIONS IN THE PERMIAN BASIN.

Our surveys indicate that in order to reduce emissions across the basin, flaring must be reduced to the lowest levels possible. With flaring volumes starting to increase again, there is an urgency to address flaring now.

menu

FLARING STUDY RESULTS

Our research indicates flares often malfunction, making flaring one of the largest sources of methane emissions in the basin.

10 PERCENT
of flares surveyed were **malfunctioning.**

Including **5%** of flares that were **completely unlit.**

THERE ARE TWO MAIN CULPRITS

COMBUSTION ISSUES

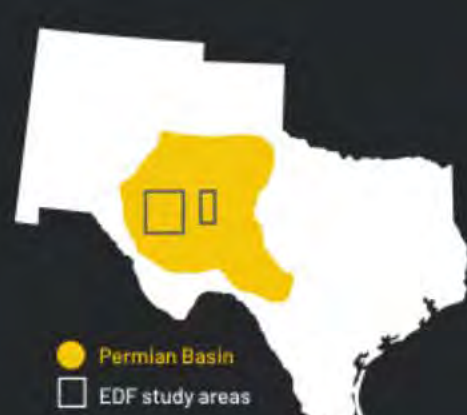
Texas 6%
New Mexico 5%

UNLIT AND VENTING

Texas 5%
New Mexico 3%

TOTAL METRIC TONS OF METHANE EMISSIONS FROM FLARING
(EDF Assessment based on VIIRS satellite data)

*EPA assumes functioning flares have 98% flaring efficiency rate



WHERE WE STUDIED

We studied 1,200 flares through aerial surveillance in New Mexico and Texas. Throughout 2020 we conducted 4 random surveys of flares in various areas, and 3 repeat surveys of flares in one specific area.

EXHIBIT 6

Onshore Oil and Natural Gas Operations on Federal and Tribal Lands in the United States

Analysis of Emissions and Lost Revenue

January 23, 2023

Olivia Griot, Lucy Metz, Ellen Carlson, Jackie Litynski, and Asa Hopkins

Report Outline

- Executive Summary
- Project Overview
- Background
- Methodology
- Results and Findings
- Conclusions

Executive Summary

- Synapse calculated the royalty value of gas lost due to venting, flaring, and leaks from natural gas operations on federal and tribal lands in 2019.

	Emissions Volume (Bcf)			Royalties (millions, 2022$)			
Type of lost gas	Total	Federal	Tribal only	Total	Federal	Tribal	State
Total	**162.65**	**106.97**	**55.68**	**$63.60**	**$21.33**	**$21.77**	**$20.50**
Flared	87.50	38.43	49.07	$34.22	$7.66	$19.19	$7.36
Vented	0.36	0.33	0.02	$0.14	$0.07	$0.01	$0.06
Leaked	74.79	68.21	6.58	$29.24	$13.60	$2.57	$13.07

- Synapse also calculated the lost state revenue from taxes collected on natural gas operations on federal lands in the top six states with the highest volume of wasted gas. These states (NM, ND, WY, UT, PA, and CO) had a combined total of 157 Bcf of wasted gas from federal and tribal lands. The lost state revenue from wasted gas on federal lands for these six states totaled $18.8 million.

- The potential sales revenue of wasted natural gas on federal and tribal lands in 2019 was $509 million, which could have met the yearly needs of 2.2 million households.

Project Overview

Project Overview

- Calculate and categorize natural gas and methane emissions volumes from venting, flaring, and leaks in the production segment on federal and tribal lands
- Determine the value of gas lost due to venting, flaring, and leaks from federal and tribal lands in 2019
  - Value lost in revenue from federal and tribal royalties
    - $63.6 million, with $21.3 million as lost federal revenue, $21.8 as lost tribal revenue, and $20.5 as lost state revenue
  - Value lost in state revenue from taxes
    - $18.8 million from the top six states with the highest volume of gas lost
  - Value lost from wasted natural gas
    - $509 million, or enough natural gas to meet the yearly needs of 2.2 million households

Background

Background

- During oil and natural gas production, natural gas is often vented (released) or flared (burned off) for various reasons. Additionally, natural gas leaks (resulting in fugitive gas) can occur throughout the production and transport process, resulting in wasted gas that could otherwise be sold.
- Venting, flaring, and leaks not only result in wasted gas and lost revenue, but also in methane emissions into the atmosphere. Methane is a potent greenhouse gas, and methane emissions contribute to climate change.
- This analysis assesses the amount and value of wasted natural gas that occurred in 2019 from venting, flaring, and leaks on federal and tribal lands.

Background: Rulemakings

- The U.S. Federal Government is proposing new actions to reduce wasted gas and address methane emissions from natural gas production.
  - Bureau of Land Management (BLM) proposed rulemaking: “Waste Prevention, Production Subject to Royalties, and Resource Conservation”
  - Environmental Protection Agency (EPA) supplementary proposal to proposed rulemaking: “Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review”

Background: BLM Rulemaking

- BLM proposed the rulemaking "Waste Prevention, Production Subject to Royalties, and Resource Conservation" on November 30, 2022.
- This proposed rule seeks to reduce the waste of natural gas from venting, flaring, and leaks during oil and gas production activities on Federal and Indian leases through:
  1. Technology requirements;
  2. Leak detection plans;
  3. Waste minimization plans and conditions on applications for permits to drill; and
  4. Monthly limits on royalty-free flaring.

Background: EPA Rulemaking

- EPA issued a supplementary proposal to update the proposed rulemaking "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review" on November 11, 2022.
- This proposed rule seeks to reduce emissions of methane from new and existing sources in the oil and natural gas industry through:
    1. Requiring routine leak monitoring;
    2. Preventing emissions at abandoned and unplugged wells;
    3. Creating a super-emitter response program;
    4. Strengthening flaring requirements;
    5. Requiring pneumatic pumps and controllers to have zero emissions; and
    6. Updating proposed requirements for compressors.

Background: Federal and Tribal Royalties

- Federal and tribal governments collect royalties for natural gas produced on leased federal and tribal lands. Royalties are assessed at the point-of-sale, according to the sales price of the gas.
- The royalty rate for a given lease is established before leases are auctioned for sale:
  - The Mineral Leasing Act of 1920 established a minimum royalty rate of 12.5%. BLM can charge a higher rate in the terms of individual leases.
  - Future leases will have higher royalty rates due to the Inflation Reduction Act and other potential future rulemakings.
- For royalties collected on federal land, 51% of that revenue is allocated to the federal government and 49% is allocated as revenue to the state in which the gas was produced.
- Natural gas that is vented, flared, or leaked before the point-of-sale often results in lost royalty revenues due to inconsistent application of the current regulations on avoidably lost gas and an uptick in royalty-free flaring requests in recent years.

Background: State Royalty and Tax Revenue

- In addition to their share of the federal royalties generated from gas production within their borders, states collect severance taxes on natural gas produced within their borders, including gas from federal lands. Severance taxes do not apply to gas from tribal lands.
- Severance tax rates vary by state (see slide 18) but are usually a percentage of the market value of the gas.
- Some states also collect other taxes on natural gas extraction.
  - New Mexico, Wyoming, and Utah collect conservation taxes in addition to their severance taxes.
  - New Mexico also collects an emergency school tax and processor's tax.
- Like severance taxes, local property taxes on natural gas producers are usually based on the value of gas extracted. This analysis does not include local taxes.
- Natural gas that is vented, flared, or leaked before the point-of-sale results in lost potential state revenues from taxes, as the emissions are not included in the sales volume on which taxes are assessed.

Background: Value of Wasted Natural Gas

- Natural gas provides energy for various uses, such as heating, cooling, cooking, and combined heat and power systems.
- Venting, flaring, and leaks waste a resource that could be used productively for these purposes.
- Wasted natural gas either results in increased gas production to compensate for leaks, which leads to additional production costs, or results in lower supply relative to demand, which increases prices.
- The value of lost natural gas can be measured through the market price of natural gas.

Methodology

Methodology: Overview

- This analysis examines wasted natural gas in 2019 because it is the most recent year available that is most reflective of the industry.
  - 2020 and 2021 data are available but are not reflective of the industry and were an aberration due to the COVID-19 pandemic.
- All values are presented in 2022 dollars.
- Data sources:
  - Henry Hub price data is from the U.S. Energy Information Administration (EIA) Natural Gas Spot and Futures Prices (NYMEX)
  - Natural gas consumption data for residential customers is from EIA's Natural Gas Consumption by End Use data series
  - U.S. EPA Greenhouse Gas Reporting Program data
  - Enverus well and production data
  - VIIRS satellite data

Methodology: Volume of Wasted Gas - Leaked and Vented

EDF provided natural gas volumes from leaks, venting, and flaring on federal and tribal lands for the production segment for 2019. To estimate leaked and vented methane emissions, EDF used its Synthesis model based on Alvarez et al. 2018. This model uses well pad data from Enverus and production-dependent emission factors to estimate site-level total methane emissions. EPA GHGRP data and a statistical model are used to estimate vented emissions at the well-pad-level. To get the volumes of emissions on federal and tribal lands, EDF used GIS shapefiles from BLM (oil and gas leases), USFS (mineral rights), and BIA (surface ownership) to extract just those well pads on federal and tribal lands. As there is not a comprehensive databased of tribal mineral ownership, surface ownership was used as a proxy for determining wells on tribal lands." to extract just those well pads on federal and tribal lands. EDF converted methane emissions to volumes of natural gas assuming an 80% methane content in natural gas in the production segment.

Note: This analysis does not include any emissions from AK, MI, NE, IL, and IN, though we would expect some level of emissions due to reported production on BLM leases in those states. Emissions in AK are challenging to estimate because most gas is reinjected. For MI, NE, IL, and IN, data limitations prevent direct estimation of emissions, but we expect fugitive and vented natural gas volumes to be less than 0.1 BCF based on the number of wells on federal and tribal lands in those states.

Methodology: Volume of Wasted Gas - Flared

For flared volumes, EDF used location-specific flaring volumes from the VIIRS satellite [Elvidge, C.D.; Zhizhin, M.; Baugh, K.; Hsu, F.-C.; Ghosh, T. 2016. "Methods for Global Survey of Natural Gas Flaring from Visible Infrared Imaging Radiometer Suite Data." *Energies*, *9*, 14. https://doi.org/10.3390/en9010014]. We overlayed these flared volumes with the same GIS shapefiles to extract flared volumes just on federal and tribal lands.

Note: We estimate uncertainties in the extracted VIIRS flared volumes on federal/tribal lands to be +15%/-25% due to coarse spatial location accuracy of the VIIRS satellite.

Methodology: Lost Royalty Revenue from Federal and Tribal Lands

- Synapse used the prior 2019 royalty rate of 12.5% to reflect historical revenues.
  - 12.5% was the minimum royalty rate prior to the passage of the Inflation Reduction Act.
  - Royalty rates can vary on tribal lands. Following interviews with federal staff, EDF, TCS, and Synapse decided that 12.5% is the most appropriate royalty rate to use for tribal lands.
- Synapse calculated the sales price of gas lost from federal lands using the historical Henry Hub price for 2019, which is $3.01 per MMBtu (2022 dollars).
- Lost federal and tribal royalties from wasted gas is equal to the royalty rate times the sales price of gas lost from venting, flaring, and leaks, as this gas is emitted before it could be sold and assessed for royalties.
  - The federal government receives 51% of this royalty revenue, and the remaining 49% goes to the states.

Methodology: Lost State Tax and Royalty Revenue

- Synapse calculated the amount of revenue that state governments lost in 2019 as a result of wasted natural gas from public lands for the six states with the largest quantities of wasted gas: New Mexico, North Dakota, Wyoming, Utah, Pennsylvania, and Colorado.
- See Slide 18 for a summary of the tax rates in each state. Note that state severance taxes apply to federal lands only (not tribal lands).
  - Lost state tax revenue from wasted gas is equal to the Synapse assumption for the state's tax rate times the sales price of gas lost from venting, flaring, and leaks for states with a market-value-based tax. For states with a volume-based tax, lost tax revenue is equal to the Synapse assumption for the state's tax rate times the volume of gas lost from venting, flaring, and leaks.
  - For states whose severance taxes allow for federal royalty deductions, Synapse calculated the deduction using the 2019 BLM rate of 12.5%.
- Lost state revenue also includes each state’s share of federal royalties. States receive 49% of the federal royalties collected on natural gas extraction from federal lands within their borders.

Methodology: Lost State Tax Revenue

State	Tax Rate	Synapse Assumption	Allows Federal Royalty Deduction
NM	Severance tax: 3.75% of taxable value Conservation tax: 0.0019% of taxable value Emergency school tax: 4% of taxable value Processor's tax: Base rate of $0.0065 per MMBtu multiplied by an adjustment factor equal to the average value of natural gas from the preceding calendar year divided by $1.33.	7.7519% composite tax rate plus $20,360 per Bcf processor's tax	Yes
ND	Severance tax rate changes annually based on producer price index for gas.	$78,650 per Bcf of natural gas (average of FY19 and FY20 prices)	No
WY	Severance tax: 6% of fair market value Conservation tax: 0.05% of fair market value	6.05% composite tax rate	No
UT	Severance tax: tiered rate (3-5%) Conservation tax: 0.2% of taxable value	4.24% composite tax rate	Yes
PA	Impact fee/unconventional gas well fee (fee assessed on per-well basis)	None, state revenue does not depend on volume of gas extracted	n/a
CO	Severance tax: tiered rate (2-5%) Conservation levy: $0.0015 per dollar of gas sold	3.65% composite tax rate	No

Methodology: Lost Value of Wasted Natural Gas

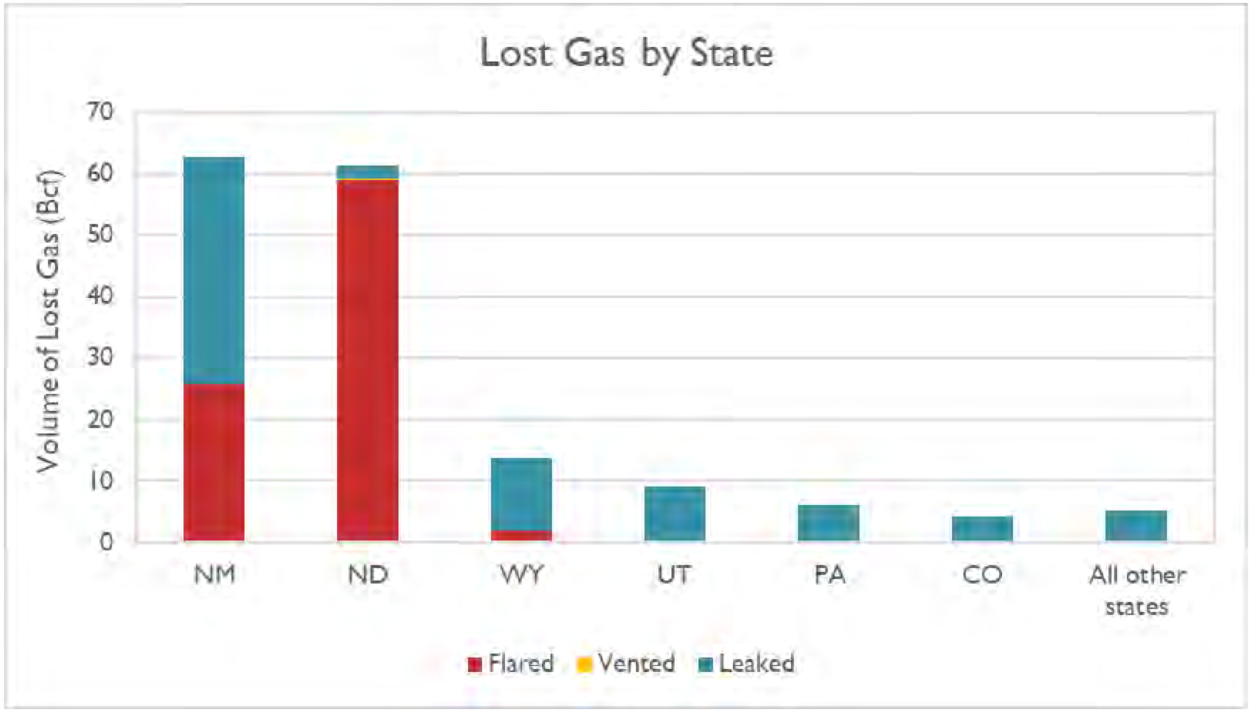
- Synapse calculated the value of the wasted natural gas lost from federal and tribal lands using historical Henry Hub gas price data from the Energy Information Administration.
- To estimate the number of households whose needs could be met with that wasted natural gas, Synapse used EIA’s natural gas consumption data for natural gas consumed by residential consumers and divided that by the number of residential consumers to get the average amount of gas consumed per household.
- This value is the lost value of the gas to society, as it is not being used productively.

 |

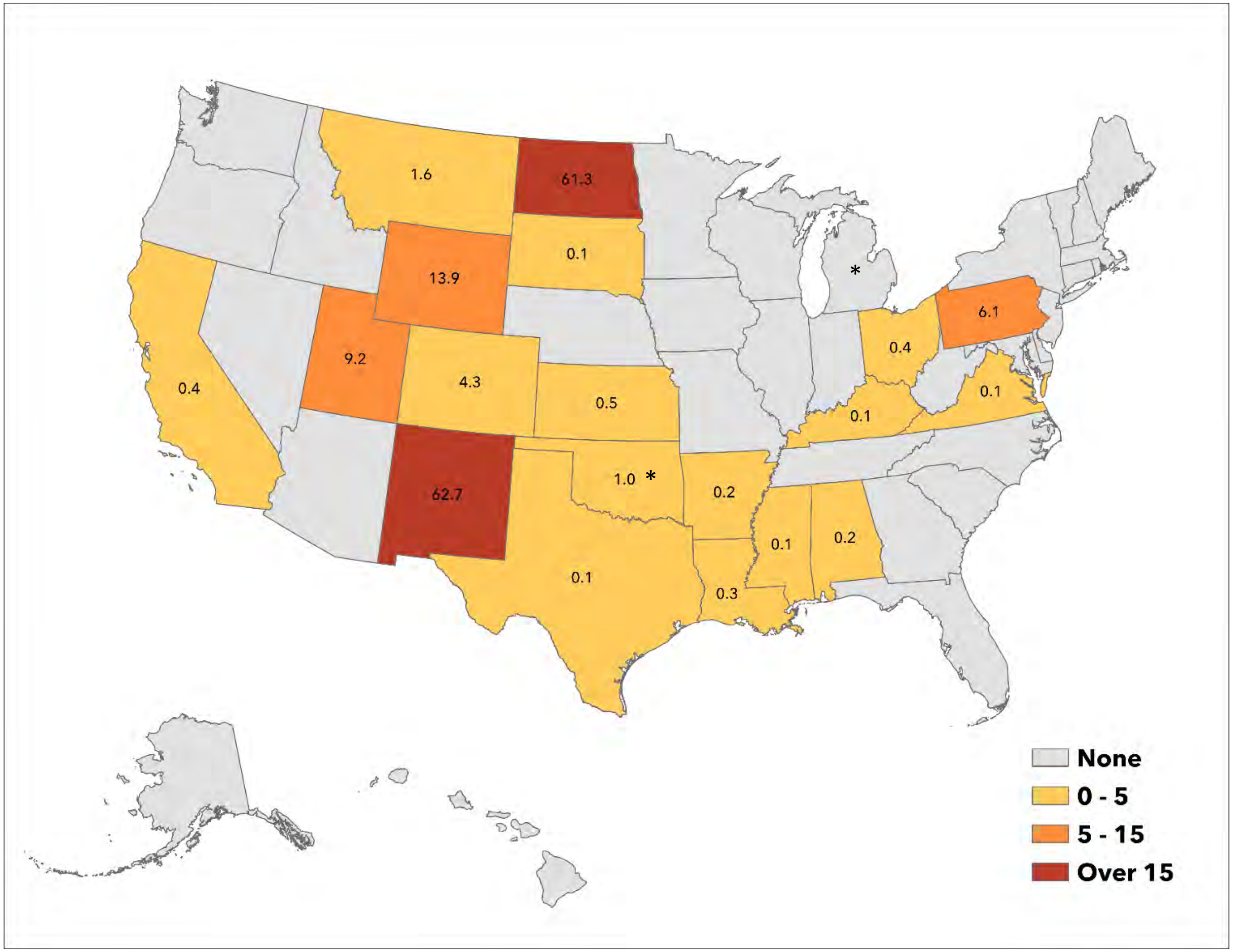
Results and Findings

Results and Findings: Volume of Lost Gas from Federal and Tribal Lands

- In 2019, leaks accounted for 46% of lost gas, flaring for 54%, and venting for less than 1%.
- The six states with the highest volume of gas lost from federal and tribal lands are New Mexico, North Dakota, Wyoming, Utah, Pennsylvania, and Colorado.

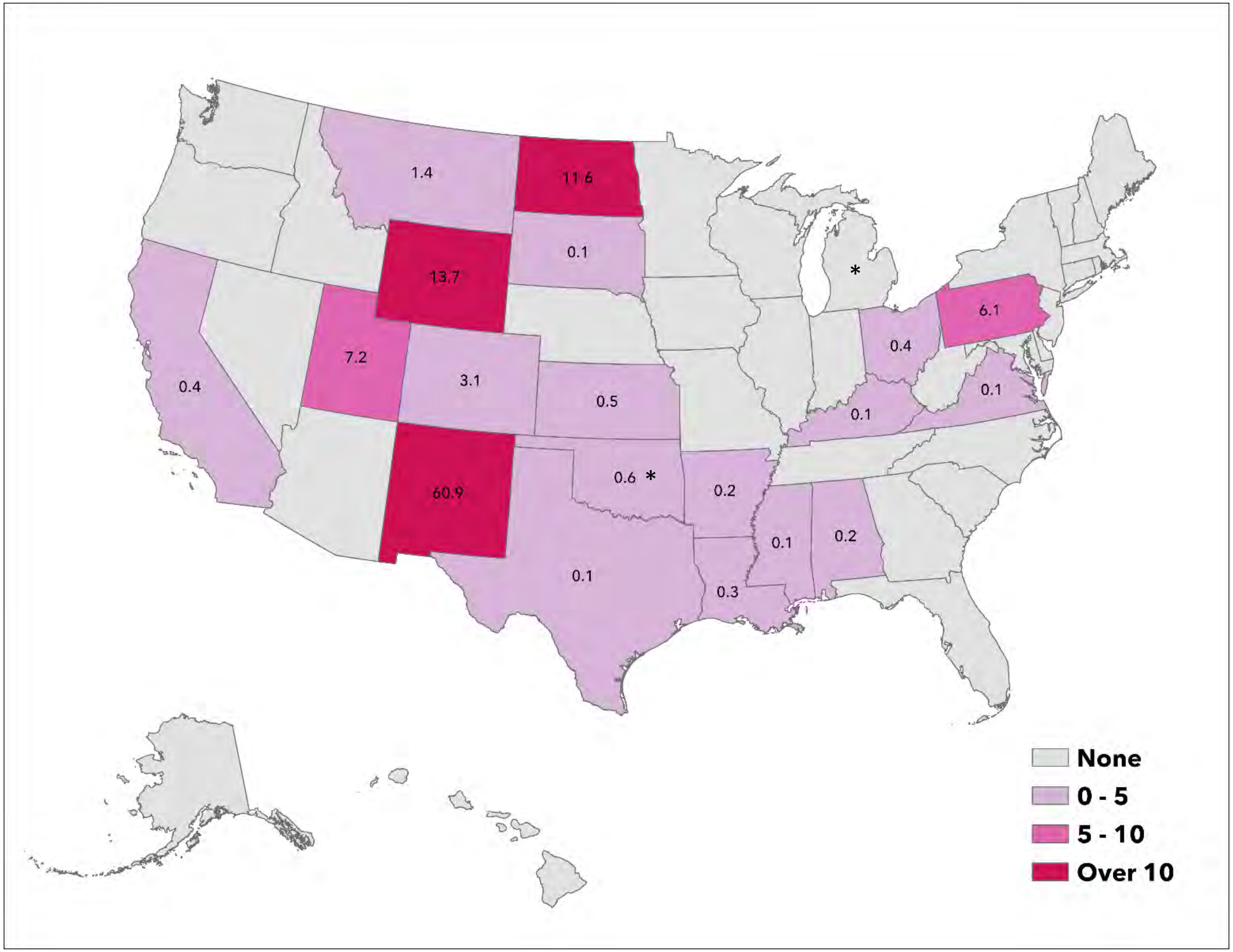


Results and Findings: Vented, Flared, and Leaked Gas from Federal and Tribal Lands (Bcf)



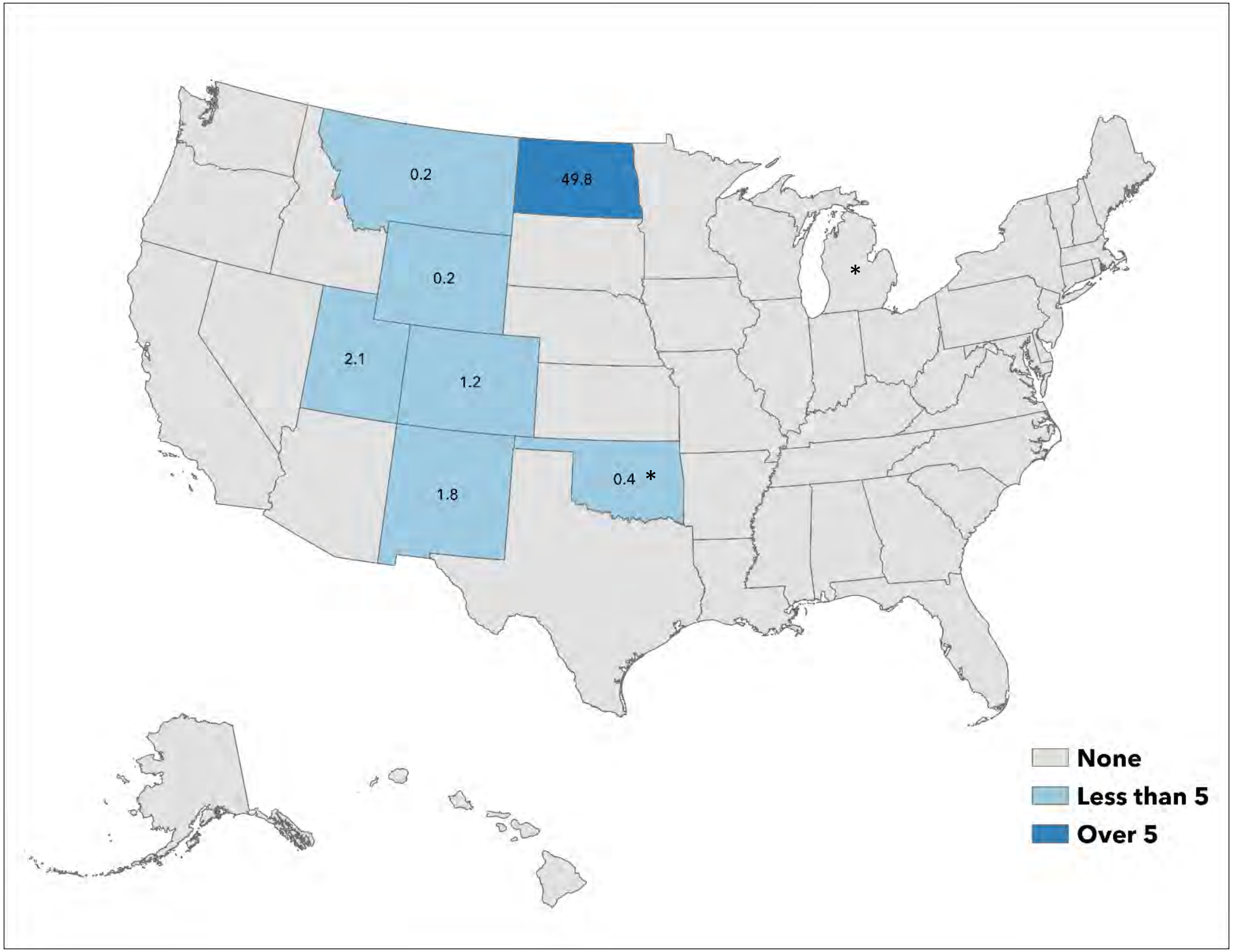
** These are likely underestimates due to data limitations and will be updated in the future*

Results and Findings: Vented, Flared, and Leaked Gas from Federal Lands (Bcf)



** These are likely underestimates due to data limitations and will be updated in the future*

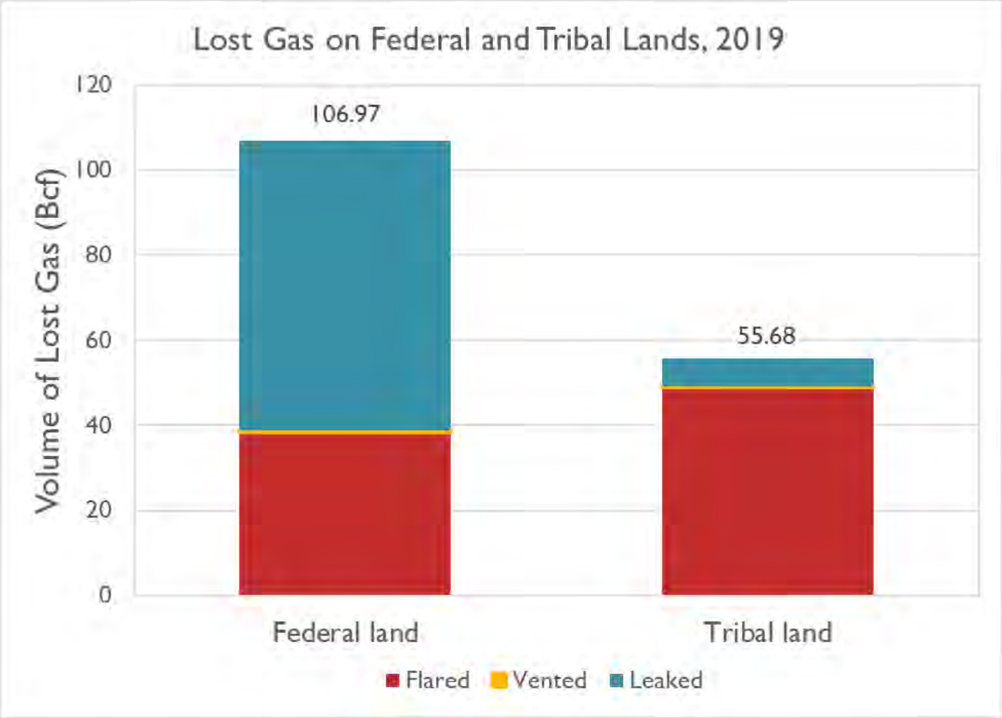
Results and Findings: Vented, Flared, and Leaked Gas from Tribal Lands (Bcf)



** These are likely underestimates due to data limitations and will be updated in the future*

Results and Findings: Lost Gas from Federal and Tribal Lands

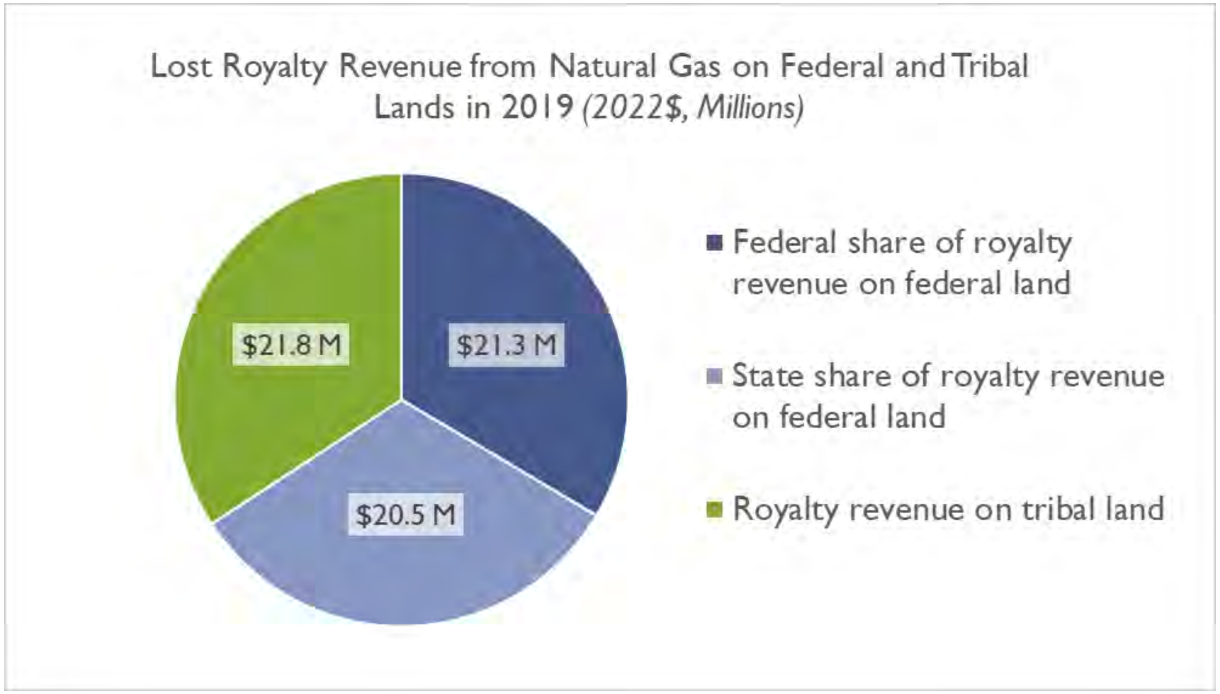
- On federal land, the majority of lost gas is leaked.
- On tribal land, the majority of lost gas is flared.



Lost gas on federal & tribal lands in 2019 (Bcf)	Total	Federal only	Tribal only
Total	**162.65**	**106.97**	**55.68**
Flared gas	87.50	38.43	49.07
Vented gas	0.36	0.33	0.02
Leaked gas	74.79	68.21	6.58

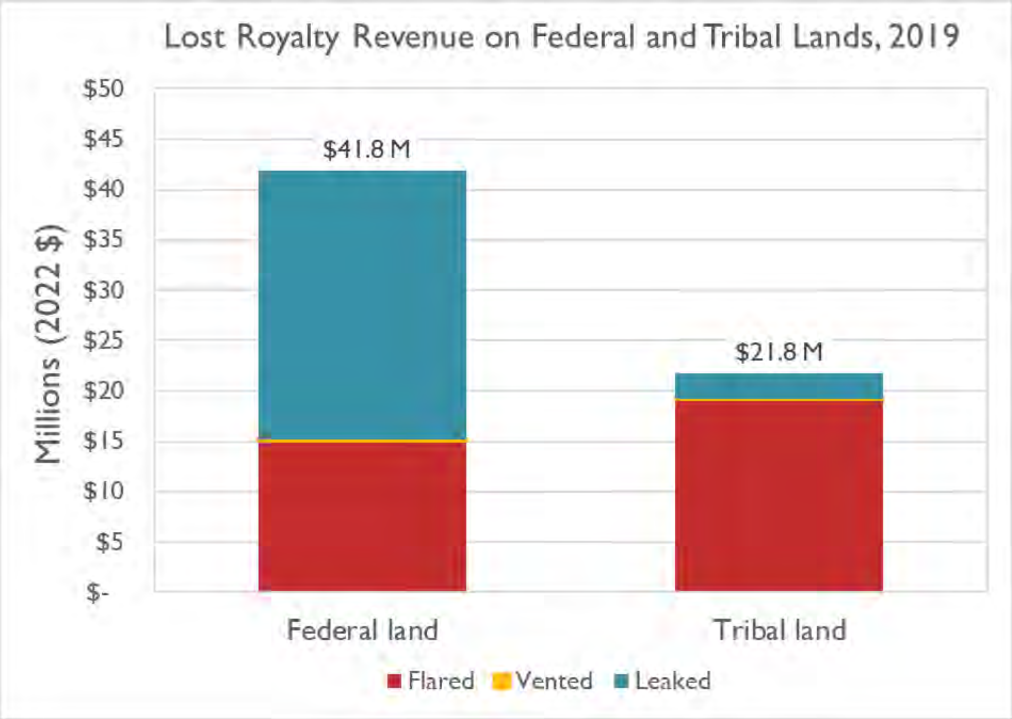
Results and Findings: Lost Royalty Revenue from Federal and Tribal Lands

- Using the historical rate of 12.5%, the total lost royalty revenue from natural gas produced on federal and tribal lands in 2019 was $63.6 million (2022 dollars).
  - Of this, 34% of lost royalty revenues ($21.8 million) was from natural gas lost on tribal land.
  - Royalty revenues from gas lost on federal land ($35.6 M) is split between the federal (51%) and state government (49%).



Results and Findings: Lost Royalty Revenue from Federal and Tribal Lands

- In total, flaring accounts for 53.8% of lost revenues on tribal and federal land, leaks for 46%, and venting for 0.2%.



Lost royalty revenues on federal & tribal lands in 2019 (2022$)	Total	Federal only	Tribal only
Total	**$63,600,000**	**$41,830,000**	**$21,770,000**
Flared gas	$34,220,000	$15,030,000	$19,190,000
Vented gas	$138,900	$130,700	$8,200
Leaked gas	$29,240,000	$26,670,000	$2,570,000

Results and Findings: Lost State Tax and Royalty Revenue

- The six states with the highest volume of wasted gas from public lands lost a combined $18.8 million in state tax revenue and $19.6 in federal royalty revenue in 2019.

State	Volume of wasted gas from federal and tribal lands* (Bcf)	Lost state revenue from state taxes (millions 2022$)	Lost state revenue from federal royalties (millions 2022$)
NM	62.7	$14.2	$11.7
ND	61.3	$0.908	$2.21
WY	13.9	$2.59	$2.63
UT	9.24	$0.833	$1.37
PA	6.06	-	$1.16
CO	4.29	$0.355	$0.596
Total	**157**	**$18.8**	**$19.6**

**Note that lost state revenue is based on the portion of this gas that is from federal lands only.*

Results and Findings: Lost Value of Wasted Natural Gas

- The total volume of wasted natural gas on federal and tribal lands in 2019 was 162.65 billion cubic feet, which is worth $509 million (2022$), based on the Energy Information Administration's 2019 Henry Hub gas price.
- This is enough natural gas to meet the yearly needs of 2.2 million households, nearly as many households as New Mexico, North Dakota, Utah, and Wyoming combined.

Lost value of natural gas in 2019 (2022$) ***Federal & Tribal lands***	
Total lost value from emissions	**$508,790,000**
Flared gas	$273,720,000
Vented gas	$1,110,000
Leaked gas	$233,950,000

Conclusions

1. Strengthening rules that reduce methane waste from natural gas production has the potential to provide federal, state, and tribal government with significant revenue that is currently being wasted.
2. Flared and leaked gas comprises the vast majority of wasted gas, and actions that address these types of emissions will provide the most benefit and the most saved revenue.
3. Reducing wasted natural gas would mean millions of households could be powered without the need for additional natural gas drilling, saving money and resources.

EXHIBIT 7

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REVIEW ARTICLE

The demographic characteristics of populations living near oil and gas wells in the USA

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Abstract

This study documents the prevalence of historically marginalized populations (across age, income, education, race-ethnicity, and language) living near active oil and gas wells throughout the USA, at both local and aggregated scales. This is performed by way of areal apportionment using well location data and population characteristics from the American Community Survey. A clustering analysis of marginalized populations living near a high density of wells reveals four distinct regions of high prevalence: southern California, southwest Texas, Appalachia, and northwest New Mexico. At the nationwide scale, we find large absolute numbers of people living near wells, including marginalized groups: nearly 18 million people in total across the USA, many of which are Hispanic (3.3 million), Black (1.8 million), Asian (0.7 million), and Native American (0.5 million), live below the poverty line (3 million), older individuals (3 million), or young children (over 1 million). In certain states, this represents a large share of the total population – over 50% in the case of West Virginia and Oklahoma. Estimates are subsequently compared to county-level control groups to assess patterns of disproportionality. Wide variations are found across regions and metrics, underscoring the locally specific nature of these data. Our research contributes to the field of environmental justice by describing the populations living near oil and gas wells.

Keywords Oil and gas wells · Fossil fuel production · Demographics

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Introduction

New developments in crude oil and natural gas production technology have led to increasingly rapid deployment of wells across the USA. There are currently over one million known active wells (DrillingInfo, 2018). Concurrently, the scientific community is building a more holistic understanding of the environmental impacts resulting from this growth. Besides observed air, surface water and groundwater pollution, and explosion hazards and climate disruption due to methane leakage (Adgate et al., 2014; Osborn et al., 2011), increased attention is being paid to public health effects. McKenzie et al., (2017, 2018) for example documented increased cancer risk (in one case, over 8 times EPA's standard) for populations living in the proximity of oil and gas operations due to inhalation of non-methane hydrocarbons. This is one piece of a growing body of literature illustrating health risks across a range of impacts, including respiratory conditions (notably asthma), birth complications, and observations of increased hospitalization across a variety of medical fields, including cardiology, neurology, and oncology (Currie et al., 2017; Jemielita et al., 2015; Rasmussen et al., 2016; Stacy, 2017; Whitworth et al., 2018). These public health threats are associated with unconventional (i.e., shale/coalbed/tight) gas development in particular. Additional effects on these populations include losses in aesthetic and property values (Evensen & Stedman, 2018; McKenzie et al., 2016; Muehlenbachs et al., 2015) as well as increases in violent crime (Bartik et al., 2019).

Many studies exploring environmental justice issues demonstrate how adverse externalities are most likely to fall upon historically marginalized communities. Researchers have documented ubiquitous evidence of environmental inequities based upon race and other factors (Banzhaf, 2012; Banzhaf et al., 2019; Mohai et al., 2009; Taylor, 2014). These groups have been historically underserved and often at greater risk of exposure to environmental impacts.

To date, several prior analyses have explored community-level characteristics surrounding oil and gas wells. Most have used the same methods as herein and explored population and subgroup counts in specific production basins (Clough & Bell, 2016; Meng, 2015; Ogneva-Himmelberger & Huang, 2015; Pellow, 2016; Slonecker & Milheim, 2015), while few have explored national-level counts (Czolowski et al., 2017; Earthworks, 2018; Long et al., 2016). However, no prior studies have assessed, on a national scale, trends in narrower population groups, looking specifically at marginalized communities. In addition, few other studies disclose census margins of error with population estimates. This article addresses these research gaps.

Kroepsch et al. (2019) identified a range of critical questions for developing a research agenda on environmental justice in this context, and this study informs one of them: who lives near wells? This is a first, but critical step, in better understanding distributional inequity in this context. We hope this study will assist researchers, policymakers, and advocates to uncovering the mechanisms that resulted in systemic inequity and addressing persistent environmental injustice (Ma, 2020).

Methods

Input datasets

Demographic data was obtained using the U.S. Census Bureau's American Community Survey (henceforth, ACS; U.S. Census Bureau, 2021) 5-year estimates for 2012–2016. Census tracts provide the starting point for the analyses herein and represent the best balance between depth of demographic insight, accuracy of estimates, minimizing margin of error, and geographical resolution. While census block or block groups would have been more desirable in reducing the systematic uncertainty inherent to the areal apportionment calculations, margins of error were unfortunately too large for most demographic metrics at these scales.

Locations of over one million identifiable active oil and gas wells in 2015, both conventional and unconventional, were taken from the DrillingInfo database (2018). This database has near comprehensive national coverage and is a compilation of public datasets from state agencies. Exact locations of wells are given by latitude/longitude coordinates in the database. Data from 2015 were used, despite some states possessing more recent production data, because it provided the most comprehensive single-year database nationwide. Indiana and Illinois are not included due to the low quality of source data for these states, where characteristics such as production, specific location, well type, and status are rarely specified. Thus, marginalized groups in these two states are unfortunately not able to be represented in this analysis. It is estimated that the database covers ~ 95% of the nation's wells and ~ 94% of its population (DrillingInfo, 2018).

Demographic estimation

We recombined ACS variables to create a shortlist of 13 demographic metrics to investigate covering race-ethnicity, educational attainment, language, age, unemployment, and income (see Online Resource 1 for additional details). These metrics were selected for this study due to their utility in the literature of environmental justice (Federal Interagency Working Group on Environmental Justice, 2016; Flanagan et al., 2018; U.S. Environmental Protection Agency, 2017). Our focus was on exploring links to race-ethnicity in addition to key socioeconomic metrics, such as poverty, unemployment, age, language, and education.

We extracted population counts of each population group living within four different buffer distances of each well (radii of 1/10, 1/4, 1/2, and 1 mile). The latter two distances are employed in intercomparisons with other studies (see Online Resource 2), and are the most common metric in extant literature (1 mile in particular). The former two are used in recognition of the fact that currently documented health impacts typically occur in very close proximity to wells with 1/10 mile representing an important threshold (McKenzie et al., 2018). Buffer zones were then overlaid on each census tract, and the share of each tract intersecting a buffer is calculated via areal apportionment, the most commonly used approach for this type of demographic analysis (Chakraborty et al., 2011).

Once population estimates are extracted at the census tract level, additional metrics (counts as a percent of total population and margins of error) are calculated. These are then aggregated up to county, state, and national levels.

Population statistics for each group are produced, and the margin of error (MOE; using the Census Bureau standard 90% confidence level) is calculated according to:

$$MOE_{agg} = \pm\sqrt{\sum\nolimits_{c} MOE_c^2}$$

where MOE_c is the MOE of the cth component estimate. This step is reproduced for aggregation to the state and national levels. Water bodies were omitted using the 2015 Census Areal Hydrography National Geodatabase (U.S. Census Bureau, 2015).

To explore the prevalence of regions where marginalized groups live near wells, and metrics overlap, we perform a clustering analysis and develop an index. First, statistically high values for a subset of each population were identified by binning distributions into five categories according to the Jenks natural breaks classification method (i.e., minimizing variance within bins while maximizing variance between them). Online Resource 3 depicts the geographic distributions for the highest bin of each population. Then, to create a multivariate index, a score of 1 was assigned to each well-variable pair that fell into the highest bin. These were summed, such that for any given well, a score may range from 0 to 11 depending on the amount of demographic metrics exhibiting high values. The resulting index can be interpreted as a localized, overlapping measure of marginalized communities.

This index is smoothed using a kernel density function according to:

$$f(x) = \frac{1}{n}\sum_{i=1}^{n} K\left(\frac{x - x(i)}{h}\right)$$

where x is a datapoint (well), n is 1,040,537 (wells), K is a quartic kernel estimator, and h is 0.5 decimal degrees. This specific bandwidth parameter (h) was chosen as it represented the best tradeoff between highlighting local clusters and ensuring they were clearly visible in the full extent of the map. This smoothing process is performed only for Fig. 1C to enable an intuitive interpretation of results at a national scale and account for the role of well density in cumulating and exacerbating potential health impacts. Only wells with scores of 1 or above are depicted.

Comparative statistics

Population estimates were also compared with respective control groups. Within counties, this is performed by contrasting our estimate of the share of populations living near wells to that of corresponding county-wide estimates for the same group, as given by:

$$e_{i,b,j} = \left(1 - \left(\frac{p_{i,b}}{t_{i,b}} \div \frac{p_{i,j}}{t_{i,j}}\right)\right) \times 100$$

where p is the population estimate for demographic variable i, in buffer zone b or county j. Denominators t represent total population estimates for respective variable/region pairs. The resulting metric, e, is perhaps best understood as a county/variable pair's percent deviation from the expected value of its control group. To determine whether these deviations are statistically significant, we then follow the Census Bureau guidelines and apply the z-score formula below:

$$z_{i,b,j} = \frac{\left|Est_{i,b} - Est_{i,j}\right|}{\sqrt{MoE_{i,b}{}^2 + MoE_{i,j}{}^2}}$$

Here, *Est* refers to population estimates (as a share of total, or $\frac{p}{t}$ as defined above) and *MoE* denotes associated census margins of error. This yields a z-score for each county/variable pair that describes the extent to which estimates are statistically different from their control group counterparts at a 90% confidence level. Limitations of our methodology are discussed in the supplementary information.

Results

Population-specific clustering

Oil and gas resources are extracted across a wide swath of the USA – the combined land area within one mile of all wells covers approximately 270,000 mi^2, or ~ 7.6% of the country. Figure 1A and B illustrate the degree to which this infrastructure is not only widespread but also concentrated in the same large production basins.

We begin with a local, census tract level analysis of each population group in isolation. This allows us to explore the prevalence of clusters or regions across the country where certain marginalized groups may be living near wells in relatively high numbers, as a share of total population. An array of maps highlighting the predominant clusters by group are provided in Online Resource 3. For Blacks, these stretch across several southern states (LA, MS, AL, AR) and several urban settings (Los Angeles, Cleveland, Akron, Youngstown). Alaskan Native and Native American clusters can be observed in Alaska (Prudhoe Bay, Utqiagvik, Anchorage) and pueblos in northwestern New Mexico. For Asian communities, these are largely concentrated in California, in urban settings of the San Joaquin Delta and greater Los Angeles area, as are Hawaiians and Pacific Islanders. Clusters of Hispanic populations stretch across large expanses of California and Texas.

In terms of socioeconomic metrics, clusters of populations with lower levels of educational attainment are predominantly located in California (Central Valley, Los Angeles), Texas (mainly near the U.S.-Mexico border), Louisiana (Lafayette, New Orleans), southwest West Virginia, and eastern Kentucky. These regions are

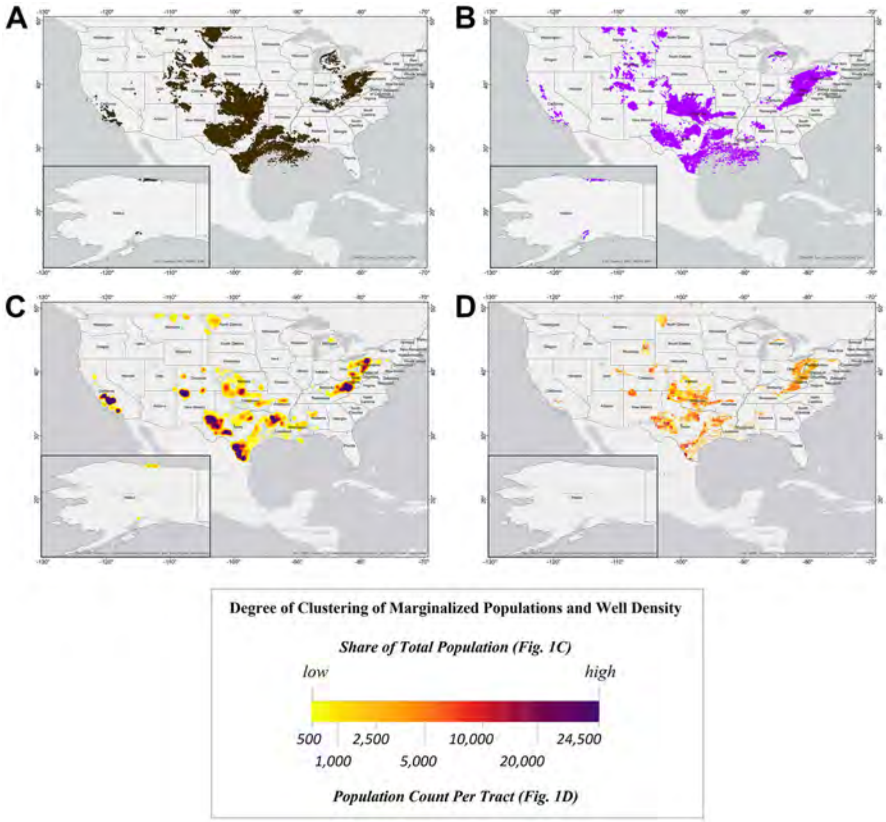

Fig. 1 Disposition of oil and gas wells and marginalized population clusters across the USA. **A** depicts active oil wells in black (n = 473,469), and **B** active gas wells in purple (n = 377,738) for the year 2015. **C** and **D** illustrate clustering of multiple marginalized population groups overlapping with areas of high well density. **C** denotes an index score calculated using an equally weighted aggregate statistic, representing how many marginalized populations overlap as a share of total population living near wells. **D** depicts these data terms of absolute population count per census tract, rather than relative shares as in **C**. All well types are factored into this analysis (n = 1,040,537); Hawaii is omitted in this figure given its lack of wells

mirrored in the findings both for communities with high unemployment and those under the poverty line, with the addition of several regions (San Joaquin Delta, CA; Farmington, NM; north-central MT, areas across LA/MS/Appalachia). Limited English-speaking communities are concentrated in northern Alaska, California (Central Valley, Los Angeles), Texas (South Texas and the Rio Grande Valley, Houston and Dallas metro areas), and Garden City (KS).

Regarding age groups, communities with relatively higher numbers of children under 5 years old are found in California's Central Valley, throughout Texas (particularly across the Eagle Ford, Permian, and Anadarko Basins), and in the North (north-central MT, western ND in the Bakken Formation). These regions are comprised of children composing up to 13% of the total population living near wells – over double the national average. Communities with high levels of older individuals (over 64 years old) are observed across the nation, yet are concentrated in the following states: MT, ND, TX, KS, OK, NE, CO, MI, WV, TN, OH, and PA. A subset of these (CO, NE, MI) intersect very little with other demographic metrics.

Additional income metrics (in particular the GINI coefficient) reveal many communities facing relatively high income inequality in southern states (TX, LA, MS, OK), in Appalachian states (WV, OH, PA), and in Montana. Median Family Income metrics further highlight clustering in both poor and affluent neighborhoods, with the latter typically surrounding major cities where fossil fuel extraction is prevalent.

Marginalized population overlap index

We then created a national index to highlight regions where clusters across multiple marginalized population groups and areas of high well density coincide. Figure 1C illustrates areas with a high degree of intersectionality for all wells across the country. Approximately 41 distinct (non-contiguous) clusters can be observed. The highest ones are found in CA's Central Valley, notably near Bakersfield and Coalinga (in the San Joaquin Basin). Moving east, a large cluster can be observed in the area surrounding Farmington, NM – a region containing several Native American tribes, with the Navajo Nation, Southern Ute, and Jicarilla Apache Nation having the greatest overlap. In the Permian Basin, two clusters emerge (one northwest of Odessa, TX, and the other west of Sonora, TX). Nearby, we observe three distinct clusters on the TX-Mexico border, near the environs of Laredo, TX (Eagle Ford Shale). Three significant clusters remain: one located northwest of Shreveport, LA (Haynesville-Bossier Shale), and two in Appalachia: south of Charleston, WV, and near Allegheny National Forest, PA. Figure 1D adapts the approach used in panel 1C to use absolute population counts, rather than relative shares. Clusters remain largely the same with the exception of some regions diminishing (e.g., California and Wyoming). This underlines the fact that these clusters represent areas where marginalized groups are found both in disproportion and in high numbers.

Summary statistics by distance from well

A local lens is most useful to identify larger disparities and truly explore questions of environmental justice. The analyses presented above were completed to provide a deeper and more focused assessment of such trends. Though it conveys a limited perspective, aggregation at the national and state levels is helpful for obtaining a broad snapshot of trends.

Table 1 summarizes national statistics for each population within one mile of a well. For each group, two comparative statistics are provided: national totals and control counties. The latter represents a control group reflecting demographic trends specific to oil and gas producing regions: population estimates for counties within which wells are located. There is a varying degree to which the county-level population estimates are significantly statistically different from controls (5–57%; 90% CI),

Table 1 National summary statistics of population counts within one mile of a well. Percentage rows denote population counts as a share of the total population within the same one-mile buffer. The control counties column denotes population counts for population groups within the counties where wells are located. Column 3 shows differences between estimates of population shares within a one-mile buffer, and their respective county controls. Column 4 provides summaries of the overall share of counties that exhibited significantly different estimates from their control groups, while column 5 provides *p*-values from this analysis (see Online Resource 5 for county/variable level detail)

Population group	Population living within one mile of a well	Difference in share of population in one mile proximity, versus county controls (%)	Aggregate share of counties with estimates significantly different from control groups (%)	Mean *p*-value (normal dist., 90% CI)	Control counties	National total
Black	1,836,200	−1.9	41	0.069	12,773,100	44,654,400
[%]	10.00%				11.90%	13.90%
Asian	697,500	−3.3	24	0.244	7,668,400	16,614,600
[%]	3.80%				7.10%	5.20%
Hawaiian/Pacific Islander	34,600	−0.1	5	0.377	361,700	560,000
[%]	0.20%				0.30%	0.20%
Hispanic	3,318,000	−6	34	0.17	25,776,600	58,691,300
[%]	18.00%				24.00%	18.20%
Native American	457,000	0.5	16	0.298	2,172,600	5,430,300
[%]	2.50%				2.00%	1.70%
White	15,129,100	7.1	41	0.054	80,570,800	244,659,400
[%]	82.20%				75.10%	76.00%
Below poverty line	2,872,400	−0.4	23	0.297	17,230,500	48,509,300
[%]	15.60%				16.00%	15.10%
Under 5 years old	1,184,400	−0.1	17	0.346	6,981,800	20,050,500
[%]	6.40%				6.50%	6.20%
Over 64 years old	2,692,000	0.9	26	0.296	14,682,500	46,794,900
[%]	14.60%				13.70%	14.50%
Less than HS degree	1,814,600	4.7	19	0.315	10,870,100	28,445,400
[%]	14.80%				10.10%	13.30%

Table 1 (continued)

Population group	Population living within one mile of a well	Difference in share of population in one mile proximity, versus county controls (%)	Aggregate share of counties with estimates significantly different from control groups (%)	Mean *p*-value (normal dist., 90% CI)	Control counties	National total
Limited English spoken	143,300	−0.2	7	0.378	1,119,400	6,136,700
[%]	0.80%				1.00%	1.90%
Unemployed	604,700	−0.4	10	0.368	3,979,800	12,032,700
[%]	3.30%				3.70%	3.70%
Total population	18,405,100				107,301,000	322,087,500
[%]	5.70%				100.00%	100.00%

depending on the metric (see Table 1). For many counties, population numbers were simply too low and/or metrics had margins of error too large to yield strong statistical power in the relationships explored. Significance measures for each county/variable pair are provided in Online Resource 4, and summary statistics for the half, quarter, and tenth mile buffer distances are found in Online Resource 5.

These results underscore the degree to which the US population and oil and gas production are intertwined. Over 18 million people live within one mile of wells. Many of these consist of marginalized groups (Hispanic: 3.3 m; Black: 1.8 m; Asian: 0.7 m; Native American: 0.5 m; below the poverty line: 2.9 m; over 64 years old: 2.7 m; under 5 years old: 1.2 m). From a relative standpoint, at a national aggregated scale, most population groups are found to be less prevalent near wells than their county-level controls. The exceptions to this are Native Americans, Whites, people over 64 years old, and people with less than a high school degree. For these populations, we find a respective 25.0%, 9.5%, 6.6%, and 46.6% higher prevalence living within one mile of wells than controls.

State-level tables were also derived to depict population counts by demographic group within one mile of wells. Online Resource 6 provides data for the 29 states where oil and gas production is prevalent. The five states with the greatest number of people living near wells are Texas (5.0 m), Ohio (3.0 m), California (2.2 m), Oklahoma (1.9 m), and Pennsylvania (1.9 m). On a percentage of total state population basis, these are: West Virginia (50.9%), Oklahoma (50.1%), Ohio (25.9%), Texas (18.7%), and Pennsylvania (15.0%). These measures highlight the fact that many people across the country are bearing the externalities of oil and gas development – particularly in West Virginia and Oklahoma where a majority of people live near active wells.

With respect to summary results, a subset for one mile and ½ mile (state and national levels) can be compared to other estimates in the literature; see Online Resource 2 for a comprehensive assessment. In cases where metrics and methodological approaches overlap, our findings are extremely similar.

The comparative analyses outlined in this section were performed as an additional means of investigating disproportionality through county, state, and national scales. Percentage differences from respective control groups for each county/variable pair can be found in Online Resource 4. These data illustrate the wide distribution that can be seen across counties, in terms of disproportionality for any given population, and emphasize the locally specific nature of these findings.

Discussion

In this study, we shine a light on the colocation of historically marginalized groups and wells. While the negative impacts of production are real and widespread, a nuanced approach is needed in moving beyond this framework and exposing cases of environmental injustice. A key factor to acknowledge is that oil and gas development may be desired and spurred on by local communities, in seeking royalties and potential employment. This stands to reason as Bartik et al. (2019) have noted large positive welfare implications on frontline communities. This economic benefit is likely to be more tangibly perceived than the indirect negative externalities, particularly with respect to health impacts that are still being uncovered. It should be noted that, more generally, the permitting process for oil and gas development differs on Native American lands, where most of these populations live.

Production also relies on labor inputs, meaning that fossil fuel extraction industries and inhabited areas frequently overlap. The analysis presented herein is not causal, but correlative; we provide a characterization of the extent to which the colocation phenomenon is prevalent. Developing this knowledge is particularly important in light of the fact that there is evidence of health impacts for populations living in close proximity to wells (Gold & McGinty, 2013; Macey et al., 2014; Rabinowitz et al., 2015; Steinzor et al., 2013). Additionally, there have been numerous examples of recent incidents involving gas leaks from wellheads, such as in Belmont County, Ohio, in February 2018. Vulnerable communities are often at a disadvantage when it comes to mitigating environmental exposures and overcoming impacts, so it is critical to understand where they might be most readily exposed to the negative externalities of production. In turn, understanding where and how oil and gas development intersect with diverse communities should aid in formulating the appropriate industry practices and public policies to reduce impacts to proximate populations.

There are four notable regions in the country where intersectionality across marginalized groups points to a need for deeper region-specific research, particularly surrounding health impacts. The first such region is southern California, particularly in greater Los Angeles and the Central Valley. The former reveals a prevalence of Hispanic, Asian, Black, and Hawaiian/Pacific Islander populations living in proximity to oil and gas wells, while the latter registers more along metrics such as language, poverty, and unemployment, among Hispanic communities. This is in large part explained by the fact that wells in the Los Angeles urban setting tend to be located within ethnically diverse central neighborhoods, while the Central Valley is home to a large agricultural workforce facing its own set of socioeconomic challenges.

The second notable region, concentrated in southwest Texas, includes the Permian Basin and the Eagle Ford Shale. These regions mirror similar characteristics as California's Central Valley. A third major region of note, Appalachia, differs somewhat from the others in terms of demographics. Here, these are predominantly elderly White populations and groups with low income and high unemployment. Finally, a fourth region to highlight appears in northwest New Mexico, largely composed of Native American populations and communities with high unemployment, poverty, and children under the age of five. These areas should form a primary focus for science and policy given the degree to which this colocation and cumulation can dramatically worsen inequities and health disparities (Morello-Frosch et al., 2011).

Another important policy aspect for exploration in subsequent research is the relationship between employment and populations living near wells. Our results highlight widespread clusters of high unemployment near wells 4–12 times the national average (Online Resource 3). While this question has been explored nationally in the context of shale wells (Maniloff & Mastromonaco, 2017), the approach presented in this study, supplemented by time-series analysis and causal inference methods (e.g., using difference-in-differences or instrumental variables), is well suited to exploring this question for a broader range of well types using the frequent (i.e., annual) time step proffered by the ACS.

Our study differs in several key ways to the most similar prior analyses (Czolowski et al., 2017; Earthworks, 2018; Gold & McGinty, 2013). One chief aspect is that our study uncovers national statistics for 12 new population groups, and the intersectionality of these. It is the first national study to include census margins of error alongside estimates, and uses more recent data for both wells and populations: all prior national studies rely on the 2010 Census and demographic trends have likely changed significantly since then, particularly in fossil fuel extraction zones. Finally, Alaska is also included in our scope of analysis, exposing areas of potential interest (particularly near Prudhoe Bay).

We envision multiple ways in which these findings can be useful to a variety of audiences. First, for policymakers having a responsibility to ensure the safety and welfare of people living near oil and gas operations, these data can aid in crafting policy tailored to protecting vulnerable populations on the front lines. Second, these communities themselves and representative organizations will have the means to contextualize and quantify affected groups, in advocacy efforts aimed at addressing environmental injustice. Third, researchers can more accurately scope areas of interest for studies aimed at furthering our understanding of impacts from wells on proximate populations. Fourth, industry can use these data to customize and enhance their stakeholder outreach efforts and operational considerations by better understanding the makeup of the populations with which operators interact.

Our findings illustrate the sheer extent to which aggregate numbers of people live in close proximity to wells, both in terms of marginalized populations and specific geographies where fossil fuel production is prevalent. The data highlights key areas of layered social vulnerability, and by way of these quantification efforts, reinforces the need to further understand how frontline communities are impacted by oil and gas development.

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Declarations

Conflict of interest The authors declare no competing interests.

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EXHIBIT 8

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Flaring from Unconventional Oil and Gas Development and Birth Outcomes in the Eagle Ford Shale in South Texas

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Background: Prior studies suggest exposure to oil and gas development (OGD) adversely affects birth outcomes, but no studies have examined flaring—the open combustion of natural gas—from OGD.

Objectives: We investigated whether residential proximity to flaring from OGD was associated with shorter gestation and reduced fetal growth in the Eagle Ford Shale of south Texas.

Methods: We conducted a retrospective cohort study using administrative birth records from 2012 to 2015 ($N = 23,487$) and satellite observations of flaring activity during pregnancy within 5 km of maternal residence. Multivariate logistic and linear regression models were used to estimate associations between four outcomes (preterm birth, small-for-gestational age, continuous gestational age, and term birthweight) and exposure to a low (1–9) or high (≥ 10) number of nightly flare events, as compared with no exposure, while controlling for known maternal risk factors. We also examined associations with the number of oil and gas wells within 5 km using data from DrillingInfo (now Enverus).

Results: Exposure to a high number of nightly flare events was associated with a 50% higher odds of preterm birth [odds ratio (OR) = 1.50 (95% CI: 1.23, 1.83)] and shorter gestation [mean difference = − 1.9 (95% CI: −2.8, −0.9) d] compared with no exposure. Effect estimates were slightly reduced after adjustment for the number of wells within 5 km. In stratified models these associations were present only among Hispanic women. Flaring and fetal growth outcomes were not significantly associated. Women exposed to a high number of wells (fourth quartile, ≥27) vs. no wells within 5 km had a higher odds of preterm birth [OR = 1.31 (95% CI: 1.14, 1.49)], shorter gestation [−1.3 (95% CI: −1.9, −0.8) d], and lower average birthweight [−19.4 (95% CI: −36.7, −2.0) g].

Discussion: Our study suggests exposure to flaring from OGD is associated with an increased risk of preterm birth. Our findings need to be confirmed in other populations. https://doi.org/10.1289/EHP6394

Introduction

Domestic oil production in the United States has nearly doubled in the last decade, whereas natural gas production has risen roughly 50% to an all-time historical high (EIA 2019c, 2019b). Unconventional techniques of directional drilling and hydraulic fracturing (fracking) have allowed for the exploration and extraction of oil and gas from areas that were previously inaccessible or uneconomic and, in many regions, brought oil and gas development (OGD) into closer proximity to homes. More than 17 million people currently live within 1 mi of an oil or gas well in the United States, increasing the potential for exposure to contaminants associated with fossil fuel extraction (Czolowski et al. 2017). The potential health hazards associated with OGD activity include contamination of air (Adgate et al. 2014; Shonkoff et al. 2014; Werner et al. 2015) and water (Jackson et al. 2013) by hazardous chemicals and increased psychosocial stress as a result of noise, increased seismic activity, and social hazards associated with disruptions to the local social fabric (Allshouse et al. 2019; Richburg and Slagley 2019; Witter et al. 2013; Adgate et al. 2014). Fracking involves the injection of fluids, sands, and chemical additives into wells to reduce friction, decrease drill time, or stimulate production and include chemicals that are known carcinogens, mutagens, reproductive and developmental toxins, or endocrine disruptors (Webb et al. 2014; Kassotis et al. 2016; Yost et al. 2016; Stringfellow et al. 2017). These compounds can enter the nearby environment through spills, leaks, and volatilization and the disposal of wastewater.

Several recent studies have suggested that living near OGD during pregnancy may elevate the risk of adverse birth outcomes, including preterm birth (Casey et al. 2016; Whitworth et al. 2018), small-for-gestational age (SGA) birth (Stacy et al. 2015; Tran et al. 2020), low birth weight (Hill 2018; Tran et al. 2020), and neural tube defects (Janitz et al. 2019; Mckenzie et al. 2014). However, the findings have not been consistent across studies: McKenzie et al. (2014), Stacy et al. (2015), and Tran et al. (2020) found no association with preterm birth, and Casey et al. (2016) and Whitworth et al. (2018) found no association with SGA. Fetuses are considered to be highly vulnerable to a variety of toxicants because of their physiologic immaturity and developmental susceptibility (Perera et al. 1999). Preterm birth—which is a major predictor of perinatal mortality and may lead to long-term health problems—remains a major public health concern in the United States, where nearly 400,000 babies are born prematurely each year (Martin et al. 2019). Birthweight is also a significant predictor of later cognitive function and cardiovascular disease, even for infants within the normal weight range born at term (Barker 2006; Shenkin et al. 2004).

The exact exposures through which OGD may elevate the risk of adverse birth outcomes remain unclear. One pathway of exposure that has not yet been examined is flaring. Flaring in this context refers to the intentional, controlled combustion of natural gas during the exploration, production, and processing of natural gas, liquids, and oil. Flaring is used for several days or weeks during well production testing after an oil or gas well is initially drilled and hydraulically fractured. Flaring is also used while performing well maintenance and equipment repairs and as a safety measure at processing plants when equipment becomes overpressurized. In addition, flaring is commonly used to dispose of the natural gas that is dissolved in the oil recovered from oil wells. In

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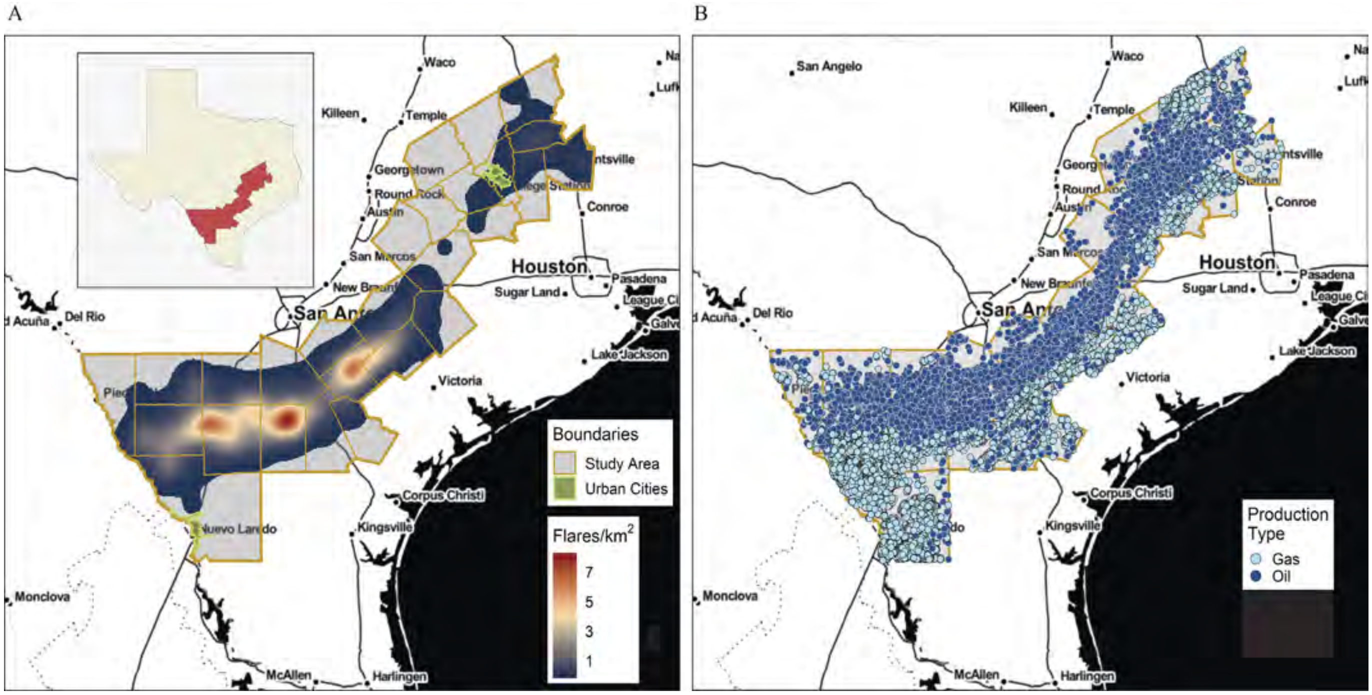

Figure 1. Density of (A) nightly flare events and (B) oil and gas wells across the 27-county Eagle Ford study area, excluding urban areas. Data sources: VIIRS Nightfire (https://www.ngdc.noaa.gov/eog/viirs/) and DrillingInfo (2018) (now Enverus). Counties are delineated in yellow. Green boundaries delineate cities with more than 75,000 people, which were excluded from the analysis. Note: VIIRS, Visible Infrared Imaging Radiometer Suite.

the United States, hydraulic fracturing has enabled the development of previously inaccessible oil shale formations, resulting in the rapid construction of many widely dispersed oil wells in places that lack a pipeline and other infrastructure to economically collect the associated gas. When local opportunities to use the natural gas are also lacking—for example, for reinjection to enhance oil recovery or for electricity generation on site—it is either vented directly to the atmosphere or combusted in routine flaring that can operate continuously for days or months. Global estimates indicate that more than 139 billion m^3 of gas are flared annually, or about 4.6% of the world's natural gas consumption (Elvidge et al. 2009). The United States has the largest number of flare sites globally, burning an estimated 6.5 billion m^3 of natural gas in 2012 (Elvidge et al. 2016). However, regulation and data on the location and timing of flaring is minimal. Monitoring studies indicate that incomplete combustion during the flaring process releases a variety of volatile organic compounds and polycyclic aromatic hydrocarbons along with carbon monoxide, nitrogen oxides, heavy metals, and black carbon (Ite and Ibok 2013; Kindzierski 2000; Leahey et al. 2001; Prenni et al. 2016; Strosher 1996, 2000). Although there have been no studies specifically examining health effects associated with flaring, several of these combustion-related pollutants have been associated with a higher risk of preterm and reduced birthweight in other contexts (Ballester et al. 2010; Brauer et al. 2008; Dadvand et al. 2013). Because flaring is very visible and audible and may produce odors, the practice may also impact fetal growth and development by adding to the anxiety of nearby residents or interrupting sleep (Hiller 2016).

In this study, we utilized satellite observations to characterize exposure to flaring in the Eagle Ford Shale play of south Texas among pregnant women giving birth between 2012 and 2015. The Eagle Ford Shale, which encompasses 27 counties in Southern and Eastern Texas, is one of the most productive oil and gas regions in the country and has experienced a recent boom in production (Figure 1). Due to a weakening of state regulations that previously banned flaring (Willyard 2019), a lack of pipeline capacity for transporting the volumes of natural gas being produced, as well as low gas prices, flaring is a routine practice here. According to the U.S. Energy Information Administration (EIA), Texas flares more natural gas than any other U.S. state (EIA 2019a). Our prior work identified over 43,000 nightly flare events in the region between 2012 and 2016, with a peak in flaring in 2014 and an estimated 4.5 billion m^3 of gas flared over the 5-y period (Franklin et al. 2019). Given the high frequency of flaring in the Eagle Ford Shale, we sought to characterize the effects of prenatal exposure to flaring on the risk of multiple adverse birth outcomes among pregnant women as a possible additional mechanism through which OGD may negatively impact the health of nearby communities.

Methods

Study Population

Study protocols were approved by the institutional review boards of the University of Southern California (#HS-17-00652) and the Texas Department of State Health Service (#14-044). Geocoded administrative birth records were obtained from the Texas Department of State Health Services for the years 2012–2015. Our study population consisted of all singleton births lacking birth anomalies and born to women residing within rural areas of the 27 counties comprising the Texas Eagle Ford Shale play (Texas Railroad Commission 2019) between 19 July 2012 and 31 December 2015 (Figure 1). Women residing in cities with a population of more than 75,000 people were excluded because their exposure to other background sources of air pollutants likely differ from women residing in rural areas. This resulted in the exclusion of residents within the municipal boundaries of Laredo, College Station, and Bryan, Texas. The study start date was chosen because the satellite data used to characterize exposure to flaring became available only beginning 1 March 2012. As such, 19 July 2012 was the first possible birth date of an infant born at ≥20 completed weeks (the shortest gestational age in our sample) and, hence, the earliest birth date for which we could assign complete prenatal exposure. The assembly of our study population is illustrated in Figure S1. Gestational age in days was calculated by taking the difference between recorded last menstrual period (LMP) and date of birth. Records missing the year of LMP, month of LMP, or both, were excluded (3.2% of observations); records missing only the day of LMP were recoded using the 15th of the month (2.3% of observations). We excluded a further 1% of births if their gestational age exceeded 44 completed weeks, they were missing gestational age or birthweight, or if they had an improbable combination of sex-specific birthweight for gestational age, following Alexander et al. (1996). Finally, we excluded 13.9% additional observations by restricting our population to women with an LMP between 1 March 2012 and 20 February 2015 to control for truncation or fixed cohort bias (Strand et al. 2011; Wolf and Armstrong 2012). This restriction ensured that all women pregnant during the study period were included in the analysis and resulted in a final sample of $N=23{,}487$ births. Controlling for truncation bias by restricting on LMP rather than date of birth is particularly important when the start and end day of the study period are not consecutive dates (e.g., 1 January and 31 December), as is the case in our study, and when the exposure of interest is seasonal (as was the case with flaring during our study period, which exhibited some seasonality and peaked in winter).

Oil and Gas Wells

The locations of oil and gas wells were obtained from DrillingInfo (2018) (now Enverus). Our analysis included any permitted well location that had an active lease between 1990 and 2016, excluding inactive wells with a plug date or last reported production date before 1 March 2012. We calculated the number of oil or gas wells within a 5-km radius of the maternal residence as recorded in the birth record and geocoded by the Texas Department of State Health Services. The number of wells within 5 km was then categorized as none, low (1–8), medium (9–26), or high (27–954); these cutoffs corresponded roughly to quartiles of exposure.

Flares

The Nightfire algorithm developed by the National Oceanic and Atmospheric Administration (https://www.ngdc.noaa.gov/eog/viirs/) Earth Observation Group (https://payneinstitute.mines.edu/eog/) detects subpixel (<750-m) combustion sources at night based on multispectral observations obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar Partnership satellite (SNPP) (Elvidge et al. 2013). To characterize OGD-related flaring from these data we included only high-temperature observations of >1,600 K, removing lower temperature observations that are more typical of other industrial and biomass burning sources (Elvidge et al. 2016). Furthermore, we applied a hierarchical density-based spatial clustering method to differentiate flares—which tend to persist for many nights, sometimes for months—from aberrant observations, which we excluded. Details on the clustering method used to filter out aberrant observations are provided elsewhere (Franklin et al. 2019).

In the main analysis, exposure to flaring was estimated for all women residing within 5 km of an oil or gas well and was defined as the number of individual nightly flare events occurring during pregnancy within a 5-km radius of the maternal residence. Exposure to flaring was further categorized into two exposure levels based on the median of exposure among the exposed: low (1–9 flares) or high (10–562 flares). More fine-grained categorization of exposure was not possible due to the low prevalence of exposure in our population (<8%) which would have resulted in a small numbers of cases in each category of exposure and zero cells when including covariates. We also considered the total flared area (in meters squared) from all flares occurring during pregnancy within 5 km of the maternal residence and categorized this variable similarly based on the median of exposure among the exposed: low ($1–24.0\ m^2$) vs. high ($24.2–1{,}563.6\ m^2$). We considered flared area because it may be a better proxy for the volume of gas flared and, hence, the quantity of air pollutant emissions. Unlike the estimates we previously derived for flared gas volume (Franklin et al. 2019)—which were derived in aggregate for the study region and rely upon field-level, monthly self-reported administrative data from the State of Texas—flared area is available for individual nightly flare observations directly from VIIRS. Using flared area thus avoids some of the uncertainty in our flared gas volume estimates at the individual flare level and also allows our method to be more easily reproduced in other areas where data on flared gas volume may not be available. Third, we considered the inverse squared distance-weighted sum of flares within 5 km, similarly categorized based on the median of exposure among the exposed: low (4.0×10^{-8} to 1.0×10^{-6} flares/m^2) vs. high (1.0×10^{-6} to 1.0×10^{-3} flares/m^2). The inverse squared distance-weighted sum was calculated as follows:

$$\sum_{i=1}^{n}\frac{1}{d_i^2},$$

where i indexes each nightly flare observation within 5 km, d is the distance between each nightly flare and the maternal residence in meters, and n is the total number of nightly flares within 5 km.

Finally, we calculated trimester-specific estimates using our main exposure variable of the number of flares within 5 km. However, because trimester-specific and pregnancy-long exposure estimates were highly correlated (Spearman correlation coefficients of 0.73–0.79; see Figure S2), we did not conduct further analysis of trimester-specific exposures.

Outcome Measures

We investigated four outcomes: preterm birth (<37 completed weeks of gestation), SGA, continuous gestational age in days, and birthweight among term births (tBW; ≥37 completed weeks of gestation). SGA was defined as birthweight below the sex-specific 10th percentile of birthweight by gestational week based on the smoothed percentiles for U.S. singleton live births during 2009–2010 (Talge et al. 2014). SGA status was not determined for births at <22 weeks of gestation because the distributions provided in Talge et al. (2014) included only gestational ages between 22 and 44 weeks.

Statistical Analysis

We used separate multivariate linear or logistic regression models to estimate the association between flares and our four outcomes while adjusting for the following known risk factors: maternal age (in 5-y increments from <20 to ≥35 y), race/ethnicity (Hispanic, non-Hispanic white, other), nativity (U.S. or foreign born), educational attainment (<high school, high school or equivalent, >high school), prepregnancy body mass index [BMI; underweight or normal ($\leq 25\ kg/m^2$), overweight ($\geq 25–30\ kg/m^2$), or obese ($\geq 30\ kg/m^2$)], smoking (ever/never during pregnancy), insurance based on primary source of expected payment (private vs. Medicaid, self-pay, or other), parity (nulliparous vs. multiparous), high-risk pregnancy (any of the following: prepregnancy or gestational hypertension or diabetes, preeclampsia, or eclampsia), sex of infant, adequacy of prenatal care (no care, inadequate, intermediate, adequate, >adequate), year of birth (to control for secular trends), and season of birth. Models of tBW were additionally adjusted for gestational age (in weeks). Maternal BMI was calculated from recorded maternal height and weight. Because the prevalence of underweight was very low in our population (3.2%), the categories of underweight and normal BMI were collapsed. Prenatal care was characterized using the Kotelchuck or Adequacy of Prenatal Care Utilization Index, which combines the initiation of prenatal care and the number of prenatal visits to derive a ratio of observed to expected visits, with the number of expected visits based on the American College of Obstetricians and Gynecologists prenatal care standards for uncomplicated pregnancies and adjusted for the gestational age when care began and for the gestational age at delivery (Kotelchuck 1994). Women with expected primary sources of payment of self-pay or other were categorized with the publicly insured due to their low counts and because they more closely resembled those with public insurance than they did women with private insurance with respect to education, nativity, race/ethnicity, and prenatal care. Of the 23,487 births in our sample population, 23,158 included nonmissing information for all covariates and constituted the sample for the multivariate regression analyses.

Because proximity to wells has been associated with adverse birth outcomes in prior studies, and flaring does not occur at all well sites, we conducted a secondary analysis in which we included the number of wells within 5 km as an additional covariate in our models. Because prior studies suggest that women of color may be more vulnerable to air pollutant exposures (Ito and Thurston 1996; Morello-Frosch et al. 2010), we conducted a stratified analysis to examine the effects of flaring among Hispanic women and non-Hispanic white women. There were too few women of other races or ethnicities to enable additional stratification. In a post hoc analysis, we also included an indicator variable for residence in a census-designated place (in our study area, a small town or settlement, as opposed to a more rural setting) to see if rurality confounded the association between flaring and the outcomes. All statistical modeling was conducted using Stata IC (release 15.1; StataCorp).

Results

The final sample population included 23,487 births, 10.6% of which were preterm. The majority (55%) of women in the study population identified as Latina or Hispanic, 37% as non-Hispanic white, with few women identifying as non-Hispanic black (6.5%) or Asian or Pacific Islander (0.66%). Nearly 60% of women were on public health insurance (Medicaid) and 17% were foreign born. Other characteristics of the sample population are given in Table 1.

Most women (92%) were not exposed to flares within 5 km of their residence during pregnancy, whereas 74% were exposed to at least one oil or gas well within 5 km. Women who were exposed to flaring were slightly younger, less likely to be African American, less likely to be foreign born, and received lower levels of prenatal care than women who were not exposed to flaring (Table 1). The unadjusted preterm birth rate, mean gestational age, and tBW varied between women exposed to flaring and those who were not ($p < 0.0005$, $p = 0.02$ and $p = 0.06$, respectively, Pearson's chi-square or F-test), with women exposed to high levels of flaring having a higher preterm birth rate and lower mean gestational age and tBW compared with those who were not exposed (Table 2). Similar patterns were observed with respect to residential proximity to oil and gas wells (higher preterm birth rate, $p = 0.04$; shorter gestational age, $p = 0.0005$; and lower tBW, $p = 0.007$ compared with the unexposed). As expected, our outcomes also varied by the risk factors we identified *a priori*, including maternal age, education, race/ethnicity, prenatal care, smoking, insurance, high-risk pregnancy status, and parity (see Table S1).

In multivariate models, exposure to a high level of flaring was associated with a 50% higher odds of preterm birth {odds ratio (OR) = 1.50 [95% confidence interval (CI): 1.23, 1.83]} and shorter gestation [mean difference of −1.9 (95% CI: −2.8, −0.9) d] compared with no exposure (Figure 2A,C). Adjusting for the number of wells within 5 km reduced the effect estimates slightly [OR for preterm birth = 1.41 (95% CI: 1.11, 1.69); mean difference of −1.5 (95% CI: −2.4, −0.5) d] and also suggested that exposure to low levels of flaring (1–9 flares) was associated with a reduced odds of preterm birth [OR = 0.76 (95% CI: 0.60, 0.97)] (Figure 2A,C). Associations between flaring and fetal growth outcomes (SGA and tBW) were not statistically significant at $p < 0.05$ (Figure 2B,D). In models that included both the number of flares and wells within 5 km, the number of wells was a significant predictor of a higher odds of preterm birth [OR = 1.31 (95% CI: 1.14, 1.49) comparing the highest quartile vs. no exposure], shorter gestational age [mean difference of −1.3 (95% CI: −1.9, −0.8) d comparing the highest quartile vs. no exposure], as well as reduced tBW [mean difference of −19.4 (95% CI: −36.7, −2.0) g comparing the highest quartile vs. no exposure and controlling for gestational age] (see Tables S2 and S3). All other covariates generally had effect estimates in the expected direction.

When we modeled exposure to flaring as flared area within 5 km, rather than counts, results were generally consistent: Exposure to a high-flared area was associated with a 47% increased odds of preterm birth [OR = 1.47 (95% CI: 1.20, 1.79)] and a reduction in mean gestational age [−2.0 (95% CI: −3.0, −1.1) d] compared with the unexposed in models that did not adjust for the number of wells within 5 km (see Tables S4 and S5). Including the number of wells in the models again reduced these effects estimates slightly [OR for preterm birth = 1.34 (95% CI: 1.08, 1.65); mean difference of −1.7 (95% CI: −2.6, −0.7) d] (see Tables S4 and S5). Associations between exposure to a high-flared area and SGA or tBW were not statistically significant. Exposure to a low-flared area was associated with a reduced odds of preterm birth, but the association was not statistically significant at $p < 0.05$ in models with or without adjustment for the number of wells within 5 km. The number of wells remained a significant predictor of higher odds of preterm birth [OR = 1.31 (95% CI: 1.14, 1.49) comparing the highest quartile vs. no exposure], shorter gestational age [mean difference of −1.3 (95% CI: −1.9, −0.8) d comparing the highest quartile vs. no exposure], and reduced tBW [mean difference of −19.5 (95% CI: −36.8, −2.2) g comparing the highest quartile vs. no exposure and controlling for gestational age] in models of flared area. Multivariate models using our third exposure metric of inverse squared distance-weighted sum of flares within 5 km also resulted in very similar effect estimates for the associations between high exposure to flares and our four outcomes (see Tables S6 and S7).

Stratified models using our primary exposure metric suggested that the association between the number of flares within 5 km and preterm birth was present only among Hispanic women. Among Hispanics, exposure to a high level of flaring was associated with a 61% higher odds of preterm birth [OR = 1.61 (95% CI: 1.25, 2.08)] and shorter gestation [mean difference = −2.2 (95% CI: −3.4, −0.9) d] in models that controlled for the number of wells within 5 km (Figure 3A,C; see also Tables S8 and S9). Among non-Hispanic white women, the corresponding OR for preterm birth = 0.78 (95% CI: 0.50, 1.20); the corresponding mean differences in gestational age = 0.0 (95% CI: −1.5, 1.5) d (Figure 3A,C; see also Tables S8 and S9). Associations between flaring and SGA or tBW were not statistically significant in stratified models of Hispanic or non-Hispanic white women (Figure 3B,D).

Table 1. Characteristics of the study population by degree of flaring within 5 km of the maternal residence, Eagle Ford Shale, Texas, births between 19 July 2012 and 31 December 2015 ($N = 23{,}487$).

Variable	All ($N = 23{,}487$)	No flaring ($n = 21{,}635$)	Low flaring ($n = 921$)	High flaring ($n = 931$)	p-Value[a]
Age [y (mean ± SD)]	26.4 ± 5.8	26.4 ± 5.8	26.2 ± 5.7	25.9 ± 5.6	0.032
Education [n (%)]					0.15
<High school	5,318 (23)	4,907 (23)	203 (22)	208 (22)	
High school diploma/GED	7,776 (33)	7,127 (33)	306 (33)	343 (37)	
Some college or more	10,375 (44)	9,583 (44)	412 (45)	380 (41)	
Missing	18 (0.1)	18 (0.1)	—	—	
Race/ethnicity [n (%)]					<0.0005
Hispanic	12,904 (55)	11,853 (55)	488 (53)	563 (60)	
Non-Hispanic white	8,704 (37)	7,992 (37)	388 (42)	324 (35)	
Non-Hispanic black	1,535 (6.5)	1,470 (6.8)	36 (3.9)	29 (3.1)	
Non-Hispanic Asian/Pacific Islander	156 (0.7)	143 (0.7)	<10	<10	
Other, including mixed race	160 (0.7)	153 (0.7)	<10	<10	
Missing	28 (0.1)	24 (0.1)	—	<10	
Foreign born [n (%)]					<0.0005
No	19,539 (83)	17,861 (83)	822 (89)	856 (92)	
Yes	3,941 (17)	3,768 (17)	98 (11)	75 (8.1)	
Missing	<10	<10	<10	—	
BMI {kg/m^2 [n (%)]}					0.33
Underweight/normal	10,026 (43)	9,227 (43)	416 (45)	383 (41)	
Overweight	6,185 (26)	5,689 (26)	227 (25)	269 (29)	
Obese	7,106 (30)	6,559 (30)	270 (29)	277 (30)	
Missing	170 (0.7)	160 (0.7)	<10	<10	
Prenatal care [n (%)]					<0.0005
None	1,858 (7.9)	1,708 (7.9)	62 (6.7)	88 (9.5)	
Inadequate	4,227 (18)	3,834 (18)	190 (21)	203 (22)	
Intermediate	1,994 (8.5)	1,807 (8.4)	87 (9.5)	100 (11)	
Adequate	7,531 (32)	6,951 (32)	291 (32)	289 (31)	
>Adequate	7,877 (34)	7,335 (34)	291 (32)	251 (27)	
Smoking during pregnancy [n (%)]					0.69
No	22,226 (95)	20,479 (95)	867 (94)	880 (95)	
Yes	1,183 (5.0)	1,082 (5.0)	51 (5.5)	50 (5.4)	
Missing	78 (0.3)	74 (0.3)	<10	<10	
Insurance [n (%)]					0.02
Public	13,808 (59)	12,695 (59)	566 (61)	547 (59)	
Private	7,690 (33)	7,068 (33)	296 (32)	326 (35)	
Self-pay	963 (4.1)	910 (4.2)	23 (2.5)	30 (3.2)	
Other	994 (4.2)	931 (4.3)	36 (3.9)	27 (2.9)	
Missing	32 (0.1)	31 (0.1)	—	<10	
High-risk pregnancy [n (%)]	2,240 (10)	2,045 (9.5)	99 (11)	96 (10)	0.32
Parity					0.56
Nulliparous	8,243 (35)	7,611 (35)	320 (35)	312 (34)	
Multiparous	15,237 (65)	14,017 (65)	601 (65)	619 (65)	
Missing	<10	<10	—	—	
Year of birth [n (%)]					<0.0005
2012	698 (3.0)	655 (3.0)	14 (1.5)	29 (3.1)	
2013	7,471 (32)	6,765 (31)	444 (48)	262 (28)	
2014	8,088 (34)	7,474 (35)	316 (34)	298 (32)	
2015	7,230 (31)	6,741 (31)	147 (16)	342 (37)	
Season of birth [n (%)]					0.38
Spring (MAM)	5,443 (23)	5,002 (23)	218 (24)	223 (24)	
Summer (JJA)	6,229 (27)	5,727 (26)	268 (29)	234 (25)	
Fall (SON)	5,974 (25)	5,505 (25)	218 (24)	251 (27)	
Winter (DJF)	5,841 (25)	5,401 (25)	217 (24)	223 (24)	
Residence in census-designated place [n (%)]	11,883 (51)	10,809 (50)	475 (52)	599 (64)	<0.0005

Note: Cells with counts <10 have been suppressed. Percents may not sum to 100 due to rounding. Exposure to flaring was defined based on the median number of flares within 5 km during pregnancy among the exposed (low: 1–9, high: ≥10). —, No data; BMI, body mass index; DJF, December, January, February; GED, general education development; JJA, June, July, August; MAM, March, April, May; SD, standard deviation; SON, September, October, November.

[a]Pearson's chi-square test or F-test by level of flaring exposure.

Our post hoc sensitivity analysis including residence in a census-designated place in the main preterm birth model did not change the magnitude, direction, or statistical significance of effect estimates. The coefficients for census-designated place was also not statistically significant (see Table S10).

Discussion

As far as we are aware, this is the first study to examine the potential effects of flaring from oil and gas extraction on human health. Our retrospective cohort study of births between 2012 and 2015 in the Eagle Ford Shale region of south Texas suggests that prenatal exposure to flaring from OGD is associated with a significant increase in the risk of preterm birth and a shorter length of gestation among pregnant women living nearby. Because we included the number of oil and gas wells in our models, our findings suggest the effects of flaring on the length of gestation are independent of other potential exposures related to oil and gas wells.

Our stratified analysis suggested that Hispanic women were vulnerable to the effects of flaring on preterm birth, whereas non-Hispanic white women were not. As far as we are aware, this is the

Table 2. Birth outcomes by degree of flaring during pregnancy and number of oil and gas wells within 5 km of the maternal residence, Eagle Ford Shale, Texas, 2012–2015 ($N = 23,487$).

	Flares within 5 km				Wells within 5 km				
	0 ($n = 21,634$)	Low ($n = 921$)	High ($n = 931$)	p-Value[a]	0 ($n = 6,176$)	Low ($n = 6,215$)	Medium ($n = 5,482$)	High ($n = 5,614$)	p-Value[a]
Preterm birth [n (%)]	2,269 (10.5)	81 (8.8)	131 (14.1)	<0.0005	598 (9.7)	656 (10.6)	618 (11.3)	609 (10.9)	0.04
Small for gestational age [n (%)]	2,224 (10.3)	86 (9.3)	94 (10.1)	0.65	635 (10.3)	648 (10.4)	574 (10.5)	547 (9.7)	0.56
Gestational age [weeks (mean ± SD)]	38.5 ± 2.1	38.6 ± 1.9	38.3 ± 2.2	0.02	38.6 ± 2.1	38.5 ± 2.2	38.5 ± 2.2	38.5 ± 2.1	0.0005
Term birthweight [g (mean ± SD)]	3,284 ± 543	3,288 ± 509	3,241 ± 529	0.06	3,301 ± 545	3,282 ± 548	3,268 ± 540	3,276 ± 529	0.007

Note: Exposure to flaring was defined based on the number of nightly flares (low: 1–9, high: 10–562), with the cutoff corresponding to the median of exposure among the exposed. The number of wells was categorized as zero, low (1–8), medium (9–26), or high (27–524), with cutoffs corresponding roughly to quartiles of exposure. SD, standard deviation.
[a]Pearson's chi-square test or F-test by level of exposure.

first study to document greater health impacts associated with OGD among women of color. A history of government-sanctioned discrimination in housing, employment, and education have led Hispanics in Texas to be socioeconomically disadvantaged, with a 2014 median household income of \$41,177 compared with \$65,786 for non-Hispanic whites and with a greater proportion living below the federal poverty level (23% vs. 9.3% among non-Hispanic whites) (Texas Health and Human Services Commission 2014). Reasons why women of color and lower socioeconomic status may experience greater vulnerability to flaring could relate to differences in preexisting health status (because income and education are directly related to health); greater co-exposures to other pollutants (e.g., because pollution sources are disproportionately located in communities of color); a compromised ability to cope with the adverse effects of pollution due to poor nutrition or limited access to health care, preventative or social services; and modifying effects of psychosocial stress associated with living in poverty or experiencing discrimination. Belonging to a racial or ethnic group that experiences systemic discrimination may confer greater vulnerability due to the physiological effects of chronic psychosocial stress (Geronimus 1992). Evidence suggests that chronic stress can result in physiological wear and tear on the body that can increase vulnerability to environmental stressors by impairing immune function, increasing the absorption of toxicants (McEwen 1998), by compromising the body's defense systems, or by directly causing illness or affecting the same physiological process as the environmental toxicant (Clougherty and Kubzansky 2009; Gee and Payne-Sturges 2004; Gordon 2003; Morello-Frosch and Shenassa 2006). Although we were not able to directly examine stress or say why Hispanic women in our study were more vulnerable, our findings are consistent with prior studies that found socially disadvantaged women—including African Americans and residents of socioeconomically disadvantaged neighborhoods—are more vulnerable to the impacts of ambient air pollution, including larger reductions in birth weight associated with exposure to particulate matter (Erickson et al. 2016; Morello-Frosch et al.

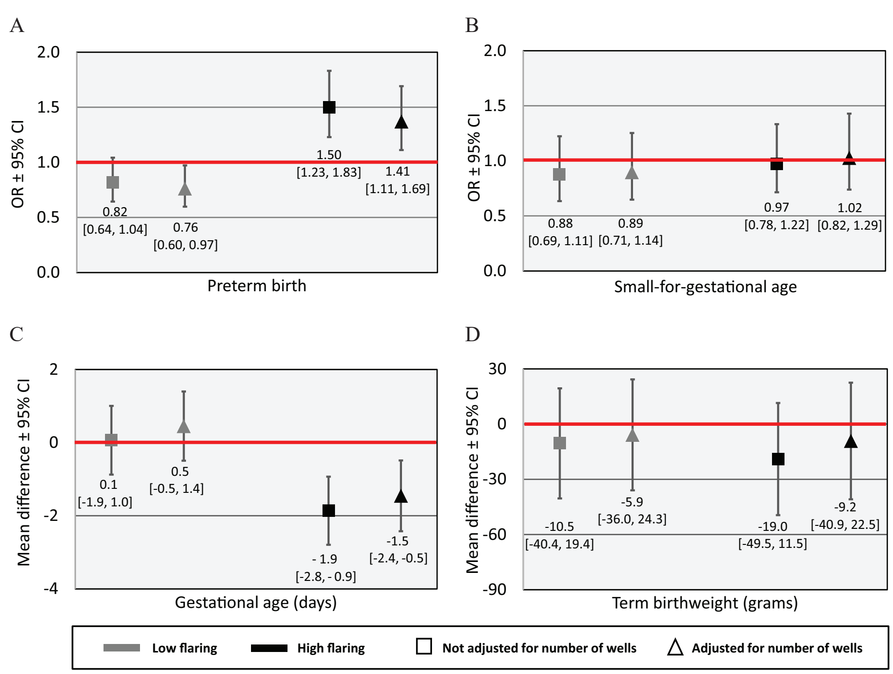

Figure 2. Estimated associations between the number of flares within 5 km of maternal residence and (A) the odds of preterm birth, (B) the odds of small-for-gestational age birth, (C) gestational age, and (D) term birthweight, Eagle Ford Shale, Texas, 2012–2015 ($N = 23,158$). Full numeric data for models that are unadjusted (Model 1) and adjusted (Model 2) for the number of oil and gas wells within 5 km are provided in Tables S2 and S3. Figures show effect estimate and 95% CIs comparing infants with prenatal exposure to a low (1–9) and high (10–562) number of nightly flare events within 5 km of the maternal residence to unexposed infants. All estimates are adjusted for maternal age, race/ethnicity, nativity, education, prepregnancy BMI, smoking, insurance, parity, high-risk pregnancy, infant sex, prenatal care, year of birth, and season of birth. Models of term birthweight additionally controlled for gestational age. Red lines indicate the null. Note: BMI, body mass index; CI, confidence interval; OR, odds ratio.

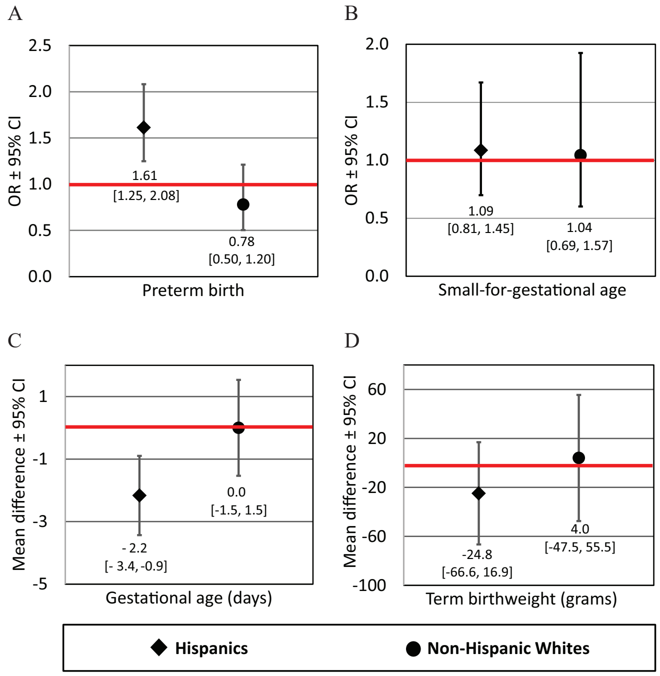

Figure 3. Estimated associations from models stratified by ethnicity between the number of flares within 5 km of maternal residence and (A) the odds of preterm birth, (B) the odds of small-for-gestational age birth, (C) gestational age, and (D) term birthweight, Eagle Ford Shale, Texas, 2012–2015 ($N = 12{,}781$, Hispanic women and $N = 8{,}566$ non-Hispanic white women). Full numeric data are provided in Tables S8 and S9. Figures show effect estimates and 95% CIs comparing infants with prenatal exposure to a low (1–9) and high (10–562) number of nightly flare events within 5 km of the maternal residence to unexposed infants. All estimates are adjusted for the number of oil and gas wells within 5 km, maternal age, nativity, education, prepregnancy BMI, smoking, insurance, parity, high-risk pregnancy, infant sex, prenatal care, year of birth, and season of birth. Models of term birthweight additionally control for gestational age. Red lines indicate the null. Note: BMI, body mass index; CI, confidence interval; OR, odds ratio.

2010; Westergaard et al. 2017). In addition, it is possible there is a threshold effect of flaring and that the lack of an association among non-Hispanic white women that we observed may have been the result of the fact that they were exposed to a lower average number of nightly flare events than Hispanic women (mean of 24.1 vs. 36.3 among the exposed).

We found no evidence of an association between flaring and SGA or reduced birthweight among term infants when controlling for gestational age. The lack of strong associations with these outcomes may be due to a lack of a true effect on fetal growth independent of gestational age or to power limitations resulting from the low prevalence of exposure to flaring in our study population. For example, given the prevalence of SGA (10.2%) and exposure to flaring (7.9%) in our study population, we estimate that we had power of only 0.52 to detect a true OR of 1.2 at $\alpha = 0.05$.

We found that women exposed to low levels of flaring had a reduced odds of preterm birth compared with women with no exposure in models that controlled for well density. This counterintuitive finding was no longer statistically significant when we measured exposure to flaring on the basis of flared area or the inverse squared distance-weighted sum of nightly flare events, which may better approximate the quantity and proximity of flared gas than the number of flares, suggesting the association may have been spurious, or the result of a threshold or nonlinear effect that we were not able to estimate given the small number of exposed women in our sample (<8%). It is also possible that low levels of flaring may appear protective because women exposed to low levels of flaring live in more rural settings than those exposed to no flaring [median (mean) population density = 180 (699) people per square kilometer for the low-flare group vs. 452 (1,063) for the no-flare group] and are, therefore, less exposed to other pollutants such as traffic-related air pollution, resulting in residual confounding. However, a lack of regulatory air pollution monitoring in our study region prohibits us from being able to further assess this potential source of bias. Adding an indicator variable for residence in a census-designated place (in our study area, a small town, as opposed to a more rural setting) to our models in a post hoc analysis did not change the magnitude, direction, or statistical significance of effect estimate for the association between low levels of flaring and preterm birth (see Table S9).

In addition to flaring, we also found that living within 5 km of oil and gas wells was independently associated with adverse birth outcomes, including a higher odds of preterm birth, reduced gestational age, and reduced tBW, controlling for gestational age. The association with preterm birth is consistent with previous studies from Pennsylvania and Northern Texas in areas of OGD but absent of significant flaring activity (Casey et al. 2016; Whitworth et al. 2018). Other studies from Southwest Pennsylvania, Colorado, and California have found no evidence of such an association with preterm birth (Mckenzie et al. 2014; Stacy et al. 2015; Tran et al. 2020). In contrast to our findings, the majority of previous studies have found little evidence of an association between residential proximity to OGD and birthweight, with the exception of Stacy et al. (2015) and Tran et al. (2020). Our contrasting findings could be related to differences in our study design and the nature of OGD in the Eagle Ford Shale, which includes significant oil as well as gas production and conventionally drilled as well as unconventionally drilled wells. (With the exception of the California study, prior studies have focused on natural gas wells that were unconventionally drilled.)

Our findings hold broader implications for other populations exposed to flaring from OGD. Flaring activity has increased dramatically in the United States over the last five years, spiking by nearly 50% in 2018 from the previous year, the largest absolute gains of any country (World Bank 2019). Beyond the Eagle Ford Shale, flaring is common in the Permian Basin of West Texas and Eastern New Mexico as well as the Bakken Shale of North Dakota and Western Montana. In fact, a recent study suggests that as of 2015, the Permian Basin has had more flare activity and appears to flare larger volumes, on average, than the Eagle Ford play (Willyard and Schade 2019). In the Bakken Shale play, it is estimated that 28% of North Dakota's total produced natural gas was flared (Gvakharia et al. 2017). The health impacts of flaring therefore warrant additional study, and our findings require replication in other populations. Prior work has demonstrated associations between flaring and increased risk of stillbirth among cattle as well as increased risk of calf mortality (Bamberger and Oswald 2012). However, we are unaware of any previous studies assessing the health impacts of flaring from OGD among humans.

We utilized a novel exposure metric derived from infrared satellite observations that provides an objective, highly spatially and temporally resolved measure of flaring activity. In places such as our study region, where industrial activity is minimal, combustion sources detected using this method are unlikely to come from sources other than flaring. This approach provides distinct advantages over alternative available measures of flaring, including self-reported regulatory data, which is likely to underestimate the magnitude of flaring and is provided only in the aggregate (monthly, lease-level). However, our measure only indirectly reflects potential exposures, including air pollutant emissions. We are, therefore, unable to determine the mechanism(s) through which flaring may adversely affect birth outcomes. Monitoring studies have indicated that incomplete combustion during the flaring process can release a variety of air pollutants, including particulate matter, which has been linked to preterm birth and reduced fetal growth in other contexts (Ballester et al. 2010; Brauer et al. 2008; Dadvand et al. 2013). However, there is a lack of air pollutant monitoring data in areas with flaring due to OGD, which are primarily rural.

Because we relied on live birth records, we were unable to assess potential effects of flaring on the risk of miscarriage. We were also unable to examine critical windows of exposure due to the high correlation between pregnancy-long and trimester-specific estimates of exposure to flaring in our population. Another limitation of our study is that we were unable to capture maternal mobility because only the birth mother's place of residence at the time of birth is recorded in the birth records. Prior studies have suggested that ignoring residential mobility may bias associations toward the null due to nondifferential exposure misclassification, and that moving distances during pregnancy are typically relatively short and within the same county (Bell and Belanger 2012; Chen et al. 2010; Hodgson et al. 2015; Lupo et al. 2010; Miller et al. 2010; Pennington et al. 2017).

Together, our findings suggest that living within 5 km of OGD wells and flaring activity may have had a significant adverse effect on birth outcomes among pregnant women in the Eagle Ford region. The fact that much of the region is low income and approximately 50% of residents living within 5 km of an oil or gas well are people of color raises environmental justice concerns about the potential health impacts of the oil and gas boom in south Texas (Johnston et al. 2016). Measures to minimize flaring—such as more stringent regulation of flaring or investments in renewable energy and energy efficiency measures that reduce reliance on fossil fuels overall—could protect the health of infants.

Acknowledgments

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EXHIBIT 9

Examination of Groundwater Resources in Areas of Wyoming
Proposed for the June 2022 BLM Lease Sale

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May 11, 2022

PSE Bringing science to energy policy

About PSE Healthy Energy

PSE Healthy Energy is a multidisciplinary, nonprofit research institute dedicated to supplying evidence-based scientific and technical information on the public health, environmental, and climate dimensions of energy production and use.

About the Authors

Dr. DiGiulio is a senior research scientist at Physicians, Scientists, and Engineers (PSE) for Healthy Energy and an affiliate at the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado. Dr. DiGiulio completed a B.S. in environmental engineering at Temple University, a M.S. in environmental science at Drexel University, and a Ph.D. in soil, water, and environmental science at the University of Arizona. During his 31 years with the U.S. Environmental Protection Agency (EPA), he conducted research on gas flow-based subsurface remediation (soil vacuum extraction, bioventing), groundwater sampling methodology, soil-gas sampling methodology, gas permeability testing, intrusion of subsurface vapors into indoor air (vapor intrusion), subsurface methane and carbon dioxide migration (stray gas), and solute transport of contaminants in soil and groundwater including that associated with hydraulic fracturing and pits used to dispose oil and gas waste. He assisted in development of EPA's original guidance on vapor intrusion and the EPA's Class VI Rule on geologic sequestration of carbon dioxide. While with the EPA, he routinely provided technical assistance to EPA regional offices and assisted in numerous enforcement actions. The focus of his current work is on understanding environmental impact from oil and gas development in the United States and abroad, especially in regard to surface and groundwater resources. He served as an expert witness in litigation relevant to oil and gas development, testified before State oil and gas commissions on proposed regulation, and testified before Congress on the impact of oil and gas development on water resources.

Dr. Tisherman completed a B.A. in Environmental Studies from Connecticut College in 2013 and received Ph.D. in Geology and Environmental Science at the University of Pittsburgh in January 2022. Her dissertation focused on the transport and fate of trace metal-contaminated sediments. Specifically, her research focused on the mobilization of contaminated sediments from mining, oil and gas production, and agriculture in the US and in China. Through her research, Dr. Tisherman has worked to create a chemical framework that differentiates between various sources of oil and gas water contamination. Prior to graduate school, Dr. Tisherman researched the impacts of unconventional drilling on surface water in Chengdu, China as a U.S. Fulbright Scholar. Her current work is on the water impacts from oil and gas activities.

Dr. Rossi completed a B.S. in Civil and Environmental Engineering from Penn State in 2009 and received his Ph.D. in Geology and Environmental Science at the University of Pittsburgh in 2016. His dissertation research focused on soil biogeochemistry and how land use and human activities affect hydrologic regimes, and by extension, major and trace metal dynamics. Following the completion of his dissertation, Dr. Rossi was a visiting scholar at the University of Pittsburgh and devised a project to reconstruct the environmental legacy of industrial activities and coal-fired electricity generation in Pittsburgh. Dr. Rossi held his first postdoctoral appointment in 2017 at Temple University, where he examined the impact of land use and green infrastructure on hydrology within the Philadelphia Metropolitan Area. In 2017 Dr. Rossi was awarded a NatureNet Science Fellowship with the Nature Conservancy and conducted postdoctoral research on oxygen dynamics in agricultural soils at Stanford University. Dr. Rossi's current work is on the impact of produced water from oil and gas activities on groundwater systems.

Background

The Bureau of Land Management (BLM) Office is proposing to offer 129 parcels covering approximately 132,771 acres for oil and gas leasing in Wyoming (U.S. Bureau of Land Management, 2022a). The BLM is planning on starting bidding for the parcels on June 21, 2022 and has already started a 30-day public protest period on April 18, 2022. The proposed parcels are located in Big Horn, Campbell, Carbon, Converse, Crook, Fremont, Hot Springs, Johnson, Laramie, Natrona, Niobrara, Park, Sheridan, Sublette, Sweetwater, Uinta, and Washakie counties (Table 1, Figure 1) (U.S. Bureau of Land Management, 2022b). The sale of these parcels for further oil and gas development could impact groundwater resources in Wyoming. The BLM Onshore Oil and Gas Order No. 2 states, "The proposed casing and cementing programs shall be conducted as approved to protect and/or isolate all usable water zones…Determination of casing setting depth shall be based on all relevant factors, including: presence/absence of hydrocarbons; fracture gradients; usable water zones…All indications of usable water shall be reported" (U.S. Bureau of Land Management, 1988). Usable water, according to the BLM Onshore Order No. 2 is "generally those waters containing up to 10,000 ppm (mg/L) of total dissolved solids (TDS)." It is assumed then that for wells constructed on these proposed parcels: 1) the depth of usable water needs to be known and 2) the constructed wells need to have cemented casing at all depths of usable water.

Overall, the Environmental Assessment (EA) for the June 2022 Competitive Lease Sale is contradictory and nebulous in statements regarding protections of usable water, in particular, with depths of cementing and casing. Specifically, section 3.4 of the EA states that "BLM would deny any APD where proposed drilling and/or completion process was deemed to not be protective of usable water zones as required by 43 CFR 3162.5-2(d)," and goes on to require multiple protective barriers: "(1) setting surface casing below all known aquifers and cementing the casing to the surface, and (2) extending the casing from the surface to the production or injection interval and cementing the interval." Contradictorily, the BLM also states in the same section, that "impacts to the quality of groundwater, should they occur, would likely be limited to a near wellbore location due to inferred groundwater flow conditions in the area" In short, the EA says that the BLM would deny proposed drilling if the process was not protecting usable water, but then downplays the potential impacts to usable water. The EA does not state the depths of potential usable water aquifers in proposed parcel areas, nor does it instill confidence that cementing requirements will be enforced to protect these aquifers.

This study aims to identify potential pathways for groundwater impacts based on regional hydrogeology, schematic data of existing federal wells, and identifying aquifers with usable water near proposed parcels.

Table 1 - Proposed oil and gas parcels for competitive lease sale in June 2022 with the BLM field office, the number of parcels per field office, and the acreage of the parcels per field office. Note that the available data from the BLM website used in this analysis has 130 parcels and a total of 136,132 acres in proposed parcels.

Field Office	Number of Parcels	Acres
Buffalo	45	40,257
Casper	16	10,837
Cody	5	4,296 (including 3 parcels/2,869 acres shared with the Worland field office)

Lander	17	15,890
Newcastle	3	681
Pinedale	16	21,095 (including 2 parcels/4,160 acres shared with the Rock Springs field office)
Rawlins	4	2,616
Rock Springs	17	31,850
Worland	7	8,506

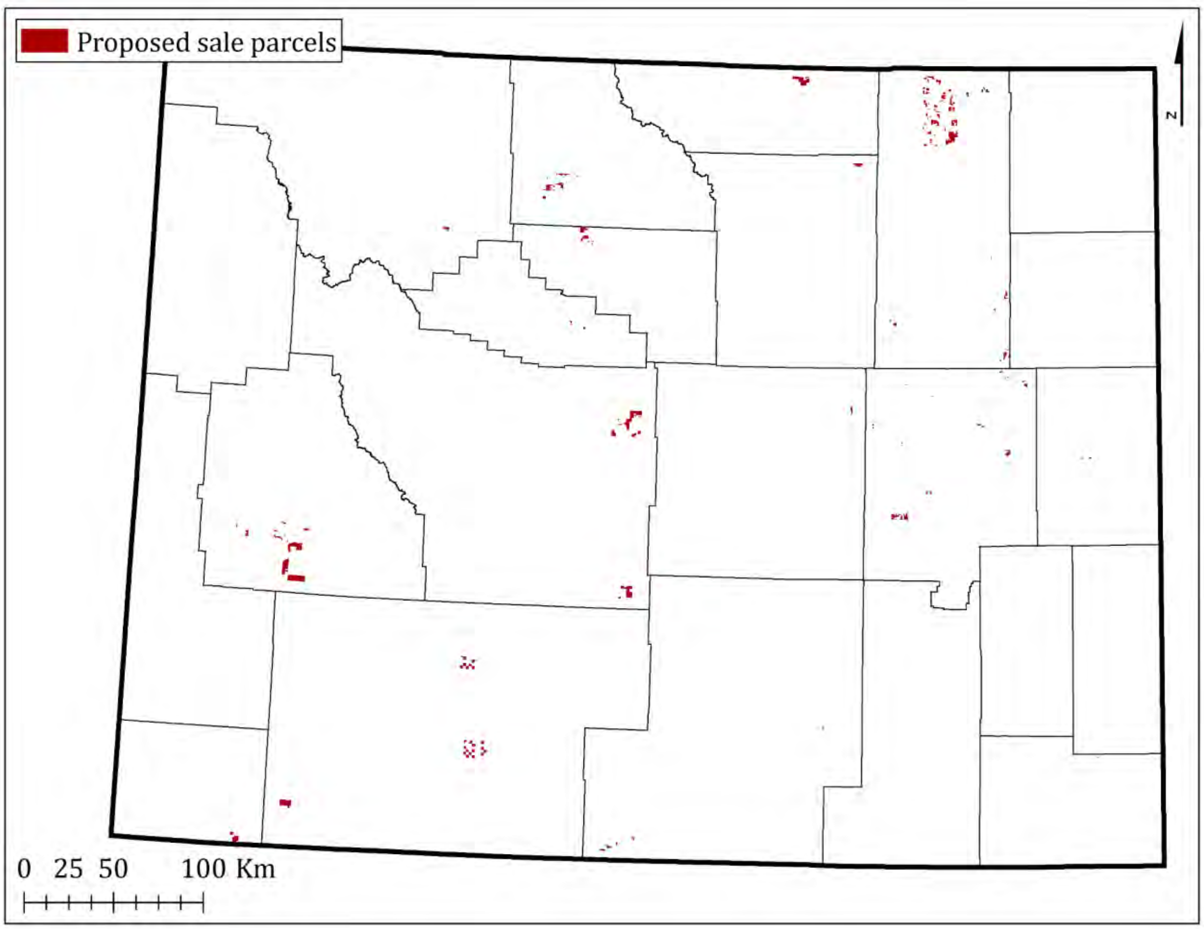

Figure 1 - Proposed oil and gas parcels for competitive lease sale in June 2022.

Methods

The goal of this analysis is to: 1) identify zones of usable water (TDS < 10,000 mg/L) around the proposed parcels and 2) determine if current federal wells are actively protecting usable water in the same areas. To accomplish our first goal, we reviewed peer-reviewed literature and government reports (primarily U.S Geological Survey) to find depths of potential usable water aquifers in the sedimentary basins underneath the proposed parcels. Then, we identified principal aquifers in Wyoming within 3,000 feet below the land surface using the U.S. Geological Survey (USGS) Brackish Water Database (Stanton et al., 2017). The combination of the basin aquifer and principal aquifer analysis will result in a total stratigraphic view of potential usable water aquifers.

After the potential usable water aquifers were identified, data on existing federal oil and gas wells near the proposed parcels was used to find gaps in surface casing and top of cement. These gaps are potential pathways for contamination of usable water in existing wells. Due to time constraints, the well analysis was conducted only for the Powder River basin, which contains the largest number of proposed parcels. First, we reviewed the U.S. Environmental Protection Agency's (EPA) aquifer exemption database to distinguish areas where proposed parcels and aquifer exemptions overlap (U.S Environmental Protection Agency, 2017). An aquifer exemption is necessary for injection of waste fluids in formations with water having TDS concentrations <10,000 mg/L. The lease parcels in aquifer exemption zones were removed from this analysis as those aquifers do not have the same protections as non-exempt aquifers. Next, we found the public land surface system (PLSS) township and range for each proposed parcel in ArcGIS 10.8.1 (Wyoming Geospatial Hub, 2017). Using the PLSS township and range, we identified all federal wells with a proposed parcel on the Wyoming Oil and Gas Conservation Commission (WOGCC) website that was completed after January 1, 2000, and active in the last 5 years (i.e., since January 1, 2017) (WOGCC, 2022). For each well, the bottom of the surface casing and top of cement was extracted from the well completion report, and the uncemented interval was calculated by taking the difference of these two depths.

Hydrogeologic Setting

The proposed oil and gas parcels are in the Bighorn, Powder River, Wind River, Green River, Hanna, and Denver-Cheyenne Basins (Figure 2). The depths of aquifers within these basins are important to consider because the BLM Onshore Oil and Gas Order No. 2 requires proposed casing and cementing programs to protect and/or isolate all usable water zones (U.S. Bureau of Land Management, 1988). This section includes a description of the hydrogeology of the primary basins with proposed parcels.

Powder River Basin

Multiple aquifer systems are present throughout the Powder River Basin, with the two uppermost principal aquifers (in order of depth) being the lower Tertiary and Upper Cretaceous aquifers (Long et al., 2014). These systems contain all groundwater resources in the Powder River Basin (Thamke et al., 2014). With the exception of the basin margins, these are primarily confined units. However, shallow aquifers within the lower Tertiary geologic units are characterized by local flow systems (Whitehead, 1996). Recharge occurs primarily via precipitation falling on outcropping portions of geologic units, or from stream leakage (Whitehead, 1996). Regional groundwater flow is south to north into the adjacent Williston structural basin (Thamke et al., 2014). The depth to water in the unconfined portions of the Lower Tertiary and Upper Cretaceous aquifer systems ranges from 0–2,497 ft (mean depth =228 ft), and is shallow near streams and deeper in upland areas (Long et al., 2014).

The lower Tertiary aquifer system may be as thick as 7,180 feet in the Powder River Basin, and the hydrogeologic units comprising this system (in order of depth) include the Upper Fort Union aquifer (comprised of the Eocene age Wasatch Formation and upper Paleocene age Tongue River Member), the Middle Fort Union hydrogeologic unit (middle Paleocene age Lebo Shale Member), and the Lower Fort Union aquifer (lower Paleocene age Tullock Member) (Long et al., 2014) (Table 2). Thicknesses of the Upper Fort Union aquifer, Middle Fort Union hydrogeologic unit, and Lower Fort Union aquifer, range from 0–4,458, 0–3,643, and 0–2,913, feet, respectively (Thamke et al., 2014) (Table 2). Ranges of hydraulic conductivities are the largest within the Upper Fort Union aquifer (Table 2).

The Upper Fort Union aquifer is comprised of massive cross bedded sandstone, sandy mudstone, gray shale, carbonaceous shale, and thick coal beds (McLelland, 1992) that were deposited in an alluvial plain draining the young Rocky Mountains (Thamke et al., 2014). The Middle Fort Union hydrogeologic unit is comprised of alternating beds of sandstone, siltstone, mudstone, and claystone (Murphy, 2001), which were deposited in a large freshwater lake that received sediments eroded by the Bighorn mountains (McLelland, 1992). The Lower Fort Union aquifer consists of sandstones and sandy mudstones composed of continental, marine, non lignite, and clastic deposits (Cvancara, 1976a). Alternating brown and gray beds of sandstone, siltstone, claystone, mudstone, and lignite are also present (Murphy, 2001; Rigby and Rigby, 1990).

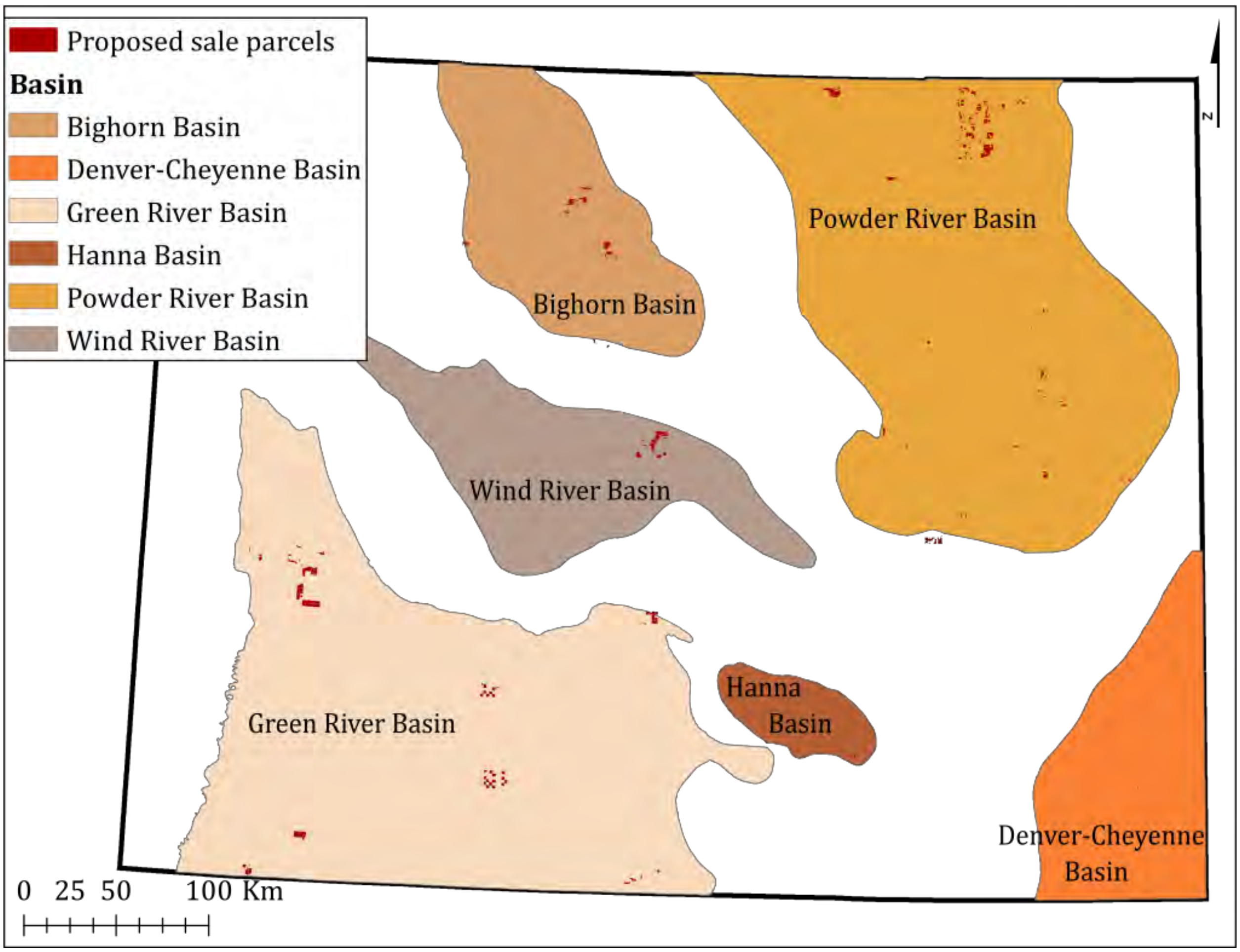

Figure 2 - Wyoming basins with proposed oil and gas parcels.

Table 2. Description of groundwater resources in the Powder River structural basin, modified from Long et al. (2014) and Thamke et al. (2014).

Period[a]	Epoch[a]	Principal aquifer system[a]	Lithostratigraphic unit[a]	Hydrogeologic unit[a]	Thickness (feet)[b]	Horizontal hydraulic conductivity (feet/day)[b]
Tertiary	Eocene	Lower Tertiary aquifer system	*Wasatch Fm*	*Upper Fort Union aquifer*	0–4,458	0.23–11
	Paleocene		*Tongue River Mbr*			
			Lebo Shale Mbr	*Middle Fort Union hydrogeologic unit*	0–3,643	0.10–7.1
			Tullock Mbr	*Lower Fort Union aquifer*	0–2,913	0.26–6.4
Cretaceous	Upper Cretaceous	Upper Cretaceous aquifer system	*Lance Fm (upper part)*	*Upper Hell Creek hydrogeologic unit*	0–3,002	0.03–5.7
			Lance Fm (lower part)	*Lower Hell Creek aquifer*	0–3,274	0.02–1.4
			Fox Hills Fm	*Fox Hills aquifer*		
			Pierre Shale	*Basal confining unit*		

[a]Long et al. (2014)
[b]Thamke et al. (2014)

The Upper Cretaceous aquifer system may be as thick as 5,070 feet in the Powder River Basin, and the hydrogeologic units comprising this system (in order of depth) include the Upper Hell Creek hydrogeologic unit (comprised of the upper part of the Lance Formation), the Lower Hell Creek aquifer (comprised of the lower part of the Lance Formation), and the Fox Hills aquifer (Fox Hills Formation) (Long et al., 2014) (Table 2). Thicknesses of the Upper Hell Creek hydrogeologic unit, and combined Lower Hell Creek aquifer and Fox Hills aquifer (subsurface contacts for these units have not been mapped in the Powder River Basin), range from 0–3,002 and 0–3,274, feet, respectively (Thamke et al., 2014) (Table 2). While minimum hydraulic conductivity values are relatively similar between the Upper Hell Creek and combined Lower Hell Creek/Fox Hills aquifers, the Upper Hell Creek hydrogeologic unit has been observed to have higher maximum hydraulic conductivity values (Thamke et al., 2014) (Table 2).

Both the Upper Hell Creek hydrogeologic unit and Lower Hell Creek aquifer are composed of alternating layers of mudstone, siltstone, sandstone, and sparse lignite beds (Thamke et al., 2014). In general, the relative percentage of sandstone is used to differentiate between these units, with the Upper Hell Creek having smaller percentages than those of the Lower Hell Creek and is determined using resistivity logs (Thamke et al., 2014).The Upper Hell Creek hydrogeologic unit consists of fluvial sediments deposited by meandering channels with point bars and channel plugs, whereas the Lower Hell Creek exhibits channel deposits and erosional surfaces (Flores, 1992). The Fox Hills aquifer consists of marine mudstones, siltstones, and sandstones deposited in a near-shore deltaic plain (Cvancara, 1976b; Murphy, 2001).

Green River Basin

The Green River and Wasatch formations in the Green River structural basin have complex lacustrine and fluvial lithologies deposited from lake-level fluctuations in an ancient lake environment (Bartos et al., 2015). Aquifers in these layered sedimentary rocks are often used as water sources in the Green River basin. The geohydrologic units of Tertiary rocks containing aquifers in the Green River basin consist of four major aquifers (localized and smaller aquifers are considered part of the major aquifer) and two confining units (Martin, 1996). In descending order, the aquifers are: Bridger aquifer, Laney aquifer, New Fork/Farson Sandstone Alkali Creek aquifer, and Wasatch-Fort Union (Martin, 1996). The confining units are the Wilkins Peak and Tipton, separating the Bridger and Laney aquifers from the New Fork/Farson Sandstone Alkali Creek aquifer and Wasatch-Fort Union aquifers (Bartos et al., 2015; Martin, 1996). The Wasatch-Fort Union is subdivided into two zones, the Wasatch zone and the Fort Union zone due to differences in hydrologic properties across the Green River basin (Martin, 1996).

The Bridger aquifer is at the surface and is generally less than 1,000 ft thick but in the southern Green River basin can be up to 1,500 ft thick (Martin, 1996). The Laney aquifer is underneath the Bridger aquifer so it can start at the surface or 1,500 ft bls (below land surface), and is typically 100 to 600 feet thick, but exceeds 1,000 feet thick in the south-central part of the Green River Basin (Martin, 1996). The Wilkins Peak confining unit then separates the Laney aquifer from the New Fork/Farson Sandstone Alkali Creek aquifer (Bartos et al., 2015). The confining unit is generally 100 to 600 feet thick but exceeds 1,000 feet in the southeastern part of the basin (Martin, 1996). The New Fork/Farson Sandstone-Alkali Creek aquifer is typically 350 ft thick and is only located in the central basin. The Tipton confining unit underlies New Fork/Farson Sandstone-Alkali Creek aquifer in the central basin and the Wilkins confining unit elsewhere. The confining unit ranges from 30 to 150 ft thick (Martin, 1996). The rocks in the Wasatch and Fort Union zone have a total thickness of up to 11,000 ft but generally range from 2,000 to 7,000 ft thick (Martin, 1996). Groundwater in the Tertiary aquifer system in general flows from high altitude recharge locations towards lower altitudes in the basin (Bartos et al., 2015). Most wells completed in the lower Tertiary aquifer in the Green River basin are for stock use.

Wind River Basin

The Wind River Basin (WRB) is one of many structural and sedimentary basins that formed in the Western Interior Seaway during the Late Cretaceous through early Eocene(Finn, 2007a, 2007b). The WRB is fault-bounded by Laramide uplifts with Washakie Range, Owl Creek Mountains, and southern Bighorn Mountains to the north, the Wind River Range to the west, the Granite Mountains to the south, and Casper arch to the east (Finn, 2007a, 2007b; Johnson et al., 2007; L. N. R. Roberts et al., 2007). Igneous and metamorphic rocks of Precambrian age comprise the core of the mountain ranges and underlie sedimentary rocks within the basin. The center part of the basin is filled with nearly horizontal fluvial and lacustrine Quaternary and Cenozoic Tertiary age sediment, overlying Paleozoic and Mesozoic age rocks.

Hydrocarbon production in the WRB is primarily from the Paleocene Fort Union and overlying Early Eocene Wind River Formation. The Fort Union Formation is divided into two general lithologic units. The lower unnamed member has conglomerates, sandstone, shale, claystone, and siltstone deposited under various fluvial depositional systems (Courdin and Hubert, 1969; Flores and Keighin, 1993; Johnson et al., 2007; Keefer, 1969). The upper unit is divided into two laterally equivalent members – the Waltman Shale and the Shotgun members (Keefer, 1965). The Waltman Shale is a lacustrine deposit in the central portion of the WRB that formed from an extensive body of water that developed in the basin during late Paleocene time (S. B. Roberts et al., 2007). The Shotgun Member is a marginal lacustrine deposit that formed in fluvial and shoreline areas that expanded during the late Paleocene (Keefer, 1965) and is dominated by siltstones, mudstones, carbonaceous shales, coals, and subordinated sandstones (Flores and Keighin, 1993).

The Wind River and Fort Union Formations are variably saturated fluvial depositional systems characterized by shale and fine-, medium-, and coarse-grained sandstone sequences. Lithology is highly variable and difficult to correlate from borehole data. No laterally continuous confining layers of shale exist below the maximum depth of groundwater used to confine upward solute migration. The Wind River Formation is the major aquifer system in the WRB (Daddow, 1996). The Fort Union Formation is highly productive and permeable where fractured with TDS values from 1,000 to 5,000 mg/L (McGreevy et al., 1969).

Bighorn Basin

In the Bighorn Basin, Cenozoic rocks consist of sandstone and shale with depth to groundwater ranging from 2 to 200 ft bls (Hinckley et al., 1982; Plafcan et al., 1993). The Lance, Mesaverde, and Frontier formations in the Mesozoic bedrocks are the aquifers with the most potential for water supply development in the Bighorn Basin. Wells in these formations range from 5 to 200 ft bls (Plafcan et al., 1993). The Tensleep Sandstone, Madison Limestone, Bighorn Dolomite are in the Paleozoic bedrock and yield the most abundant water supplies (Hinckley et al., 1982; Plafcan et al., 1993). These three aquifers generally recharge from mountains around the Bighorn Basin. The Tensleep sandstone is a well-sorted fine to medium-grained sandstone cemented by carbonate and silica and ranges from 50 to 200 ft thick. Groundwater elevation in the Tensleep sandstone can range from flowing aboveground to 1,000 ft bls (Plafcan et al., 1993). The Madison Limestone contains limestone, dolomite, and thin chert beds, and ranges from 500 to 800 ft thick. The Bighorn Dolomite ranges from 350 to 450 ft thick. The Madison-Bighorn aquifer ranges from 95 to 490 ft bls (Plafcan et al., 1993).

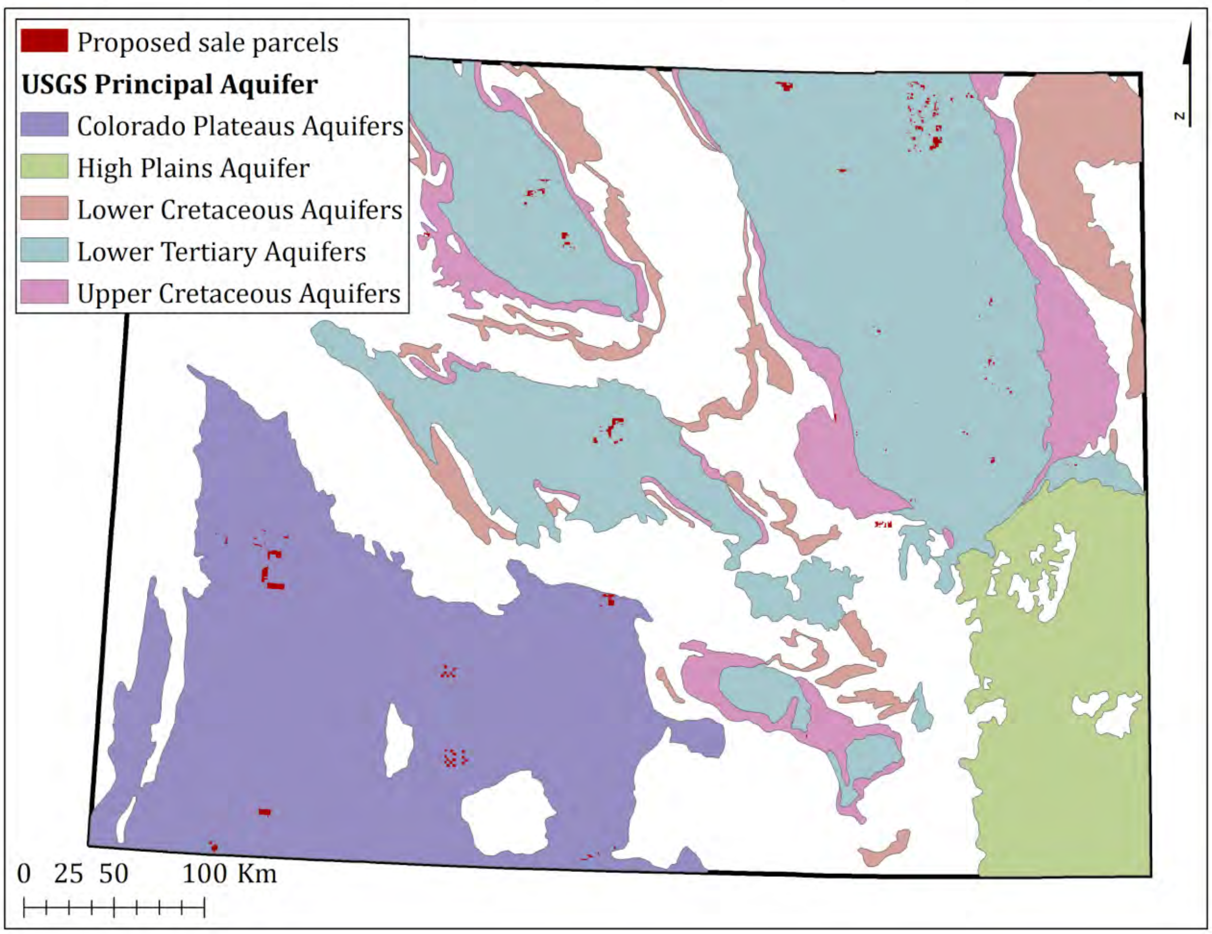

Figure 3 - USGS principal aquifers with the proposed oil and gas parcels (U.S. Geological Survey, 2021).

Identification of Principal Aquifers within 3,000 ft of Surface

Surface aquifers within 3,000 feet of the surface having brackish groundwater resources in the proposed parcel areas were identified using the USGS Brackish Water Database (Stanton et al., 2017). In the USGS report, fresh groundwater is defined as water having less than 1,000 mg/L total dissolved solids (TDS), slightly saline (brackish) has 1,000 to 3,000 mg/L TDS, moderately saline (brackish) has 3,000 to 10,000 mg/L TDS, and highly saline water is >10,00 mg/L TDS. Principal aquifers in lease areas are shown in Figure 3 and minimum and maximum groundwater depths are listed in Table 3 (Qi and Harris, 2017). The Colorado Plateaus aquifers and Lower Cretaceous aquifers exist within 3,000 feet of the surface but also extend below 3,000 feet in some areas.

Table 3 - Principal aquifers with 3,000 feet below land surface from the USGS Brackish Water Database.

Principal aquifer	Number of parcels located in aquifer	Average minimum depth of groundwater (ft bls)	Average maximum depth of groundwater (ft bls)
Colorado Plateaus aquifers	44	5,060	5,398
High Plains aquifers	1	34	185
Lower Cretaceous aquifers	1	3,983	4,296
Lower Tertiary aquifers	76	482	814
Paleozoic aquifers	0	2,278	2,629
Upper Cretaceous aquifers	4	966	1,232

(Note that 4 parcels in proposed sale are not located within available data on USGS principal aquifers)

Data for the wells used in the USGS Brackish Water Database was downloaded to quantify the average minimum and maximum groundwater well depth in the aquifers (Table 3) and to characterize the TDS levels in the aquifers to determine if there is usable water (Qi and Harris, 2017). The majority of the proposed parcel areas are located in the Colorado Plateaus aquifer and the Lower Tertiary aquifers (120 parcels). In the Colorado Plateaus aquifer (which corresponds geographically with the Green River Basin), 65% of the wells from the USGS Brackish Water Database have a TDS concentration below 10,000 mg/L (Figure 4) (Qi and Harris, 2017). Over 99% of wells in the Lower Tertiary aquifer (which corresponds geographically with the Power River, Wind River, Bighorn, and Hanna Basins) have a TDS concentration below 10,000 mg/L (Figure 5). Therefore, wells located in the Colorado Plateaus aquifers (maximum well depth is 21,322 ft bls) and the Lower Tertiary aquifers (maximum well depth is 6,930 ft bls) contain usable water. Future oil and gas wells installed in these areas on the proposed lease parcels will be subject to the requirements of BLM Onshore Oil and Gas Order No. 2.

Current aquifer exemptions exist in some of the proposed lease parcel areas (Table 4, Figure 6). There are 49 proposed parcels located in the same area as 20 aquifer exemptions (Table 4, Figure 6). Usable water as defined in BLM Onshore Order No. 2 encompasses groundwater with an aquifer exemption, and these 49 parcels are, therefore, in areas with usable water. However, the aquifer exemptions mean that such aquifers are not subject to certain requirements of the Safe Drinking Water Act. We therefore have excluded them from our examination of existing federal wells, below.

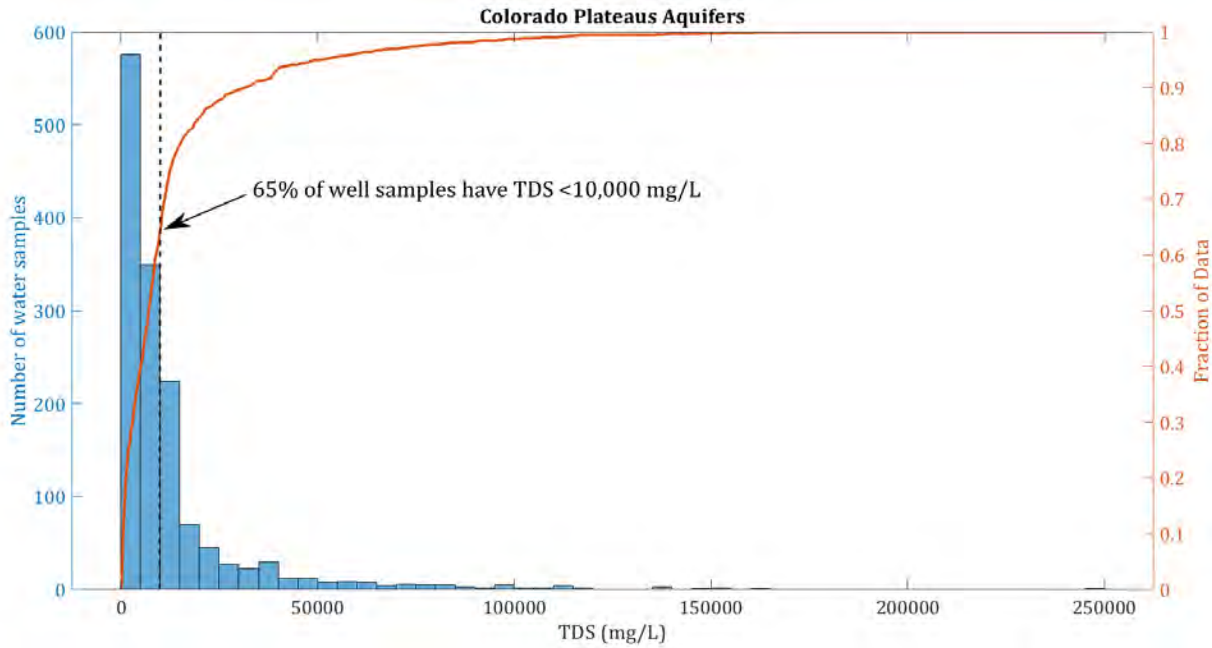

Figure 4- Total dissolved solids (TDS) levels in wells in the Colorado Plateau aquifers from the USGS Brackish Water Database (Qi and Harris, 2017).

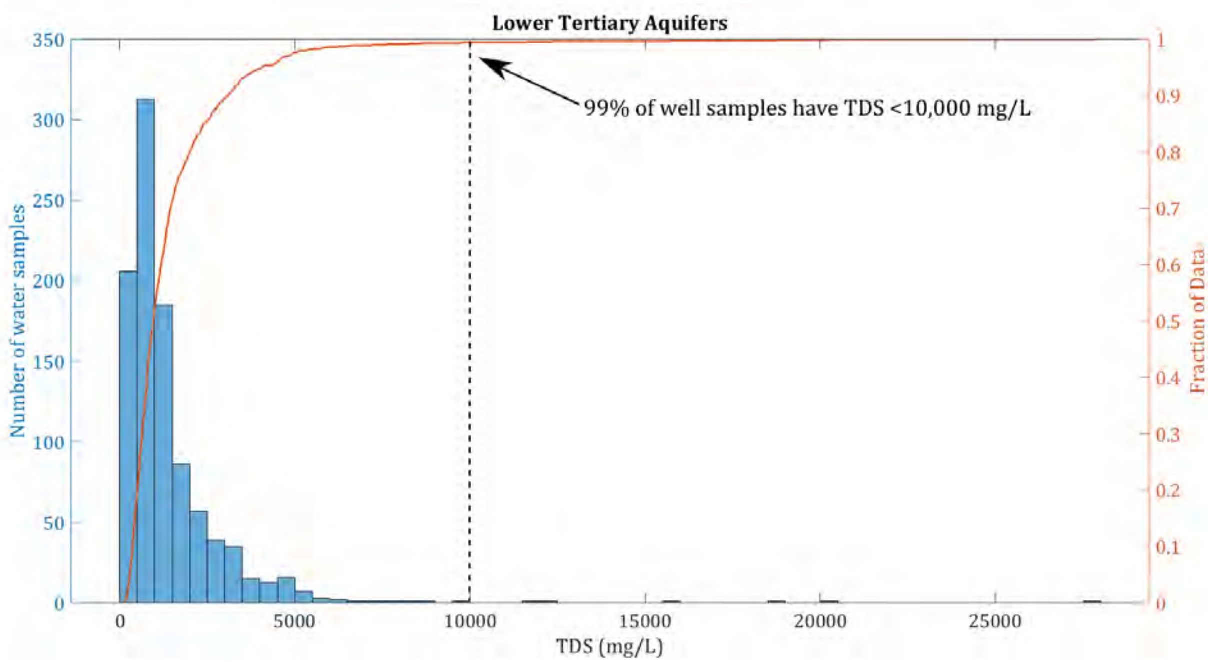

Figure 5- Total dissolved solids (TDS) levels in wells in the Lower Tertiary aquifers from the USGS Brackish Water Database (Qi and Harris, 2017).

Table 4. *Aquifer exemptions in the same locations at the proposed parcels.*

Parcel ID	Basin	Aquifer Exemption ID	Depth (ft bls)	Injection Zone
WY-202X-XX-0904	Green River Basin	8_3903	0	T-5 Sand
WY-202X-XX-0943	Powder River Basin	8_4057	9765	Minnelusa
WY-202X-XX-0950	Powder River Basin	8_3888	7525	Muddy
WY-202X-XX-0953	Powder River Basin	8_4080	6500	Muddy
WY-202X-XX-0958	Powder River Basin	8_3997	7095	Muddy
WY-202X-XX-0960	Powder River Basin	8_3997	7095	Muddy
WY-202X-XX-0966	Powder River Basin	8_4080	6500	Muddy
WY-202X-XX-0967	Powder River Basin	8_4080	6500	Muddy
WY-202X-XX-0968	Powder River Basin	8_3997	7095	Muddy
WY-202X-XX-0974		8_1030	1626	Phosphoria
WY-202X-XX-0977	Powder River Basin	8_3872	1200	1st Wall Creek
WY-202X-XX-1018		8_1886	800	Madison
WY-202X-XX-1032	Powder River Basin	8_3929	7968	Muddy
WY-202X-XX-1036	Powder River Basin	8_3929	7968	Muddy
WY-202X-XX-1043	Powder River Basin	8_3929	7968	Muddy
WY-202X-XX-1054	Powder River Basin	8_3980	7968	Muddy
WY-202X-XX-1132	Powder River Basin	8_3888	7525	Muddy
WY-202X-XX-1201	Wind River Basin	8_1009	4919	Shotgun Member of the Ft Union
WY-202X-XX-1212	Wind River Basin	8_1074	3268	Shotgun Member of the Ft Union
WY-202X-XX-1234	Powder River Basin	8_1052	7243	Minnelusa C
WY-202X-XX-6979	Powder River Basin	8_4093	6299	Dakota
WY-202X-XX-6995	Green River Basin	8_3903	0	T-5 Sand
WY-202X-XX-7000	Green River Basin	8_3903	0	T-5 Sand
WY-202X-XX-7003	Green River Basin	8_3903	0	T-5 Sand
WY-202X-XX-7022	Powder River Basin	8_3888	7525	Muddy
WY-202X-XX-7025	Powder River Basin	8_4080	6500	Muddy
WY-202X-XX-7026	Powder River Basin	8_4068	6350	Muddy
WY-202X-XX-7027	Powder River Basin	8_3997	7095	Muddy

WY-202X-XX-7030	Powder River Basin	8_4080	6500	Muddy
WY-202X-XX-7031	Powder River Basin	8_4080	6500	Muddy
WY-202X-XX-7032	Powder River Basin	8_3929	7968	Muddy
WY-202X-XX-7033	Powder River Basin	8_3980	7968	Muddy
WY-202X-XX-7035	Powder River Basin	8_1062	200	Wasatch "F" Sand
WY-202X-XX-7036	Powder River Basin	8_3888	7525	Muddy
WY-202X-XX-7053	Green River Basin	8_1854	4735	Fort Union Sands
WY-202X-XX-7060	Green River Basin	8_3927	4700	Almond
WY-202X-XX-7074	Powder River Basin	8_3929	7968	Muddy
WY-202X-XX-7100	Green River Basin	8_3927	4700	Almond
WY-202X-XX-7107	Green River Basin	8_3927	4700	Almond
WY-202X-XX-7110	Green River Basin	8_3927	4700	Almond
WY-202X-XX-7122	Powder River Basin	8_3929	7968	Muddy
WY-202X-XX-7134	Powder River Basin	8_3997	7095	Muddy
WY-202X-XX-7135	Powder River Basin	8_3980	7968	Muddy
WY-202X-XX-7173	Powder River Basin	8_3980	7968	Muddy
WY-202X-XX-7174	Powder River Basin	8_3980	7968	Muddy
WY-202X-XX-7177	Powder River Basin	8_3980	7968	Muddy
WY-202X-XX-7192	Green River Basin	8_3914	3640	Almy Stray 3-4
WY-202X-XX-7193	Powder River Basin	8_3991	0	Teckla
WY-202X-XX-7204	Wind River Basin	8_1009	4919	Shotgun Member of the Ft Union

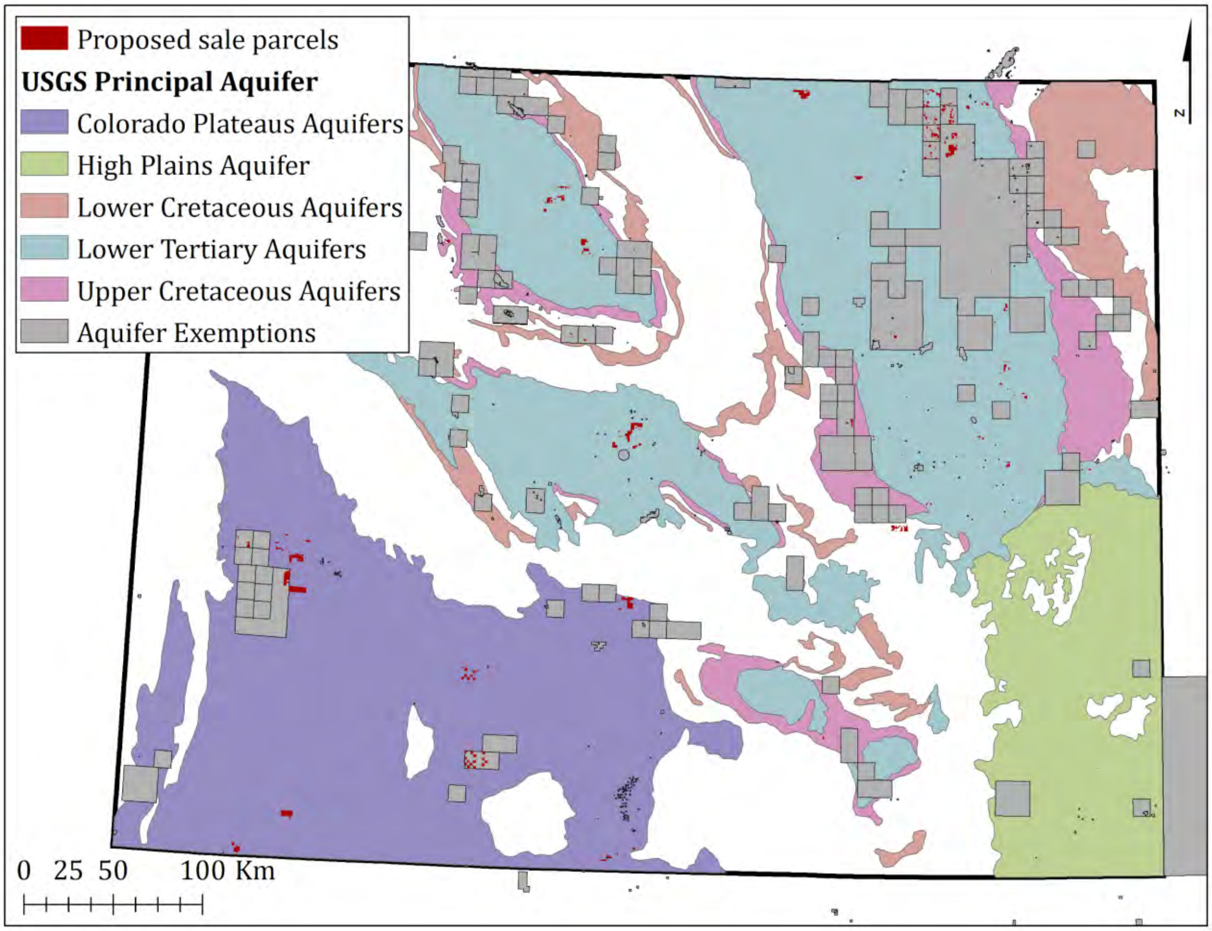

Figure 6 - Aquifer exemptions in Wyoming, shown with the proposed parcels and USGS principal aquifers (U.S Environmental Protection Agency, 2017; U.S. Geological Survey, 2021)

Examination of Current Federal Wells in the Powder River Basin

Onshore Oil and Gas Order No. 2 requires federal wells to protect usable water by properly cementing the casings around usable water zones (U.S. Bureau of Land Management, 1988). The top of cement and bottom of surface casing for active federal well construction logs were analyzed to assess if this requirement was being met, and thus determine if current federal wells are protecting usable water zones near the proposed parcel areas. For any well, if a gap exists between the surface casing and top of cement in a usable water zone, the well is endangering groundwater resources. Moreover, if existing wells have been approved by BLM without protecting all usable water zones as required by Onshore Order No. 2, it appears likely that oil and gas wells also will be approved in the future on the proposed lease parcels without requiring them to be constructed to protect groundwater resources.

In the Powder River basin, there are 62 federal wells that have been completed since January 1, 2000, and remained active within the last 5 years in the same townships and ranges as the proposed lease parcels (outside of areas with aquifer exemptions) (Table 5). Among these 62 identified wells, 36 have a gap between the bottom of surface casing and the top of cement (Figure 7). The length of these gaps' ranges from 275 to 7,714 ft with an average gap length of 2,653 ft. The average depth of surface casing in well with gaps is 2,196 ft bls (minimum 444 ft and maximum 3,550 ft). The average depth of top of cement in well with gaps is 4,850 ft bls (minimum 2,060 ft and maximum 9,970 ft).

These gaps cross usable water zones. Seventeen of the wells have an uncemented gap occurring at less than 3,000 feet below surface (Table 5). This gap is located within the Lower Tertiary principal aquifer, which primarily contains usable water (TDS <10,000 mg/L) (Figures 5 and 7). Therefore, these seventeen wells have a gap in cement and surface casing that is threatening usable water and thus may not be in compliance with Onshore Oil and Gas Order No. 2.

Nineteen of the wells have an uncemented gap occurring more than 3,000 ft bls (Figure 7). These gaps cross the lower Tertiary and upper Cretaceous aquifers. The lower Tertiary aquifer system may be as thick as 7,180 feet in the Powder River Basin so all but 4 of the wells with gaps could be threatening the usable water in that aquifer.

Below the lower Tertiary aquifer system is the upper Cretaceous aquifer, which contains the Lance and Fox Hills formations. While this aquifer system is more than 3,000 ft bls, it also contains usable water. Previous studies found that mean TDS levels estimated from oil and gas wells and produced water records found that water from 3,000-7,000 ft bls in the Powder River basin are all below <10,000 mg/L (Table 5) (Taboga et al., 2018). In wells installed between 1,000-6,000 ft bls, 95% had TDS levels <10,000 mg/L, while 83% of wells installed 6,000-7,000 ft bls had TDS levels <10,000 mg/L (Taboga et al., 2018). Thus, the nineteen wells with uncemented gaps occurring more than 3,000 ft bls are likely also in usable water aquifers.

Conclusion

- Numerous proposed lease parcels are located in areas with usable water, particularly those in the Green River Basin (Colorado Plateaus aquifers) and the Powder River Basin (Lower Tertiary aquifers).

- The EA, however, does not identify the depths of usable water covered by the proposed lease parcels, which creates ambiguity in surface casing and cementing requirements for new wells in WY.

- Existing federal wells in the Powder River basin are not protecting usable water. Of 61 wells reviewed in the same township and ranges as the proposed parcels, most (at least 36) had inadequate construction.

- If current active federal wells (completed since January 1, 2000) are not adequately cased and cemented, then it can be assumed that a significant portion of future wells installed on these proposed parcels will also be inadequately cased/cemented and thus pose a threat to usable water.

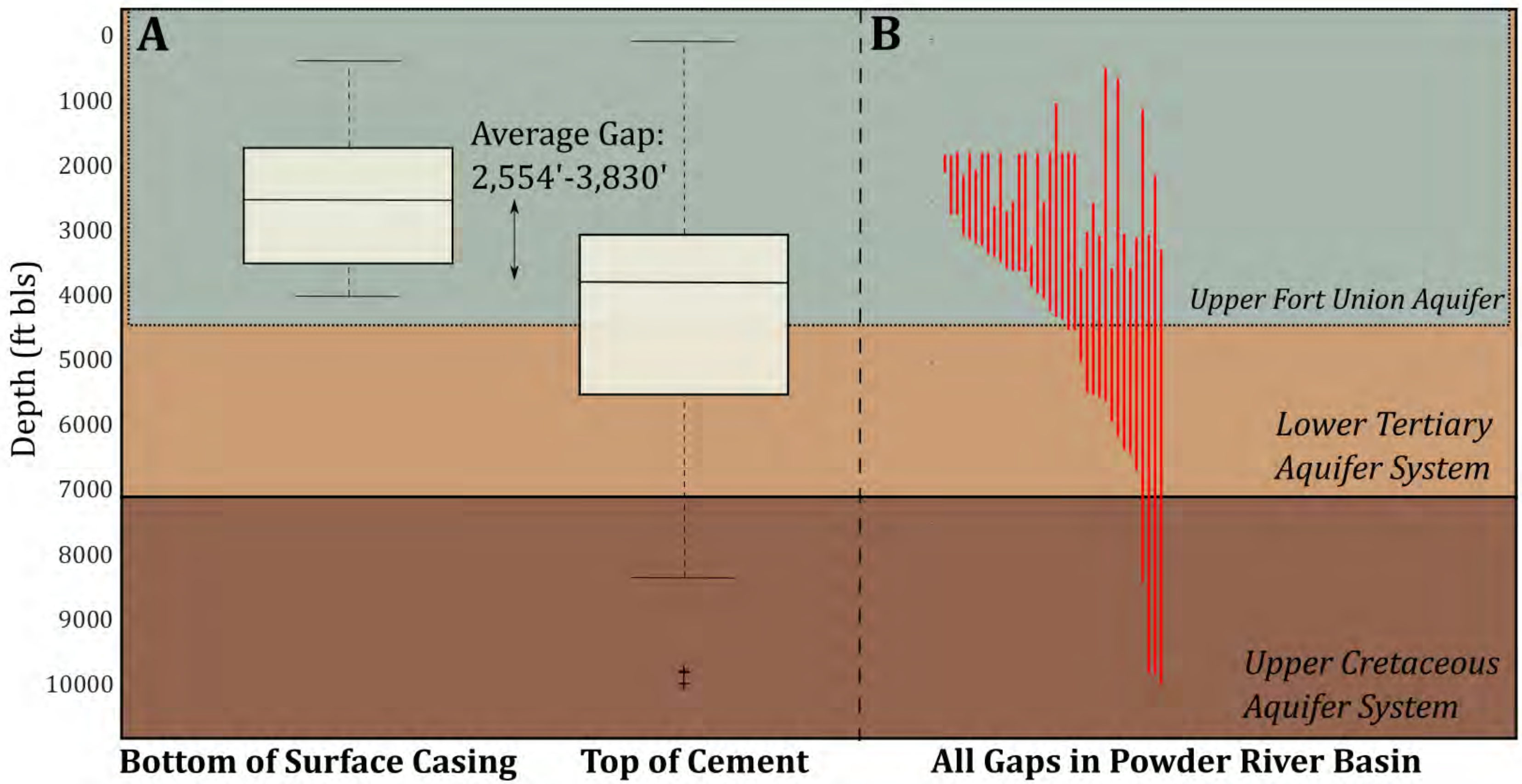

Figure 7. Boxplots with the bottom of surface casing and top of cement depths (ft bls) from the wells in the WOGCC database for the Powder River Basin (panel A) (WOGCC, 2022). A segment plot with all 36 wells in the Powder River Basin that contain gaps between surface casing and top of cement (panel B). The majority of the gaps are through the Upper Fort Union Aquifer, part of the Lower Tertiary Aquifer System. Four of the gaps stretch into the Upper Cretaceous Aquifer System.

Table 5. Federal well surface casing and top of cement data from the WOGCC database. All wells are producing oil wells except 3 that are shut-in (API 49-009-28788, 49-009-28788, and 49-045-22940). All wells had Frac Treatments except wells 49-005-68543 and 49-009-29541 where the treatment was not listed.

Township/ Range	API	Field	Reservoir	Total Depth (ft bls)	Completion Date	Last Active Date	Depth of Surface Casing (ft bls)	Top of Cement (ft bls)	Total Uncemented Interval (ft)	Uncemented Interval (ft bls)
36N 68W	49-009-28881	WC	Teapot	6477	1/27/2015	1/31/2022	1765	3931	2166	1765-3931
36N 68W	49-009-29123	WC	Teapot	6410	7/20/2017	1/31/2022	1764	4500	2736	1764-4500
36N 68W	49-009-29468	WC	Teapot	6401	10/3/2014	1/31/2022	1763	3450	1687	1763-3450
36N 68W	49-009-29596	WC	Teapot	6351	2/14/2017	1/31/2022	1763	3325	1562	1763-3325
36N 68W	49-009-29606	WC	Teapot	6222	7/26/2015	1/31/2022	1756	4200	2444	1756-4200
36N 68W	49-009-29646	WC	Teapot	6228	7/25/2015	1/31/2022	1758	3200	1442	1758-3200
36N 68W	49-009-29647	WC	Teapot	6454	1/27/2015	1/31/2022	1761	3093	1332	1761-3093
36N 68W	49-009-29651	WC	Teapot	6351	2/15/2017	1/31/2022	1756	3600	1844	1756-3600
36N 68W	49-009-29707	WC	Teapot	6440	7/27/2017	1/31/2022	1755	4490	2735	1755-4490
36N 68W	49-009-33548	WC	Teapot	6514	10/24/2019	1/31/2022	1760	4334	2574	1760-4334
36N 68W	49-009-33553	WC	Teapot	6347	6/25/2019	1/31/2022	1785	2060	275	1785-2060
36N 68W	49-009-33556	WC	Teapot	6339	6/25/2019	1/31/2022	1774	3590	1816	1774-3590
37N 75W	49-009-30017	Spearhead Ranch	Frontier	12464	08/15/2021	01/31/2022	3512	0		
37N 75W	49-009-30016	Spearhead Ranch	Frontier	12685	01/19/2020	01/31/2022	3545	0		
37N 75W	49-009-28131	WC	Dakota	13615	02/11/2008	05/04/2020	3030	9800	6770	3030-9800
37N 75W	49-009-36496	WC	Frontier	12307	12/19/2019	01/30/2022	3537	0		
37N 75W	49-009-47473	WC	Frontier	12868	01/13/2020	01/31/2022	3559	0		
37N 75W	49-009-28788	WC	Frontier	12213	01/15/2014	12/02/2021	4045	0		
37N 75W	49-009-30832	WC	Frontier	12634	10/01/2019	01/31/2022	3512	0		
37N 75W	49-009-30833	WC	Frontier	12604	09/24/2021	01/30/2022	3530	0		
37N 75W	49-009-29634	WC	Frontier	12659	08/27/2015	01/30/2022	4032	3550		
37N 75W	49-009-29417	Spearhead Ranch	Frontier	12686	09/26/2015	01/08/2022	4043	2390		
37N 75W	49-009-30004	WC	Frontier	12986	09/10/2019	01/31/2022	3582	0		

37N 75W	49-009-30005	WC	Frontier	12956	09/09/2019	01/31/2022	3630	0		
37N 75W	49-009-30020	Spearhead Ranch	Frontier	12557	08/17/2021	01/31/2022	3566	0		
37N 75W	49-009-29573	WC	Frontier	11320	02/27/2019	01/31/2022	3506	0		
37N 75W	49-009-29574	WC	Shannon	11325	02/15/2019	01/30/2022	3517	0		
37N 75W	49-009-30834	WC	Frontier	12296	12/07/2020	01/31/2022	3521	0		
37N 76W	49-009-28788	WC	Frontier	12213	1/15/2014	12/2/2021	4045	2800		
37N 76W	49-009-33872	WC	Frontier	11874	3/14/2018	1/24/2022	2531	5500	2969	2531-5500
38N 70W	49-009-37206	WC	Turner	9988	12/16/2021	1/31/2022	1764	1670		
38N 70W	49-009-47037	WC	Niobrara	9927	7/27/2020	1/31/2022	1787	1572		
38N 70W	49-009-47038	WC	Niobrara	9995	8/4/2020	1/31/2022	1815	1815		
38N 70W	49-009-47039	WC	Niobrara	9953	7/29/2020	1/19/2022	1770	170		
38N 70W	49-009-47079	WC	Turner	10329	8/2/2020	1/31/2022	1798	2710	912	1798-2710
38N 70W	49-009-47080	WC	Turner	10223	7/31/2020	1/31/2022	1751	2715	964	1751-2715
39N 73W	49-009-38135	WC	Frontier-Turner	11855	5/2/2019	1/28/2022	2515	3583	1068	2515-3583
39N 73W	49-009-38140	WC	Frontier-Turner	11855	5/2/2019	1/29/2022	2520	4016	1496	2520-4016
39N 73W	49-009-38776	WC	Turner	11769	11/15/2008	1/31/2022	2102	3035	933	2102-3035
39N 73W	49-009-38778	WC	Turner	11763	11/14/2018	1/27/2022	2106	9820	7714	2106-9820
40N 75W	49-009-41521	WC	Shannon	10696	12/03/2019	02/25/2022	3200	3830	630	3200-3830
40N 75W	49-009-44381	WC	Niobrara	11242	08/01/2019	01/31/2022	3198	0		
40N 75W	49-009-46535	Hornbuckle	Shannon	10839	03/04/2020	02/28/2022	3038	5540	2502	3038-5540
40N 75W	49-009-29614	WC	Frontier	10283	10/18/2019	01/30/2022	2977	0		
40N 75W	49-009-29652	WC	Shannon	10887	06/18/2017	01/26/2022	3550	5000	1450	3550-5000
40N 75W	49-009-45917	WC	Shannon	10676	12/05/2019	10/24/2021	3011	6350	3339	3011-6350
40N 75W	49-009-48481	WC	Shannon	10885	12/17/2020	02/28/2022	2982	5460	2478	2982-5460
40N 75W	49-009-29892	WC	Shannon	10813	02/02/2019	01/30/2022	3250	9970	6720	3250-9970
40N 75W	49-009-29368	Finley Draw	Frontier	12828	12/16/2015	01/30/2022	3545	5918	2373	3545-5918
40N 75W	49-009-31145	Hornbuckle	Shannon	10906	03/05/2020	02/12/2022	3064	6670	3606	3064-6670
40N 75W	49-009-29921	Hornbuckle	Sussex	10223	03/08/2015	02/28/2022	2673	3549	876	2673-3549
40N 75W	49-009-31205	Hornbuckle	Shannon	10761	10/08/2018	02/28/2022	3539	6400	2861	3539-6400
40N 75W	49-009-29541	WC	Sussex	10100	08/30/2018	11/29/2021	10344	6467		

40N 75W	49-009-44138	WC	Niobrara	11815	12/20/2019	01/31/2022	2578	3368	790	2578-3368
41N 69W	49-005-26275	School Creek	Muddy	9906	03/03/2012	12/01/2021	1075	8390	7315	1075-8390
42N 69W	49-005-57862	Thunder Creek	Muddy	9790	04/30/2008	11/06/2018	991	4300	3309	991-4300
44N 69W	49-005-60608	WC	Mowry	11688	11/03/2009	01/17/2022	2015	3160	1145	2015-3160
45N 68W	49-045-22930	Quest		7583	7/31/2000	12/14/2021	414	No CBL		
45N 68W	49-045-22940	Quest	Skull Creek	7600	8/1/2001	10/31/2018	421	No CBL		
45N 68W	49-045-29091	Quest	Muddy	7581	9/13/2006	1/31/2022	444	5596	5152	444-5596
45N 68W	49-045-29273	Quest	Muddy	7650	8/5/2011	1/31/2022	603	6150	5547	603-6150
57N 72W	49-005-68543	Hunter Ranch	Minnelusa	8365	05/23/2019	01/31/2022	1138	115		

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EXHIBIT 10

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Date: January 10, 2018

Subject: Examination of Groundwater Resources in Areas of Montana Proposed for the March 2018 BLM Lease Sale

From: Dominic DiGiulio, Ph.D., PSE Healthy Energy

Background

The proposed action in the Billings, MT Field Office is to offer 76 lease parcels covering approximately 52,297 Federal mineral acres. The parcels are located in Musselshell, Sweet Grass, Stillwater, Golden Valley, Wheatland, and Carbon counties. The proposed action in the Butte, MT Field office is to offer 9 lease parcels covering approximately 4,307 Federal mineral acres in Park County. The Proposed Action in the North Central, MT Field Office would be to offer 24 lease parcels covering approximately 6,892 Federal mineral acres in Glacier, Liberty, Hill, Chouteau, Blaine, Phillips, and Valley counties. The location of these parcels is illustrated in **Figure 1**.

Onshore Oil and Gas Order No. 2

Onshore Order #2 requires that the proposed casing and cementing programs shall be conducted as approved to protect and/or isolate all usable water zones, and casing along with cement is extended well beyond fresh-water zones to insure [ensure] that drilling fluids remain within the well bore and do not enter groundwater.

In BLM Onshore Oil and Gas Order No. 2, usable water is defined as water *"containing up to 10,000 ppm of total dissolved solids."*

Identification of usable water necessitates collection of groundwater samples for major ion analysis and/or total dissolved solids (TDS). Wireline geophysical tools (e.g., resistivity) can be used to estimate TDS concentration. However, chemical analysis of TDS is preferred over estimation of TDS using wireline geophysical tools as the latter method requires use of algorithms which may introduce error.

Identification of Principal Aquifers in Lease Areas

The U.S. Geological Survey (USGS) recently published a report (Stanton et al. 2017 available at https://pubs.er.usgs.gov/publication/pp1833) identifying groundwater quality in principal aquifers within

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3,000 feet of the surface having fresh or brackish groundwater resources in the United States.[1] In the USGS report, fresh groundwater is defined as water having less than 1,000 mg/L TDS. Brackish groundwater is defined as water having between 1,000 to 10,000 mg/L TDS. Highly saline groundwater is defined as water having over 10,000 mg/L TDS.

Principal aquifers in lease areas covered by the Billings and Butte Field Office appear to be those associated with Lower Tertiary, Upper and Lower Cretaceous, and Paleozoic Formations (**Figure 2**). Principal aquifers in lease areas covered by the North Central Field Office appear to be those associated with Lower Cretaceous Formations (**Figure 2**).

It is evident that most domestic and municipal water wells screened within 3,000 feet of the surface within the lease areas produce fresh or brackish groundwater (**Figures 3 and 4**). Between 500 and 3,000 feet of land surface, highly saline water account for only 0%, ~5%, ~10%, and ~20% of Lower Tertiary, Upper Cretaceous, Lower Cretaceous, and Paleozoic aquifers, respectively, in lease areas (**Figure 5**). This data indicates that the parcels to be offered at the lease sale overlie aquifers containing usable water at depths between 500 and 3,000 feet.

Lower Tertiary, Upper Cretaceous, and Lower Cretaceous Formations were formed under fluvial depositional environments which varied between freshwater systems and shoreline marine systems. Information provided in the USGS reports indicates that these formations consist largely or entirely of fresh and brackish groundwater. Paleozoic aquifers formed under marine depositional systems. Fresh and brackish groundwater in these aquifers is a function of distance from a recharge zone, distance and time of groundwater travel, and replacement of connate or original highly saline water. Since, Paleozoic aquifers contain up to ~80% fresh and brackish groundwater. Displacement of connate water with less saline water is evident in these formations.

Conclusion

Significant fresh and brackish groundwater resources (usable water) exist within the lease areas necessitating careful examination of depths and formations of proposed oil and gas development to ensure that groundwater resources are not impacted. Protection of usable water required by Onshore Order #2 is not apparent in Environmental Assessments conducted by the Billings, Butte, and North Central Field Offices in Montana. Environmental Assessments from these field offices should include a methodology to identify and protect usable water.

[1] There was insufficient information available to characterize groundwater resources below 3,000 feet. Hence, is should not be interpreted that usable water 3,000 feet is absent.

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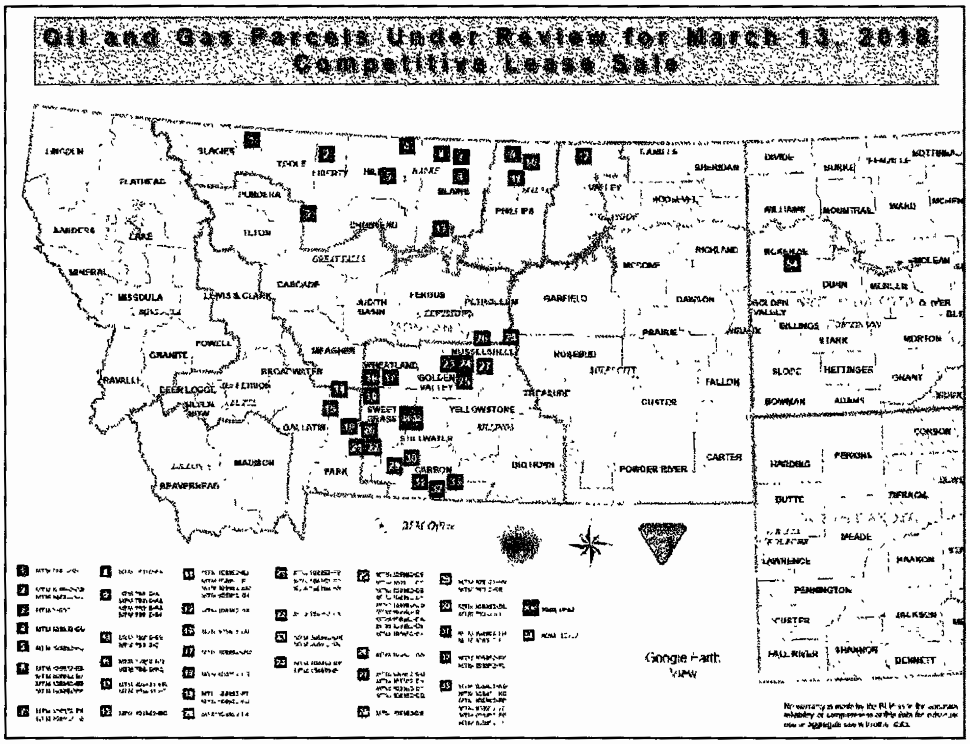

Figure 1. Oil and gas parcels under review for March 13, 2018 Competitive Lease Sale. From BLM ND Field Office. BLM has dropped the ND parcel from the final sale list.

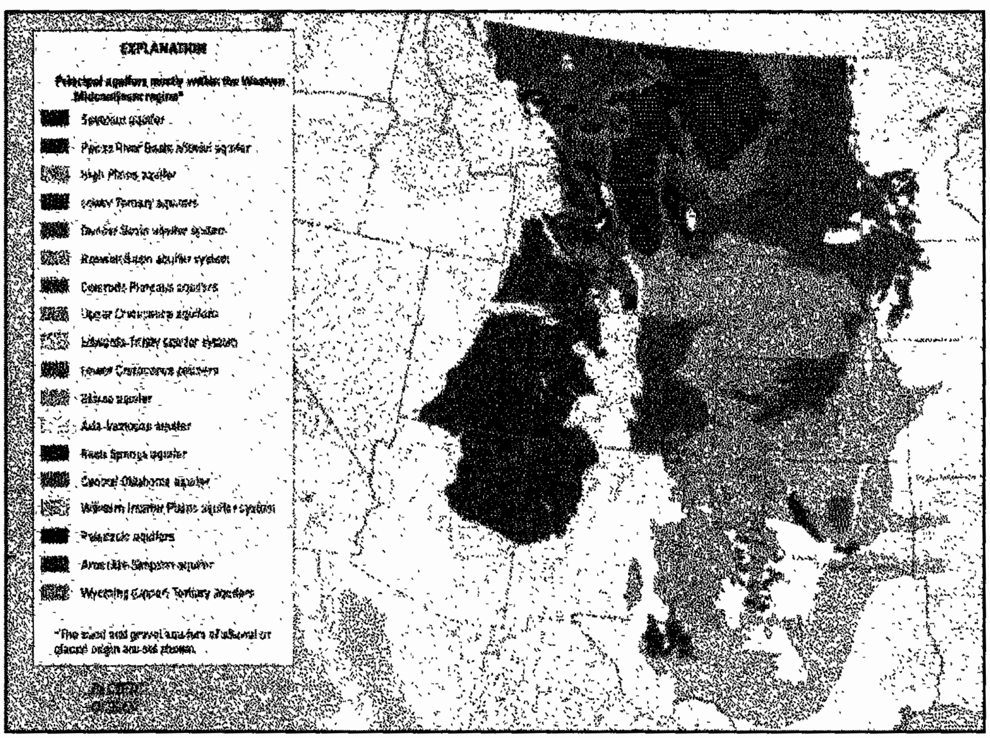

Figure 2. Principal aquifers within the Western Midcontinent. From Stanton et al. (2017) (page 122)

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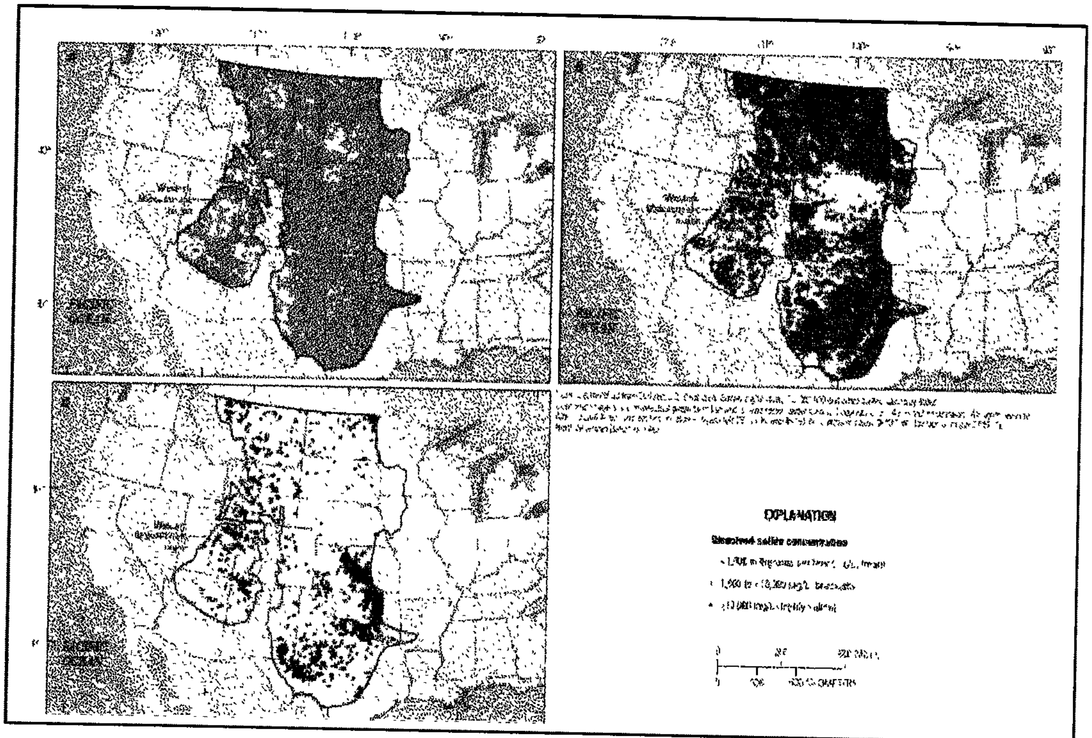

Figure 3. Locations of wells producing: a. fresh groundwater, b. brackish groundwater, and c) highly saline ground in the Western Midcontinent Region. From Stanton et al. 2017 (page 123)

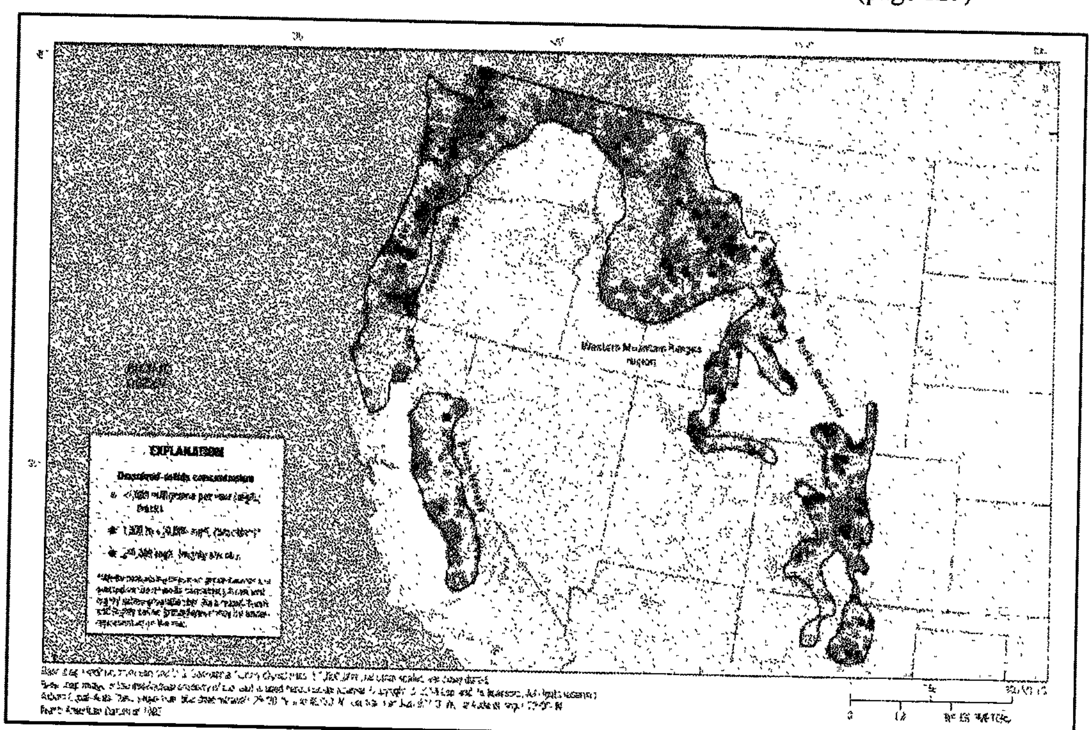

Figure 4. Locations of wells producing fresh, brackish, and highly saline groundwater from 0 to 3,000 feet below land surface in the Western Mountain Ranges Region. From Stanton et al. 2017 (page 133)

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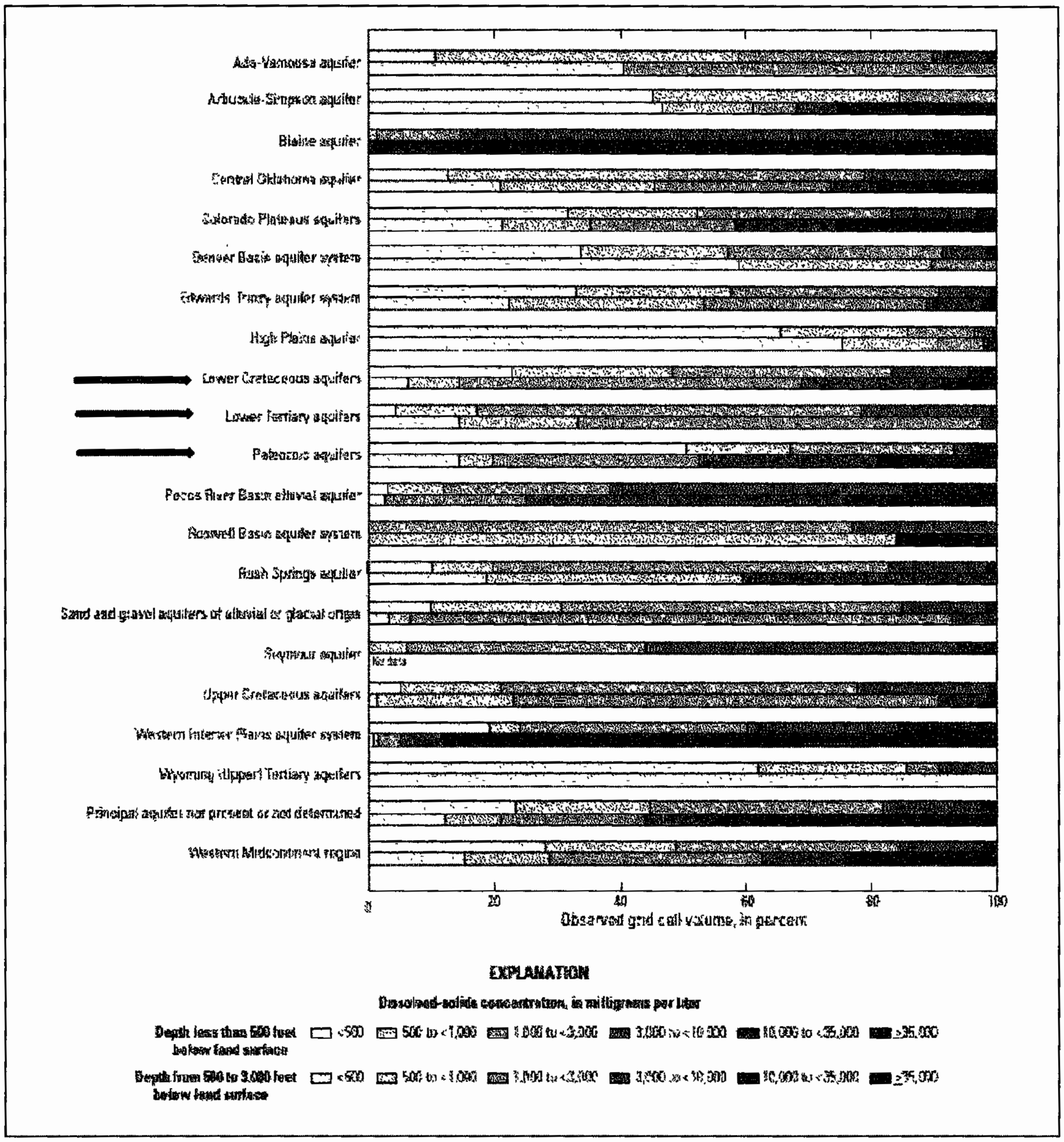

Figure 5. Distribution of dissolved solids concentrations as a percentage of observed grid volume by principal aquifer and depth in the Western Midcontinent Region. Aquifer systems denoted in black arrows are located within the March 2018 proposed lease areas. Modified from Stanton et al. 2017 (page 124).

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Date: December 22, 2017

Subject: Examination of Selected Production Files in Southcentral Montana to Support Assessment of the March 2018 BLM Lease Sale

From: Dominic DiGiulio, Ph.D., PSE Healthy Energy

To provide further assistance in evaluating the March 2018 BLM lease sale in Montana, a review of well files for 9 production wells in Carbon and Stillwater counties in Southcentral Montana was conducted. The U.S. Bureau of Land Management's Billings, MT Field office proposes to offer 18 oil and gas leases for sale in March 2018 in those two counties.[1]

The nine production wells analyzed overlie the same aquifers as the Carbon and Stillwater lease parcels to be offered at BLM's March 2018 lease sale. The Greybull sandstone was targeted in 8 of 9 production wells during conventional and unconventional oil production (**Table 1**). Federal mineral rights were present at 4 of the 9 production wells as indicated by their production well names. Surface casing for all 9 production wells was shallow - 288 to 617 feet below ground surface (bgs). Cement bond/variable density logs (CBL/VDL) were not conducted at 7 of the production wells. CBL/VDLs were conducted at 2 production wells but were not available for inspection to determine top of cement (TOC) in intermediate or production casing. At one well (Federal 14-15), there was a note in the file that TOC in intermediate casing was 3420 feet bgs, meaning that it was 3107 feet below surface casing. These files indicate that for thousands of feet beneath the surface casing, the wells lack casing or cementing to isolate them from surrounding aquifers.

We then reviewed available data to assess aquifer water quality at depths below the surface casing for the nine wells. First, it appears that most of the wells are producing from a formation (the Greybull formation) with water that has concentrations of total dissolved solids (TDS) below 10,000 mg/L. At one well (ECA Federal 1-H), 2 aqueous samples were available from the Greybull formation that indicated TDS concentrations below 5000 mg/L. At another well (Foothills 44-14H), a produced water sample from the Greybull formation was available that indicated a TDS concentration of 3220 mg/L.[2] Lithologic logs, where available, also indicated that the Greybull Formation was variably saturated with oil and water in the areas of production. At Federal 14-15, a lithologic log indicated that the Frontier Formation was saturated with water indicating that it is a water-bearing unit.

Second, we evaluated the presence of usable water in shallower formations that overlay the Greybull Formation but are below the depth of surface casing on the nine wells. We reviewed the U.S. Environmental Protection Agency's database on aquifer exemptions (EPA 2017) and U.S. Geological Survey's produced water database on produced water (USGS 2017a) for Carbon and Stillwater counties and for the State of Montana as a whole.

These databases indicate that TDS concentrations in the Eagle, Frontier, and Dakota Formations overlying the Greybull formation are ≤ 10,000 mg/L (**Table 2**) and hence meet the definition of usable

[1] https://eplanning.blm.gov/epl-front-office/projects/nepa/87544/127798/155498/Billings_3-13-18_Internet_Sale_Notice.pdf .

[2] The well file at Foothills 44-14H also indicated that a spill or spills had occurred at or near the location of this production well necessitating "*clean-up*". No information was provided on the extent of remediation (e.g., excavation of soil) or analysis of soil or groundwater impacts at the spill location. The well file also indicated that oil (presumably from the Greybull Formation) was used for road spreading near this production well.

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water as defined by the U S Bureau of Land Management's Onshore Rule #2. Also, the Eagle Formation is recognized as a principal aquifer in Montana (Ferreira et al. 1986). A principal aquifer is defined as a regionally extensive aquifer or aquifer system that has the potential to be used as a source of potable water (USGS 2017b).

Finally, we used this aquifer water quality data and the production well files to prepare a chart summarizing the depth of formations encountered by the wells that contain usable water (**Table 3**). Formations containing usable water are highlighted in blue. Based on the shallow depth of surface casing and apparent lack of cement outside intermediate or production casing at depths in contact with usable water, it does not appear that usable water was protected during production at these wells as required by Onshore Rule #2. Surface casing should have extended through usable water zones or cement and intermediate casing should have extended to surface casing through usable water zones.

Table 1. Summary of selected well files reviewed in Stillwater and Carbon Counties (Southcentral Montana)

Well Name	API Number	Date of APD approval (or spud/ completion)	Type	Orientation	Depth (ft)	Producing Formation	Surface Casing depth (ft bgs)	Top of cement in intermediate or production casing	Water Samples
ECA Federal 1-H	25-095-21275	12/13/2009	conventional	horizontal	3859	Greybull sandstone	452	No CBL/VDL	2 formations samples (4.300, 4230 mg/L TDS)
ECA Federal 2-H	25-095-21279	9/7/2012	conventional	horizontal	3976	Greybull sandstone	454	CBL/VDL conducted but not provided	No samples
ECA Federal 3-H	25-095-21280	10/14/2012	conventional	horizontal	4390	Greybull sandstone	465	No CBL/VDL	No samples
ECA Foothills 9-H	25-095-21283	9/15/2013	conventional	horizontal	3805	Greybull sandstone	460	No CBL/VDL	No samples but resistivity log exists
Federal 14-15	25-095-21153	10/28/1980	conventional	vertical	4346	Lakota sandstone	313	CBL/VDL exists – not provided. TOC indicated at 3420 ft	No samples, Frontier Formation 100% water saturation
Foothills 13-12	25-095-21153	7/10/1981	hydraulic fracturing (*"311 bbls of oil-jelled"* fluid)	vertical	3380	Greybull sandstone	288	No CBL/VDL	No samples
Foothills 13-13	25-095-21154	5/20/1981	hydraulic fracturing	vertical	3496	Greybull sandstone	357	No CBL/VDL	No samples
Foothills 44-14H	25-095-22149	4/17/1997	conventional	horizontal	3613	Greybull sandstone	412	No CBL/VDL	Produced water sample 3222 mg/L TDS
W.R. Mackay	25-009-05242	9/2/1955	hydraulic fracturing (4000 gallons of kerosene and 4000 gallons of *"Petrofrac Max"*)	vertical	3406	Greybull sandstone	617	No CBL/VDL	No samples

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Table 2. Total dissolved solids (TDS) concentrations in the Greybull and overlying formations from drillstem and produced water analysis

Formation	Median TDS (mg/L) of drillstem and produced water tests in Stillwater and Carbon Counties	Median TDS (mg/L) of drillstem and produced water samples in Montana
Eagle Sandstone	5228 (n=1)	2658 (n=32)
Frontier	5227 (n=7)	5795 (n=12)
Muddy Sandstone	No information	No information
Dakota Sandstone	5151 (n=7)	5166 (n=42)
Greybull Sandstone	no measurements	No measurements

Table 3. Geologic markers for depths to tops of formations encountered during drilling at production wells. Formations shaded in blue denote formations likely containing usable water. The Greybull sandstone is shaded in orange. Depths are in feet below ground surface.

	ECA Federal 1-H	ECA Federal 2-H	ECA Federal 3-H	ECA Foothills 9-H	Federal 14-15	Foothills 13-12	Foothills 13-13	Foothills 44-14H	W.R. Mackay
Claggett									0
Eagle sandstone									610
Carlile-Niobrara									1405
Cody Shale								1594	
Frontier		1869				1794	2202	2200	2125
1st Frontier		2388							
2nd Frontier	2612	2596		3027					
3rd Frontier	2775	2768		3186	2730				
Mowry Shale	2983	2981				2671	2735	2885	2730
Thermopolis shale	3134	3129	3587	3496					
Muddy sandstone			3929					3196	
Dakota sandstone	3647	3638	4294	3820	3994	3230	3345	3318	3255
Greybull Sandstone	3743	3734	4380	3814	4095	3334	3442	3486	

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Education

B.S., Environmental Engineering, Temple University, Philadelphia, PA (1982)
M.S., Environmental Science, Drexel University, Philadelphia, PA (1988)
Ph.D., Soil, Water, and Environmental Science, University of Arizona, Tucson, AZ (2000)

Areas of Expertise: soil vacuum extraction/bioventing, gas sparging, soil-gas sampling, gas permeability testing, vapor intrusion, stray gas (CH_4, CO_2) migration, hydraulic fracturing

Employment (in Chronological Order)

Military Service: U.S. Marine Corps: Active duty 1975-1978, Camp Pendleton, CA, Honorable Discharge in 1981.

Environmental Engineer (Remedial Project Manager): U.S. Environmental Protection Agency, Region III, Philadelphia, PA: Jun 1980 – Dec. 1981 and Sep 1982 – Jan 1988. Duties included: conducting investigations (e.g., remedial investigations, risk assessments, feasibility studies, sample collection) under the Comprehensive Environmental Response and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA), federal contractor oversight, preparation of consent orders and initiation of enforcement actions.

Environmental Engineer: Tetra-Tech, Newark, DE: Jan 1988 - Jun 1988. Duties included: conducting investigations under CERCLA and RCRA, collecting, ground-water, soil, sediment, air, and soil-gas samples.

Environmental Engineer: U.S. Environmental Protection Agency, Office of Research and Development, Ada, OK: Sep 1988 – Mar 2014 (retired). Duties included providing regulatory oversight assistance to EPA remedial project managers and conducting research related to subsurface gas flow and vapor transport. Research included: (1) Development of methods to improve the effectiveness of soil vapor extraction, bioventing, and air sparging subsurface remediation systems including lead authorship of EPA's primary technical resource document in these areas; (2) Co-development of analytical solutions and associated codes for estimation of gas permeability and gas flow in soil; (3) Development of analytical solutions to simulate combined solute and vapor transport in soil including lead authorship of the model VFLUX; (4) Development of field methods to improve active soil-gas sampling especially pertaining to leak and purge testing; (5) Development of forensic techniques (use of hydrocarbon degradation products and radon) and assistance in development of EPA guidance to evaluate vapor intrusion (migration of organic compounds from ground water to indoor air); (6) Development of ground water and soil gas monitoring strategies including assistance in development of EPA's Class VI rule on geologic sequestration of carbon dioxide; (7) Development of methods to evaluate impact to Underground Sources of Drinking Water (USDWs) under the Safe Drinking Water Act and stray gas migration due to hydraulic fracturing. Research activities included conducting seminars, workshops, and short courses to States.

Branch Chief: U.S. Environmental Protection Agency, Office of Research and Development, Ada, OK: (3 detail periods over a cumulative period of 1 ½ years) Duties included: research planning, management of funding and other scientists, and completion of various administrative functions.

Research Associate and Visiting Scholar: Stanford University, Stanford, CA: Apr 2014 - present. Duties include conducting research related to evaluating impact to UDSWs and domestic water wells as a result of hydraulic fracturing.

Environmental Engineer: Subsurface Gas Solutions, Ada, OK: June 2015 – Dec 2016. Duties included providing consulting service to EPA and private clients on issues related to subsurface gas flow and vapor transport including, vapor extraction, dual vapor extraction, bioventing, gas sparging, vapor intrusion, stray gas migration, and, soil-gas sampling.

Senior Research Scientist: PSE Healthy Energy, Ithaca, NY: Jan 2017 – present. Duties include evaluating the impact of oil and gas development on human health, water resources (groundwater and surface water), and greenhouse gas emissions in the United States and abroad.

Scientific Awards

5 EPA Bronze Medals: (1) Development of EPA Guidance Document on Soil Vacuum Extraction, (2) Technical Support to EPA's Program and Regional offices on Subsurface Gas Flow and Vapor Transport, (3) Development of EPA Guidance on Vapor Intrusion, (4) Research on Vapor Intrusion, (5) Development of Class VI Rule on Geologic Sequestration of Carbon Dioxide

3 EPA Honor Awards: (1) Development of a National Risk Management Research Laboratory Strategic Research Plan, (2) Development of a Protocol to Assess Vapor Intrusion; (3) Technical support at Leaking Underground Storage Tank Sites

3 EPA Scientific and Technological Achievement Awards: (1) Innovative Design of Soil Vacuum Extraction Systems, (2) Development of Analytical Model to Simulate Transient Flux of Volatile Organic Compounds in Soil to Ground Water and the Atmosphere, (3) Simulation of Geochemical Impacts to Ground Water from Leakage of Carbon Dioxide

Peer-Reviewed Journal Publications, EPA Reports, and Book Chapters in Chronological Order

DiGiulio, D.C.; Shonkoff, S.B.C.; Jackson, R.B. The Need to Protect Fresh and Brackish Groundwater Resources During Unconventional Oil and Gas Development. *Current Opinion in Environmental Science & Health* **2018** (accepted, undergoing revision).

DiGiulio, D.C.; Ruybal, C.J.; Hargrove, K.D.; Wilkin, R.T. *Leak, Purge, and Gas Permeability Testing to Support Active Soil-Gas Sampling*, EPA/xxx/x-xx/xxx, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, **2018** (accepted, undergoing revision)

DiGiulio, D.C.; Shonkoff, S.B.C. Is reuse of produced water safe? First, let's find out what's in it. *EM, Air & Waste Management Association*, August **2017**

DiGiulio, D.C.; Jackson, R.B Impact to Underground Sources of Drinking Water and domestic wells from production well stimulation and completion practices in the Pavillion, Wyoming Field. *Environmental Science & Technology* **2016** 50, 4524-4536.

DiGiulio, D.C.; Jackson, R.B. Response to Comment on "Impact to Underground Sources of Drinking Water and domestic wells from production well stimulation and completion practices in the Pavillion, Wyoming Field." *Environmental Science & Technology* **2016**, 50, 10771-10772.

Jackson, R.E.; Lowry, E.R.; Pickle, A.; Kang, M.; DiGiulio, D.C; Zhao, K. The Depths of Hydraulic Fracturing and Accompanying Water Use Across the United States. *Environmental Science & Technology* **2015**, 49 (15), 8969–8976.

Wilkin, R.T ; DiGiulio, D.C. Geochemical Impacts to groundwater from geologic carbon sequestration: Controls on pH and inorganic carbon concentrations from reaction path and kinetic modeling. *Environmental Science & Technology* **2010**, 44(12), 4821-4827.

DiGiulio, D.C., *Use of Soil-Gas, Gas Flux, and Ground Water Monitoring to Evaluate Potential Leakage to Underground Sources of Drinking Water, the Atmosphere, and Buildings During Geological Sequestration of Carbon* - Science in Action Fact Sheet. EPA/600/S-09/030, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, **2010**.

Schnaar, G.; DiGiulio, D.C. Computational modeling of the geologic sequestration of carbon dioxide. Computational Modeling of the Geologic Sequestration of Carbon Dioxide. *Vadose Zone Journal* **2009**, 8, 389–403.

DiGiulio, D.C., Paul, C.; Scroggins, B.; Cody, R.; Willey, R.; Clifford, S.; Mosley, R.; Lee, A.; Christensen, K.; Costa, R. *Comparison of Geoprobe PRT, AMS GVP soil-gas sampling systems with dedicated vapor probes in sandy soils at the Raymark Superfund Site*. EPA/600/R-06/11, U.S. Environmental Protection Agency Office of Research and Development, National Risk Management

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