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Geological CO_2 Storage Characterization

The Key to Deploying Clean Fossil Energy Technology

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ISSN 2194-3214 ISSN 2194-3222 (electronic)
ISBN 978-1-4614-5787-9 ISBN 978-1-4614-5788-6 (eBook)
DOI 10.1007/978-1-4614-5788-6
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2013956748

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This book is dedicated to the earth scientists who provided the geological foundation for this study. Although there are many worthy of mention, there are a few that deserve special recognition: Donald Carlisle (problem recognition and solution strategies), Clarence Hall (value of field work), Franklyn Van Houten (the art of observation on the outcrop), John Harms (reconstructing depositional environments from stratification sequences), Hans Eugster (reading the chemistry of rocks), Ken Stanley (geological syntheses), Dick Sheppard and Dick Hay (the role of diagenesis), John Warme (value of core observations), Jim Boles (attention to petrographic detail), and Donald Boyd (importance of detailed observation). All of these scientists were truly exceptional in the volume of knowledge they were readily willing to share, but whom will probably never get the recognition they deserve.

Lastly, the dedication of this book would be remiss without mention of the huge amount of work that Shanna Dahl, Deputy Director of the University of Wyoming, Carbon Management Institute, has provided to the task of constructing this book.

Ronald C. Surdam

Preface

The primary purpose of this book is to assist future CCS, or CCUS investigations in characterizing potential geological CO_2 storage sites well enough so that all of the information required by regulators to permit commercial CO_2 storage facilities are provided. The Wyoming Carbon Underground Project (WY-CUSP) is part of the U.S. Department of Energy Geological CO_2 Storage Site Characterization Program. In 2010 DOE awarded funding to 10 CO_2 geological storage characterization projects. The WY-CUSP program under the direction of the University of Wyoming Carbon Management Institute (CMI) was one of the awardees (project DE-FE0002142: Site Characterization of the Highest-Priority Geologic Formations for CO_2 Storage in Wyoming; Principal Investigator, Ronald C. Surdam). The State of Wyoming through the U.W. School of Energy Resources generously provided matching funds for the WY-CUSP program. This book deals with most of the trials and tribulations required to achieve the ultimate goal of the WY-CUSP program: delivery of a certified commercial CO_2 storage site that could be used either as a surge tank for CO_2 utilization or for permanent sequestration of greenhouse gas (GHG) emissions, or for both.

The rationale for the WY-CUSP program is manifold: first is the effort to establish a mechanism that provides the potential to stabilize or reduce GHG emissions in order to reduce the rate of global warming; secondly to protect Wyoming's coal extraction and future coal-to-chemical industries by providing storage capacity for anthropogenic CO_2; thirdly to provide a source of anthropogenic CO_2 for enhanced oil recovery projects (at present rates of CO_2 production from gas processing plants it would take 150–200 years to recover Wyoming's stranded oil; fourthly to retrieve reservoir information essential for the expansion of natural gas storage in Wyoming; and lastly to establish more robust databases for two very important hydrocarbon reservoirs in Wyoming (substantially reduce uncertainty for all dynamic models of Tensleep/Weber Sandstone and Madison Limestone fluid-flow and rock/fluid systems).

To satisfy the WY-CUSP program rationale the following goals were set: to improve estimates of CO_2 reservoir storage capacity, to evaluate the long-term integrity and permanence of confining layers, and to manage injection pressures and brine production in order to optimize CO_2 storage efficiency for the most significant storage reservoir (Tensleep/Weber and Madison Formations) at the Rock Springs Uplift (RSU), a premier CO_2 storage site in Wyoming.

To achieve this goal it was necessary to complete the following research objectives; (1) reduce uncertainty in estimates of CO_2 storage capacity of key storage reservoir intervals at the RSU; (2) evaluate and ensure CO_2 storage permanence at the RSU site by focusing on the sealing characteristics and 3-D interval heterogeneity of the Paleozoic and Mesozoic confining layers; (3) improve the efficiency of potential storage operations by designing an optimal coupled CO_2 injection/brine production strategy that ensures effective pressure management, and (4) improve the efficiency of brine treatment at the surface, including the effective use of the elevated temperature and pressure of the brines, recovery of potable water and extraction of metals.

Early efforts by the Wyoming State Geological Survey (WSGS) and the CMI determined that the Tensleep/Weber Sandstones and Madison Limestone were the highest priority CO_2 storage reservoirs in Wyoming. Regional studies also determined that the Rock Springs Uplift in southwestern Wyoming was a premier CO_2 storage structure/site in the state. The RSU is characterized by 4-way closure, with 10,000 ft of structural relief and extends from approximately 35 mi in an east-west direction, and 50 mi in a north-south direction. The WY-CUSP started with a large potential trap for storage of fluids, but with very little information regarding the nature of the reservoir intervals, distribution and continuity of confining layers or the rock/fluid properties of the reservoir and sealing lithologies. The original data available to CMI included 19 well reports that penetrated the Paleozoic stratigraphic interval in an area of approximately 2,000 mi^2, outcrops of key rock units 50–100 mi from the potential test area, well reports, regional maps and topical reports mainly housed in the Wyoming Oil and Gas Conservation Commission, WSGS, and the United States Geological Survey.

This book traces the steps taken by CMI and the WY-CUSP program to get from minimal regional data to a complete characterization of the Rock Springs Uplift as a certified commercial-level geological CO_2 storage site.

This trek will be described in 14 chapters covering the following subjects: (1) global warming and climate change: 45 million-year-old rocks in Wyoming support the concept (the context, need and role of CCUS in solving this global problem); (2) regional inventory and prioritization of potential CO_2 storage reservoirs in Wyoming: the origins of the WY-CUSP program—the search for the highest priority CO_2 geological storage site in the Rocky Mountain Region; (3) legal framework: carbon storage regulations, required permits and access to the study area; (4) the development of the WY-CUSP site characterization strategy—the role of 3-D seismic surveys and stratigraphic test wells; (5) storage site selection, with special emphasis on the proximity to sources of both anthropogenic and natural CO_2; (6) retrieval of crucial geologic data: the importance of a stratigraphic test well and 3-D seismic survey—key observations derived from core, well logs, borehole tests and seismic attribute acquisition; (7) utility of 3-D seismic attribute analysis and a VSP survey for assessing potential carbon sequestration targets (8) hydrologic data acquisition and observations—the importance of characterizing formation fluids; (9) predicting spatial permeability in targeted storage reservoirs and seals on the RSU– a method that increases the accuracy of 3-D flow simulations of CO_2 storage applications; (10) advances in estimating the geological CO_2 storage capacity of the Madison Limestone and Weber Sandstone on the RSU by utilizing detailed 3-D reservoir characterization and geological uncertainty reduction (numerical simulations that include 3-D heterogeneity of reservoir petrophysical properties; displaced fluid/pressure management; (11) displaced fluid management—the key to commercial-scale geologic CO_2 storage; (12) illustration of the advantages of deploying innovative, multiple-resource development strategies designed to foster the sustainability of energy and environmental resources—strategies that greatly increase the value of CO_2 storage and utilization; (13) a feasibility study of the integration of geological CO_2 storage with enhanced oil recovery (CO_2 flooding) in the Ordos Basin, China and elsewhere; and (14) WY-CUSP integrated strategy for the detailed and accurate characterization of potential CO_2 storage reservoir and storage sites. Taken together these 14 chapters represent an effective and efficient process to improve estimates of CO_2 reservoir storage capacity, to evaluate the long-term integrity and permanence of confining layers, and the management of injection pressures and brine production and treatment in order to optimize CO_2 storage. Although the chapters in this book represent important steps to evaluating and optimizing CO_2 storage, each of the chapters is designed to stand alone.

Our aim in constructing the book was to positively affect and assist future global CO_2 storage and utilization projects. It is our firm belief that continued industrialization and global expansion of quality of life will require ever-increasing efforts to effectively store GHG emissions—without an exponential increase in the effort to store CO_2, neither further industrialization or global improvements in the quality of life and standard of living will be possible. Hopefully this book will expedite the global effort to retrieve energy, while sustaining environmental quality. Anyone interested in CCS, or CCUS should find this body of work helpful in executing their own projects to provide economic energy, while minimizing the development of undesireable environmental footprints. There is an old adage that, "a smart person learns from experience, but a wise person learns from the experience of others." It is with that thought that we offer the WY-CUSP experience for the benefit of all others in their efforts to decrease or stabilize global GHG emissions by utilizing CO_2 geological storage.

Acknowledgements

The Wyoming Carbon Underground Storage Project (WY-CUSP) site characterization project is funded in part by the U.S. Department of Energy's National Energy Technology Laboratory (Project DE-FE0002142), and the Carbon Management Institute (CMI) would like to thank D.O.E. and our D.O.E. Project Manager Bill Aljoe. Also CMI acknowledges the financial support from the State of Wyoming. We acknowledge the help of Terry Miller in set up of the finite volume grids; and Phil Stauffer and Hailing Deng for help with details of FEHM. In addition, thanks to Dynamic Graphics, Inc. for allowing us to use their EarthVision software and to Schlumberger for allowing us access to their Eclipse and Petrel software packages. Also, we acknowledge the support provided by the Wyoming Oil and Gas Conservation Commission and the Department of Environmental Quality. Very importantly, we thank Shanna Dahl, Shauna Bury, and Allory Deiss—all colleagues at CMI—for their outstanding support.

Also we acknowledge the contributions provided to the WY-CUSP program and construction of this book made by our colleagues at the University of Wyoming: Erin Campbell-Stone and Ranie Lynds, Jim Myers and Robert Kirkwood, John Kaszuba and Vladimir Alvarado, Subhashis Mallick, Carol Frost, and their students. For the chapter on the Ordos Basin the contributions of Yongzhen Chen, Tin Tin Luo, and Jiaping Gao from the Shaanxi Provincial Institute of Energy Resources and Chemical Engineering at Northwest University, Xian, and the Yanchang Petroleum Company are acknowledged.

The Laboratory contributions made by the following facilities are gratefully acknowledged: Intertek Laboratory, USGS Core Libraries, Wyoming Analytical Laboratories, UW Stable Isotope Facility, UW Materials Characterization Laboratory, Energy Laboratories, and Wagner Petrographics.

Lastly, we acknowledge the support provided to the WY-CUSP program by our partners: Baker Hughes, Inc., including Paul Williams, Sam Zettle, Dana Dale, and Danny Dorsey, and TRUE Drilling Co. of Casper, WY.

Other major contributors to the WY-CUSP include Los Alamos National Laboratory, Lawrence Livermore National Laboratory, PetroArc International, New England Research, Geokinetics, EMTek, and the Wyoming State Geological Survey.

Other significant supporters of the WY-CUSP program include UW Vice-President of Research Bill Gern, UW Provost Myron Allen, and Mark Northam, Director of the UW School of Energy Resources. Lastly, Lynne Boomgaarden was a truly invaluable member of our team by providing the legal expertise and ability to expedite a multitude of required county, state, and federal permits, and David Copeland, a key member of our team, particularly with respect to editing manuscripts and organizing figures. To both Lynne and David we gratefully acknowledge your support.

Thanks to all the above individuals, institutions, and corporations that played a role in the success of the WY-CUSP Program.

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Chapter 1
Geological Observations Supporting Dynamic Climatic Changes

Ronald C. Surdam

Abstract The Eocene Green River Formation in Wyoming has long served as a standard for lacustrine depositional systems. This lacustrine formation, excluding the culminating phase, was deposited in a closed hydrographic basin. The position of the boundary between lake and mudflat margin was dictated by the inflow/evaporation ratio (inflow greater than evaporation = transgression; inflow less than evaporation = regression). All members of the Green River Formation are characterized by repetitive stratification sequences. In the Tipton and Laney members, the repetitive stratification sequences are laminated, kerogen-rich carbonates with fish fossils overlain by dolostone with numerous desiccation features. In contrast, in the middle member (Wilkins Peak), the typical stratification sequence is trona (evaporate) overlain by dolostone, overlain by kerogen-rich carbonate (oil shale). All these stratification sequences can be explained as products of dynamic climate change and a consequent imbalance between inflow and evaporation which probably resulted from the earth's processional variations. The evidence for global warming and climate change (prior to anthropogenic green house gas (GHG) emissions) is undeniable. The crucial question is, *are anthropogenic GHG emissions accelerating the rate of climate change?* The confluence of rising global temperature with substantial increases in GHG emissions since the beginning of the industrial revolution strongly suggests that the answer to this question is *yes*.

1.1 Climate Change and Global Warming

Over the past decade, the development of carbon capture and storage (CCS), and of clean coal technology in general, has been closely linked to climate change and global warming. As a result, some CCS detractors have discounted the importance of CCS because they simply do not believe in climate change and global warming. Much of the disagreement and resulting criticism of the importance of CCS in

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R. C. Surdam (ed.), *Geological CO_2 Storage Characterization,*
Springer Environmental Science and Engineering, DOI 10.1007/978-1-4614-5788-6_1,

near-future global energy/industrial development stems from some policymakers' misperceptions of the role of science in this controversy. In brief, science does not uncover truths: rather, science reduces uncertainties. When, over time, all observations, experiments, and measurements from diverse scientific disciplines—without serious contradiction—support a working scientific hypothesis, it becomes scientific doctrine. Examples of this process include Darwin's theory of evolution and Einstein's theory of relativity. A theory becomes doctrine when uncertainties related to the theory have been reduced as much as possible (typically, when all available observations support the stated theory). It is important to realize that scientific doctrine is not *truth*, for future new observations, experiments, and measurements may require modification or replacement of the doctrine. Thus, established scientific doctrine is constantly tested over time.

Ideologues, particularly with respect to religious and sociopolitical programs, often find themselves in contentious debate with scientific doctrine because their dogma is based in faith (firm belief in truths not subject to scientific testing). Such irresolvable debates between faith-based dogma and scientific doctrine are often marked by bitterness, divisiveness, and partisanship. No resolution of these debates seems possible because no common ground between static truth and dynamically evolving scientific doctrine exists.

Scientists debate, too, but resolution tends to follow from a mutual effort to reduce uncertainty. Initially, when the ideas of climate change and global warming—and particularly their relationship to greenhouse gas (GHG) emissions—were proposed, the scientific community was divided, and healthy debate ensued. Over time, scientific doubt concerning the relationship between GHG emissions and global warming has waned and almost disappeared, largely due to the convergence of affirmative results from multidisciplinary scientific research and testing. At present, a strong scientific consensus that anthropogenic GHG emissions are contributing to global warming exists.

To those of us familiar with the geology of the lacustrine Eocene Green River Formation in Wyoming, Colorado, and Utah, this consensus is not surprising. As discussed in the following section, scientists studying the stratigraphic framework of the Eocene Green River Formation have long considered global warming and climate change to be essential concepts that explain observations about the dynamics of ancient lakes Gosiute and Uinta (Green River Formation).

1.2 Ancient and Modern Analogs of Climate Change

The Green River Formation deposited in Eocene Lake Gosiute in southwestern Wyoming and northern Colorado is stratigraphically divided into three members, from bottom to top the Tipton, Wilkins Peak, and Laney members (Fig. 1.1). Both the Tipton and Laney members are characterized by numerous oil shale and dolostone layers (laminated kerogen-rich or kerogen-poor carbonates), and the Wilkins Peak Member is characterized by 42 or more trona beds and some oil shales

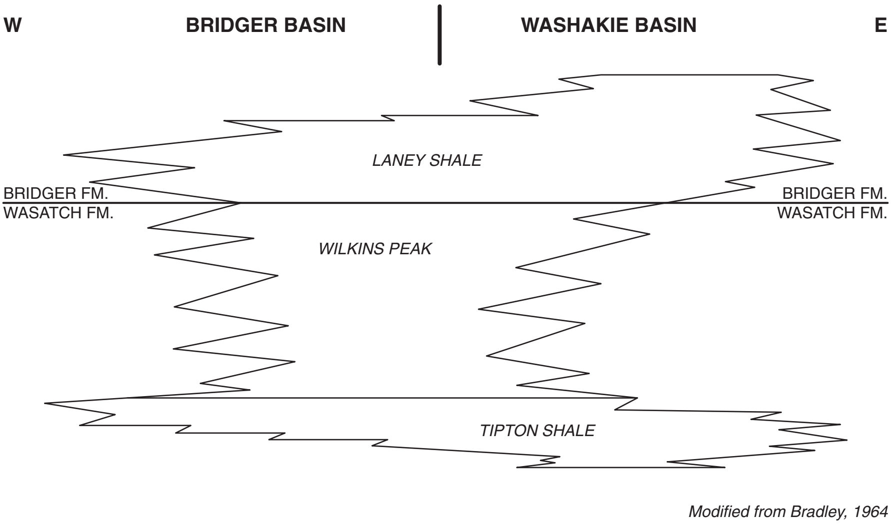

Fig. 1.1 Generalized stratigraphic framework of the Eocene Green River Formation in southwestern Wyoming (Tipton, Wilkins Peak, and Laney members). (Modified from Bradley 1964)

(Culbertson 1971). Typically, these three members are interpreted, respectively, as high, low, and high stands of Lake Gosiute. The Tipton and Laney members, dominated by kerogen-rich carbonate deposition (oil shale), are generally considered to represent a humid climate with marked seasonality (similar to that of present-day central Florida; Bradley 1973). The Wilkins Peak Member, dominated by evaporites, represents a humid climate with substantial seasonal aridity (similar to the present-day bottom of the East African Rift Valley; Eugster and Surdam 1973).

The sedimentology and resultant stratigraphy and stratification sequences characterizing each of these members were produced in a highly complex depositional system best described as a “playa-lake complex” (Eugster and Surdam 1973; Bradley 1973; Surdam and Wolfbauer 1975; Eugster and Hardie 1975; Surdam and Stanley 1979). In all stages but its culminating phase, the lake occupied a closed hydrographic basin with a lacustrine environment transgressing or regressing across a fringing playa mudflat (across an extremely low topographic gradient of probably 1–2 feet per mile) as a result of an imbalance between inflow and evaporation (Fig. 1.2). On the basis of paleobotanical evidence, MacGinitie (1969) suggested that Lake Gosiute was approximately 1000 feet above sea level during the Eocene (approximately 45 m.y.b.p.). Lake Gosiute persisted for approximately 4 million years during the Eocene (Bradley 1964). The lake level fluctuated often, with oil shale and trona beds as alternating products. Consequently, the stratification sequence in each member represents a detailed record of this dynamic inflow/evaporation imbalance (climatic change) during the Eocene.

First, consider a typical stratification sequence in the Laney Member on the playa-lake fringe (Fig. 1.3a). The sequence starts with strandline deposition (algal rip-ups, algal stromatolites, pisolites/oolites, and/or ostracodal limestones) over-

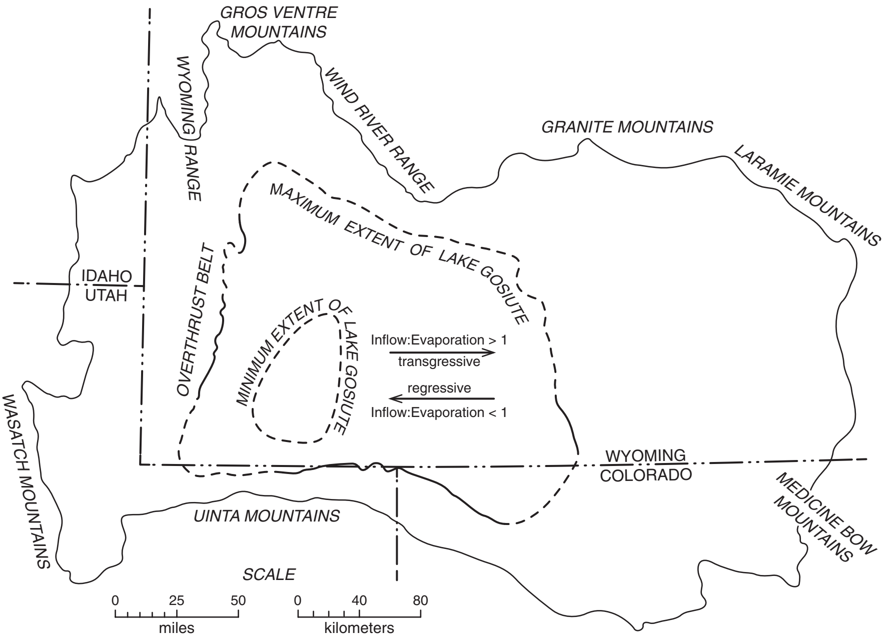

Fig. 1.2 Closed hydrostratigraphic basin characterizing all but the culminating stages of ancient Lake Gosiute. Also shown are the maximum and minimum extents of Eocene Lake Gosiute. (Modified from Bradley 1964)

lain by kerogen-rich laminated carbonate (oil shale) commonly containing fossil fish. Finally, the lacustrine portion of the sequence is overlain by dolomitic mudflat deposition commonly including saline mineral casts and molds, mud-cracks, and Magadi-type chert. This stratification sequence, or some modification of the sequence, was repeated vertically as the lake transgressed and regressed across a particular geographic location (Fig. 1.3b). In positions near the geographic center of Lake Gosiute during the Laney stage, the repetitive stratification sequences consist of alternating kerogen-rich and kerogen-poor laminated carbonate (Fig. 1.3c). When the playa fringe was minimized (inflow: evaporation ratio >1), the laminated carbonate is kerogen-rich and calcitic, whereas when the playa fringe is more dominant (inflow: evaporation ratio <1), the laminated carbonate is kerogen-poor and dolomitic (Fig. 1.3d). The Laney stratification sequences shown in Fig. 1.3a–d are typical of the interaction of the lake and fringing playa mudflat as the climate changed: variable inflow-to-evaporation ratio in a closed hydrographic basin. The Laney stratification sequences shown in Fig. 1.3c,d are typical of the sedimentologic changes that took place at the lake center as a result of climatic changes in the closed hydrographic basin during a relatively high stand of the lake.

During a relatively low stand of Lake Gosiute (Wilkins Peak Member), the depositional system also was characterized by imbalances between inflow and evaporation strongly influenced by climatic changes (Fig. 1.4a). Typically, the stratification

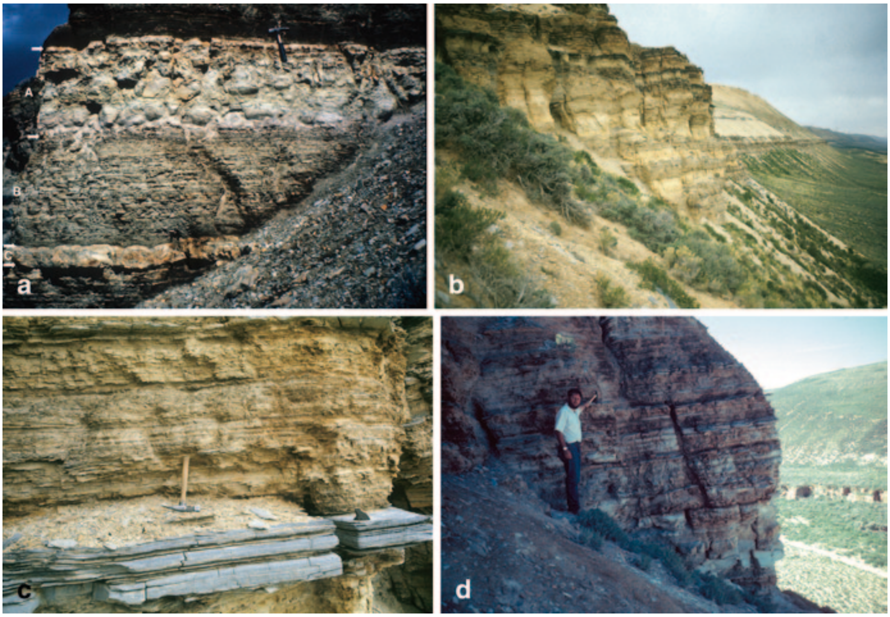

Fig. 1.3 **(a)** Typical lacustrine depositional cycle in the Laney Member along the Kinney Rim. The strandline deposits [C] composed of stromatolites, pisolites/oolites and/or ostracodal limestones, overlain by kerogenous laminated carbonates (oil shale [B] commonly containing fossil fish), is overlain by dolomitic mudstone [A] including saline mineral casts/molds, mudcracks, and Magadi-type chert. This stratification sequence is interpreted as the result of the lake transgressing over the playa-mudflat fringe (inflow:evaporation >1) and then regressing sharply due to an abrupt change in the regional inflow:evaporation ratio (>1). Rock hammer for scale. **(b)** Repetition of stratigraphic sequence shown in (a). View is to the south along the Kinney Rim, demonstrating the repetitive nature of the transgressive/regressive stratification sequences (lake-mudflat-lake). Within both the lacustrine and mudflat portions of the sequence, many vertical variations best explained by climatic dynamics exist, but note the sharp contact between the dark lacustrine sequences and the light mudflat sequences (indicating an abrupt lake-level decline). In the background, the buff-colored sequence is a tuffaceous-evaporite lithofacies (dolomite/analceme-rich rock with nahcolite/trona molds) that separates the Laney Member into similar upper and lower portions. **(c)** Stratification sequence characterizing rocks deposited in the Laney Member in a lake-center position. Note that unlike the stratification sequence shown in Fig. 1.3a (a more marginal lake position), there are no strandline deposits, but instead layers of kerogen-rich laminated carbonates (high stand with reduced influence of the fringing playa mudflat) overlain by kerogen-poor laminated carbonate (significant influence from the fringing mudflat). Both lithofacies were deposited in a lacustrine environment. Rock hammer for scale. **(d)** Repetitive stratification sequences in laminated carbonate lithofacies near geographic center of Lake Gosiute during Laney stage. Sequences are alternating layers of kerogen-rich (dark) and kerogen-poor (light) laminated carbonate in the lower part of the Laney Member at Green's Canyon near Green River, Wyoming. Kerogen-rich layers consist of calcite (depositional system dominated by lacustrine processes), whereas the kerogen-poor layers consist of dolomite (depositional system dominated by playa mudflat processes)

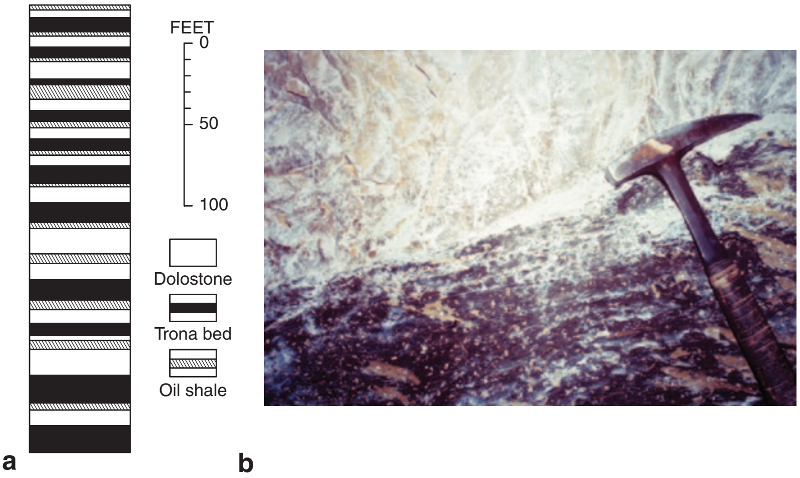

Fig. 1.4 **(a)** Partial composite columnar section of Wilkins Peak Member (Green River Formation) in the trona area of Wyoming. (Modified from Culbertson 1971). **(b)** Sharp contact between oil shale (black) and trona (white) from underground at trona mine. This photo illustrates the relationship between oil shale and trona shown in the Wilkins Peak Member in Fig. 1.3a. The sharp boundary is best interpreted as indicating an extremely rapid climatic change (change in inflow:evaporation ratio) from high-stand conditions to low-stand conditions

sequence starts with an evaporite deposit (i.e., trona with or without halite deposited from a concentrated brine-rich alkaline fluid column–relatively organic-poor and highly evaporitic lake/pond within the minimum extent of the lake) (Fig. 1.2), overlain by a dolostone (lacustrine environment dominated by a wide fringing mudflat—transport of dolomitic mud from playa fringe to lacustrine environment), and in turn overlain by an oil shale (kerogen-rich carbonate deposited as the lacustrine environment was expanding) (Fig. 1.4a). There are approximately 42 individual trona beds within the Wilkins Peak Member, almost all of which are underlain by a bed of oil shale (Fig. 1.4b) (Culbertson 1971). The sharp contact between oil shale and trona deposition (Fig. 1.4a) could only have resulted from a drastic and abrupt change in inflow and evaporation as part of a highly dynamic climatic system.

In summary, all stratigraphic sequences in both the Laney Member (high stand) and Wilkins Peak Member (low stand) are the product of climatic factors (evaporation and inflow) that caused the lake to transgress (expand) and regress (contract) across a very low topographic gradient in a closed hydrographic basin. In a transgression, the lake expands and the playa fringe shrinks, whereas during a regression, the lake shrinks and the playa fringe expands (Fig. 1.2).

To understand the climatic variations characterizing ancient Lake Gosiute, it is useful to examine modern analogs of the two lithologic end members—oil shale and trona. After a comprehensive search for modern oil shale analogs, Bradley (1970) suggested that Mud Lake in central Florida has many comparable attributes. Mud Lake (Fig. 1.5a) is very shallow: in the driest seasons, it may be as shallow as 22 cm

Fig. 1.5 **(a)** Mud Lake, in modern-day central Florida. On the basis of the work of Bradley (1970), this lake is commonly cited as a potential modern analog for oil shale deposition. (Tracy Enright, US Geologic Survey photo) **(b)** Modern Lake Magadi, Kenya. Huge amounts of trona have been deposited in this lake over the last 10,000 years

deep, and in the wettest seasons it may be 85 cm deep. The algal sediment makes up a layer about 1 m thick at the bottom of the lake (Bradley 1970).

The modern analog for trona is Lake Magadi, which lies at the lowest point in the East African Rift, Kenya (Fig. 1.5b). Except during the rainy season, which is relatively short but intense, inflow into the lake comes mainly from peripheral springs.

The observations with respect to the stratigraphic sequence described above relate only to the pre-culminating stages of basin evolution: that portion of the lake characterized as a closed hydrographic basin (Fig. 1.6). In the culminating phase of Eocene Lake Gosiute (Green River Formation), the lake evolved from a closed hydrographic regime (saline alkaline lake) to an open hydrographic regime (freshwater lake). This evolution marked a substantial enlargement of the hydrographic basin (increased inflow from the north), a rapid increase in the progradation of terrigenous material from north to south, and an outflow of lake water into the Piceance Creek basin to the south (Fig. 1.6) (Surdam and Stanley 1979, 1980).

Crucial in the analysis of climatic effects on the stratification sequences that characterize Lake Gosiute is determining the temporal aspects of the sequences in both high and low stands of the lake. In evaluating the stratigraphic sequence during a high stand of Lake Gosiute, a well-documented case from West Africa is pertinent to this discussion. Lake Bosumtwi in Ghana, West Africa is located in a meteorite impact crater in a rainforest. For at least 13,000 years, the crater has been a closed hydrographic basin (Talbot and Delibrias 1980). During this 13,000-year period, the high stands of the lake lasted for 2000–2500 years and were interrupted by short but intense regressions, or low stands (Fig. 1.7) (Talbot and Delibrias 1980; Talbot 1988; Talbot and Johannesson 1992). As shown in Fig. 1.7, the duration of lake level low stands ranged from 200 to 500 years, with very steep rates of lake level decline (inflow $\ll$ evaporation). In contrast, the high stands of the lake lasted longer and remained stable until punctuated by intense declines in lake level (Fig. 1.7).

Insight into the temporal aspects of stratigraphic sequences characterizing the Wilkins Peak Member can be gained by observing a trona-depositing modern analog: Lake Magadi in Kenya (Baker 1958, 1963; Eugster 1969, 1970). The

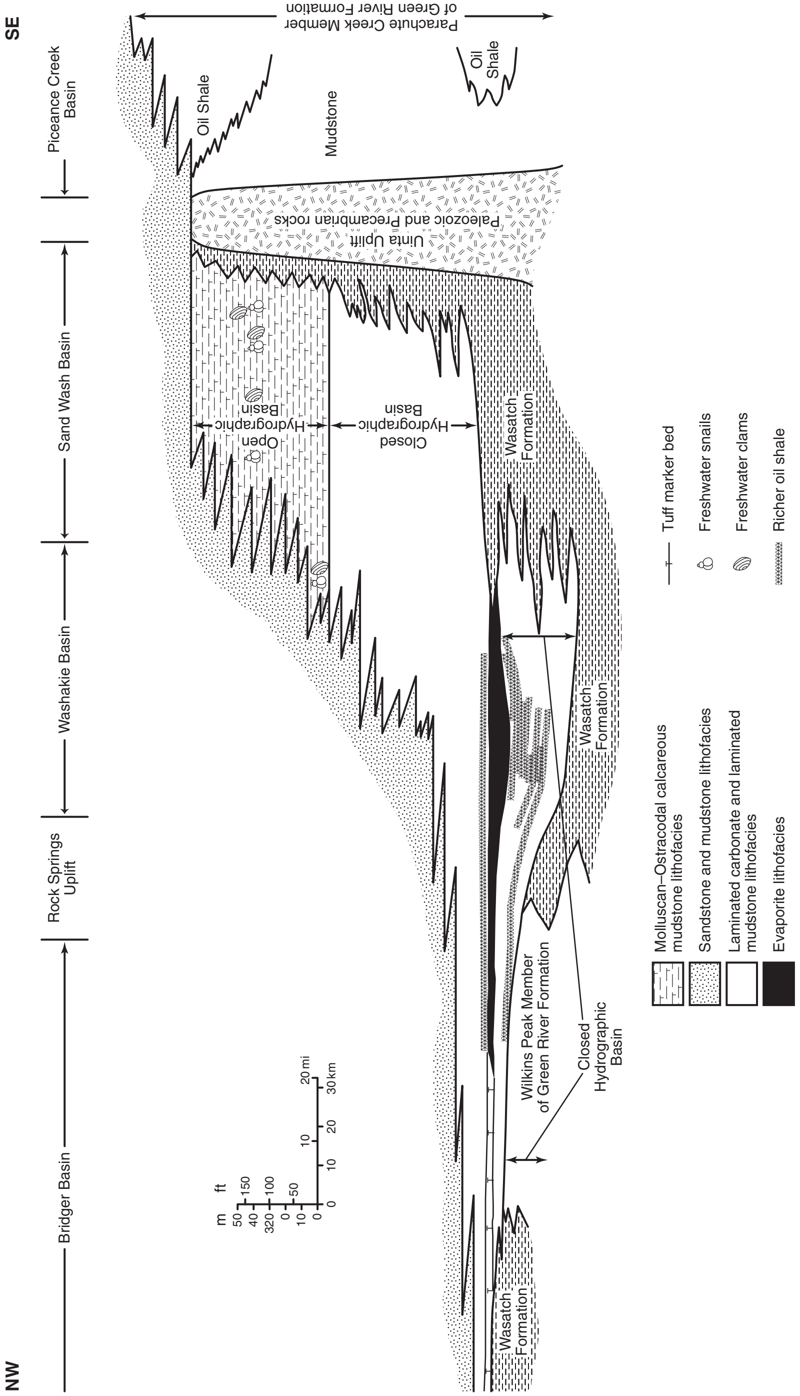

Fig. 1.6 Lithofacies and marker beds from northwest to southeast in the Laney Member, Green River Formation, Wyoming and Colorado. This cross section demonstrates that during deposition of the Laney Member, Lake Gosiute evolved from a playa lake with oil shale deposition, to a playa with evaporate deposition, to a playa lake with oil shale deposition, and finally to a fresh water lake. During all but the final stages of the lake, the hydrographic basin was closed, and deposition was controlled by the imbalance between inflow and evaporation. In the fresh-water stage, the hydrographic basin expanded and became open with additional inflow from the north and outflow to the south in the Piceance Basin. This chapter deals with Lake Gosiute only during the time period in which the hydrographic basin was closed. (Modified from Surdam and Stanley 1979)

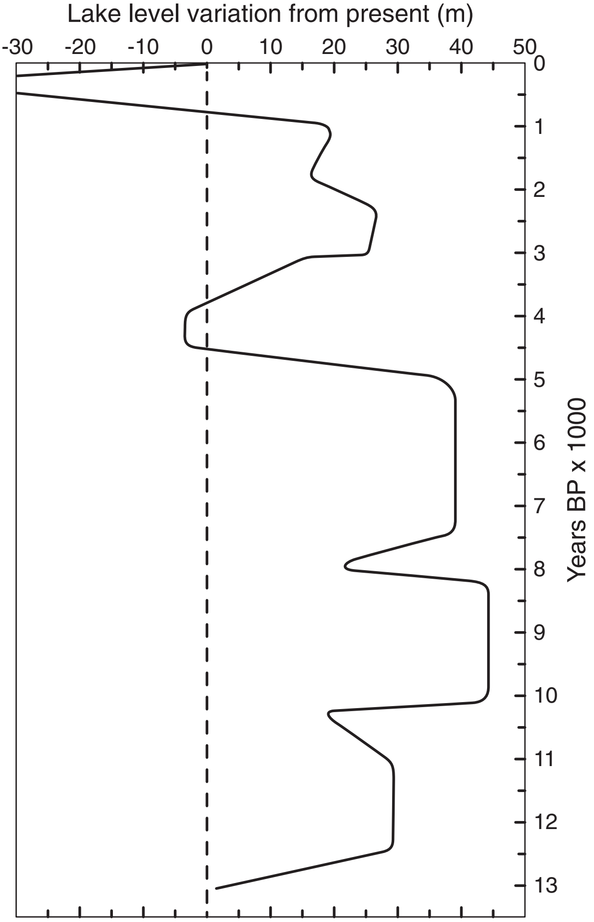

Fig. 1.7 Water level curve for Lake Bosumtwi, Ghana, West Africa over the past 13,500 years. Lake Bosumtwi is a crater lake in a closed hydrographic basin, and has been for at least the past 13,000 years. (Modified from Talbot and Delibrias 1980)

present-day evaporite series at Lake Magadi is characterized by substantial trona deposition (Fig. 1.8a). The 9100-year-old, organic-rich High Magadi Beds along the basin margin clearly express an earlier high stand of Lake Magadi (Fig. 1.8b). These are organic-rich laminated beds with a mineralogic composition of detrital silicates, saline minerals, calcite, sodium silicates, quartz, and authigenic zeolites (Surdam and Eugster 1976) (Fig. 1.8c). So, in 9000–10,000 years, the Lake Magadi depositional system (closed hydrographic basin) has evolved from organic-rich laminated sediments to trona deposits (Fig. 1.13a,c) as a result of a marked decrease in the inflow: evaporation ratio.

In both modern analogs described (high and low stands of lakes Bosumtwi and Magadi), the formation of the most recent “modern” stratification sequence occurred over 2500–10,000 years. In both cases, the stratification sequences forming at lakes Bosumtwi and Magadi are the result of climatic change. Stratification sequences of 2500–10,000 years duration fit neatly with the number of observed

Fig. 1.8 **(a)** Modern trona mining operation at Lake Magadi, Kenya. The dredge is extracting the trona beds; if the dredge shut down, it would become trona-locked because the brine is saturated with trona. The trona beds are masses of trona crystals filled with brine. As the trona is mined, the brine flows out of the trona to form the “lake” upon which the dredge is floating. **(b)** Present-day Magadi mudflats with trona efflorescent crust. The 10,000-year high-stand shoreline of Lake Magadi (High Magadi Beds) is in the background. **(c)** High Magadi Beds associated with the high-stand shoreline shown in (b). The sediments are organic-rich (black) with fish fossils. The white layers consist of magadiite, a hydrous sodium silicate that, with time, reacts to Magadi-type cherts. Carbon-14 dating suggests that these organic-rich sediments are approximately 10,000 years old. Therefore, over the past 10,000 years the lake evolved from a relatively fresh lake supporting a fish population to a saline, alkaline lake precipitating trona

stratification sequences in the Tipton, Wilkins Peak, and Laney members of the Green River Formation, and are compatible with the age dates for the Lake Gosiute temporal framework.

In summary, during the last 10,000 years in “modern” lacustrine environments, the same types of stratification sequences are observed as those repeatedly characterizing the high- and low-stand stratigraphic framework of ancient Lake Gosiute. Although the detailed climatic mechanisms driving the Eocene climate are not well understood, the best explanation for the Eocene stratification sequences is that they are the product of climatic changes resulting in substantial alterations in inflow: evaporation ratios in a closed hydrographic basin.

Fischer and Roberts (1991), studying the organic-rich laminated sediments in the Green River Formation, considered the coupled kerogen-rich and kerogen-poor layers as the result of varving (record of a year’s deposition), as did Bradley (1929). Fischer and Roberts (1991) and Ripepe et al. (1991) interpreted the variations in thickness, lithology, and color banding of the laminae couplets and series of couplets as the result of climatic change within the lacustrine environment. They suggested two strong bimodal periodicities, one following a six-year cycle resulting from an El Niño-type (ENSO) phenomenon of atmospheric dynamics, the other following an eleven-year pattern interpreted as the result of the sunspot cycle (Fischer and Roberts 1991; Ripepe et al. 1991). On a larger scale, they observed processional variations with a mean period of 20,000 years and a bundling of a set of five of these on the 100,000-year eccentricity cycle. The observations of small- and large-scale depositional aspects (cyclical variations) in the stratigraphic framework of ancient Eocene Lake Gosiute can be explained neatly by such climatic dynamics. According to Fischer and Roberts, the Surdam and Stanley (1979) interpretation of regressional shoreline cycles in the Green River Formation as processional cycles is well founded.

1.3 Global Warming—Trends and Projections

The geologic evidence for climatic change in present and ancient lacustrine environments in closed hydrographic basins is overwhelming. The vital question remaining is whether the huge increase in anthropogenic greenhouse gas emissions that began during the Industrial Revolution and continues today is accelerating the rate and intensity of climate change and global warming.

The scientific consensus is that the rapid increase in CO_2 emissions since 1900 is due to anthropogenic causes, particularly the burning of fossil fuels: from 1850–2000, annual anthropogenic CO_2 emissions increased exponentially from millions of tons to 4 billion tons (USEIA 2012). As a result, assessments by the Intergovernmental Panel on Climate Change (IPCC) (Meehl et al. 2007) suggest that the earth's climate has warmed by 1.1–1.6 °F over the past century, and that anthropogenic activity is "very likely" a dominant driving factor. Most importantly, according to the National Oceanic and Atmospheric Administration's National Climatic Data Center (2012), the warming of the globe has continued over the last decade.

In 2013 at the Hawaiian monitoring site atmospheric CO_2 was measured at 400 ppm. In 1958 the level of atmospheric CO_2 was 350 ppm, so CO_2 concentrations in the atmosphere have increased approximately 1 ppm/yr. Globally at this rate the atmospheric CO_2 concentration will reach 450 ppm in 50 years or less, and will be accompanied by a 2 °C increase in global temperature. A 2 °C in global temperature increase could result in forests in Greenland and sea level rises of 10–20 m (33–66 ft). The most alarming climate observation occurred from 1961 to 2008. The total heat content of the oceans has increased by approximately 225×10^{21} joules. (Church et. al., 2011). Clearly the danger is that the rate of global climate change will outstrip the rate of human adaptation!

The National Research Council (2011) predicts that without stabilization of CO_2 emissions at near-present-day levels, the following global and North American changes will occur.

Key global projections:

- For every 2 °F of warming, models project about a 15 % decrease in the extent of annually averaged sea ice and a 25 % decrease in September Arctic sea ice.
- The coastal sections of the Greenland and Antarctic ice sheets are expected to continue to melt or slide into the ocean. If the rate of this ice melting increases in the 21st century, the melted ice sheets would add significantly to global sea level rise.

Key US projections:

- Northern hemisphere snow cover is expected to decrease by approximately 15 % by the year 2100.
- Models project that the snow season will continue to shorten, with snow accumulation beginning later and melting starting earlier. Snowpack is expected to decrease in many regions.
- Permafrost is expected to continue to thaw in northern latitudes. This would have large impacts in Alaska.

1.4 Global Warming—the Challenge and a Necessary and Viable Countermeasure

It is evident that in North America and elsewhere on the planet, these changes will result in increased average temperatures, more frequent and intense heat waves and drought, northern areas becoming wetter and southern areas becoming drier, more heavy precipitation events, precipitation falling as rain rather than snow, and more frequent and intense Atlantic hurricanes. With anthropogenic greenhouse gas (GHG) emissions continuing to increase at the present rate, the timing of “tipping points” for adaptation will accelerate while climatic effects intensify, with societal costs rising prohibitively. Obviously, such predicted changes—should they become reality—would devastate humankind.

The work presented in this book is vitally important because carbon capture and sequestration/storage is currently the only known way to stabilize anthropogenic greenhouse gas emissions in a world of unconstrained industrialization. During the 21st century, nations with expanding economies will not be able to continue to grow without ever-increasing GHG production: in this situation, the availability of technology capable of stabilizing or reducing atmospheric GHG emissions is absolutely essential. In the following pages we will offer a strategy for storing huge amounts of CO_2.

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Chapter 2
The Story of the Wyoming Carbon Underground Storage Project (WY-CUSP), and the Regional Inventory and Prioritization of Potential CO_2 Storage Reservoirs in Wyoming

Ramsey D. Bentley and Ronald C. Surdam

Abstract The Wyoming Carbon Underground Storage Project (WY-CUSP) is a statewide effort to identify, inventory, prioritize, and characterize the most outstanding CO_2 storage reservoirs and the premier storage site in Wyoming. The WY-CUSP project is managed by the Carbon Management Institute (CMI) at the University of Wyoming with support from the US Department of Energy, State of Wyoming, and industrial partners. In its search for an optimum carbon dioxide storage reservoir in Wyoming, CMI first inventoried and examined the state's hydrocarbon reservoirs, for these are reservoirs with proven fluid storage capacity. The inventory and prioritization of storage reservoirs and storage sites was based on the following criteria: (1) thickness, areal extent, and petrophysical properties of the reservoir rocks, (2) presence of a fluid trap and adequate confining layers, (3) suitable temperature, pressure, and rock/fluid chemistry regimes, (4) salinity of the formation fluids in the storage reservoir rocks, and (5) volumetrics of the storage site. It became apparent that the Mississippian Madison Limestone and Pennsylvanian Weber/Tensleep Sandstone were the highest-priority potential CO_2 storage stratigraphic intervals, and that the Rock Springs Uplift (RSU) in southwestern Wyoming was the premier CO_2 storage site in the state. A drill site on the northeastern flank of the RSU was highly prospective in offering high-quality reservoir rock at a depth that provides sufficient temperature and pressure for carbon dioxide storage. A very-large-scale, large-capacity trap on the RSU has several competent sealing rock units, and available data show that the reservoir rocks contain very saline formation water. Abundant sources of carbon dioxide are nearby, notably the Jim Bridger Power Plant.

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R. C. Surdam (ed.), *Geological CO_2 Storage Characterization,*
Springer Environmental Science and Engineering, DOI 10.1007/978-1-4614-5788-6_2,

2.1 WY-CUSP and the RSU Model

The Wyoming Carbon Underground Storage Project (WY-CUSP) is a pioneering research initiative to investigate and characterize two potential carbon storage reservoirs, the Weber and Madison Formations, both deep saline aquifers on the Rock Springs Uplift (RSU) in southwestern Wyoming. WY-CUSP is managed by the Carbon Management Institute (CMI), a part of the University of Wyoming, School of Energy Resources. Scientists from the University of Wyoming, the Wyoming State Geologic Survey, and Los Alamos National Laboratory, and industry partners collaborated with CMI on the project. The WY-CUSP Program has resulted in a detailed characterization of the potential storage reservoirs and storage site.

Site characterization is the process of assessing the suitability of a reservoir for CO_2 storage. This process includes conducting geophysical surveys, drilling test wells, and using sophisticated computer models to predict where the injected CO_2 will migrate, how efficiently the storage volume will be filled, and how well the storage site will perform over time. The strategy, evolution, techniques, and results of our site characterization on the Rock Springs Uplift, described in subsequent chapters, compose the RSU Model for carbon sequestration, storage, and use.

2.2 Inventory and Evaluation of Potential Storage Reservoirs

To inform our choice among possible CO_2 storage reservoirs and storage sites in Wyoming, CMI first inventoried and examined the state's hydrocarbon reservoirs, for these are reservoirs with proven fluid storage capacity. Wyoming has an abundance of hydrocarbon reservoirs. To determine their suitability as target sites and formations for carbon storage and sequestration, these reservoirs were inventoried and examined statewide. Every major sedimentary basin in the state showed potential, and each contained the promising target formations described below, although in a variety of geologic settings (Fig. 2.1). Cretaceous reservoirs in the Powder River Basin were of particular interest, as were several older and deeper Paleozoic units in all the basins.

To identify an optimum CO_2 storage reservoir in Wyoming and a corresponding optimum WY-CUSP test well site, CMI prioritized reservoirs on the basis of the following characteristics (Surdam and Jiao 2007):

- Reservoir rock of sufficient area and thickness (capacity) and with sufficient porosity (unit capacity, percentage of voids) and permeability (deliverability) to accommodate substantial amounts of CO_2.
- A fluid trap, a geologic setting in which the reservoir-rock fluids are trapped by adjacent nearly impermeable rock units and sealing faults.
- Reservoir conditions of temperature, pressure, and rock/fluid chemistry that allow the reservoir to accept large amounts of CO_2 without incurring damage.

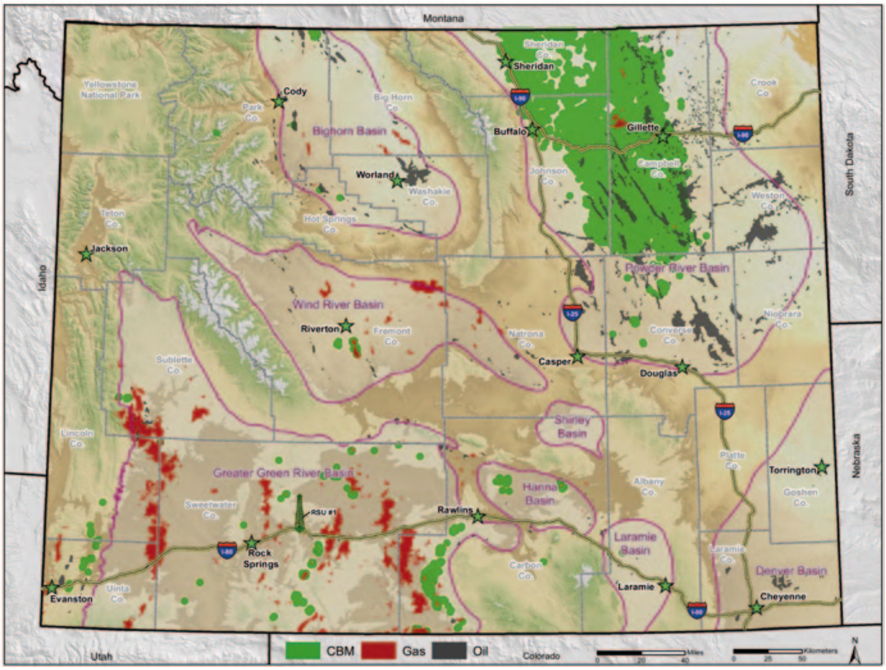

Fig. 2.1 Major sedimentary basins and hydrocarbon reservoirs in Wyoming. Modified from Debruin, 2007, 2012

- Water quality in the reservoir of more than 10,000 ppm total dissolved solids, as prescribed by the Safe Drinking Water Act Underground Sources of Drinking Water (USDW) criterion that groundwater containing less than 10,000 ppm total dissolved solids may be suitable for development as drinking water and therefore must be protected.

Upper and Lower Cretaceous rocks in the Powder River Basin (PRB) were targeted primarily because many of them were oil and gas producers characterized as discrete compartmentalized sandstone units fully sealed and encased by shales. Because they were isolated as compartmentalized units, once they had been produced for hydrocarbons and essentially "emptied out" of fluids they could provide space for CO_2 storage; their impermeable enclosing seals would preclude refilling by meteoric or formation water from aquifers above or below the compartmentalized units. Included in this field category was the Muddy Sandstone in several fields, including Amos Draw. Other targets included the Dakota Sandstone (uppermost Cloverly Formation) at Buck Draw, and the Shannon Sandstone at Hartzog Draw and Sussex Sandstone at House Creek (both members of the Cody Shale).

Although these field areas were promising, they are relatively small. Large storage capacity is necessary for commercial-scale sequestration because the sources of the CO_2, power plants and other stationary fossil-fuel-burning sites, produce large amounts of CO_2. This size factor does not preclude these smaller sites as potential