Burial Histories of Mississippian Potential Source and Shale-Gas Reservoir Rocks, Central and Western Utah

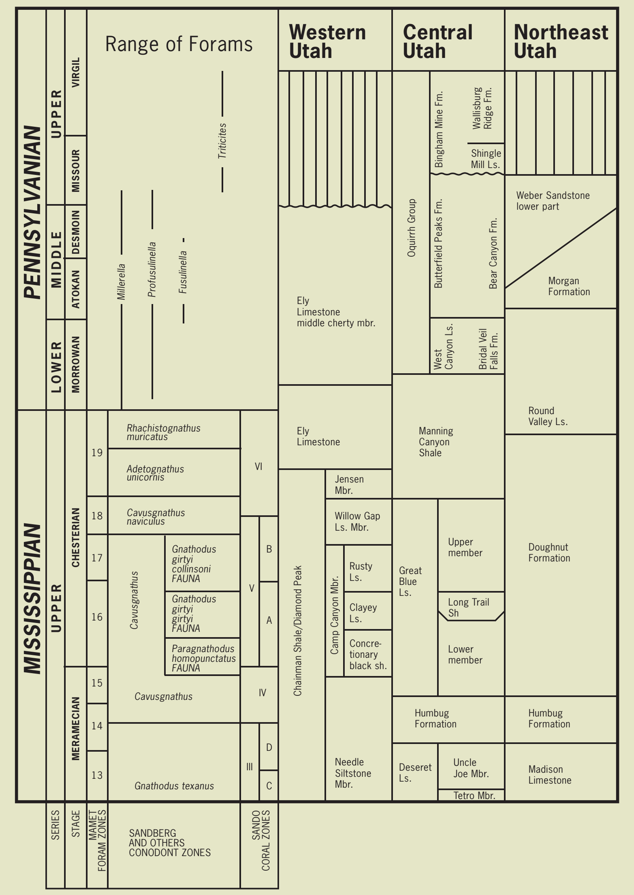
Robert Ressetar,
Utah Geological Survey
Salt Lake City, Utah

Abstract

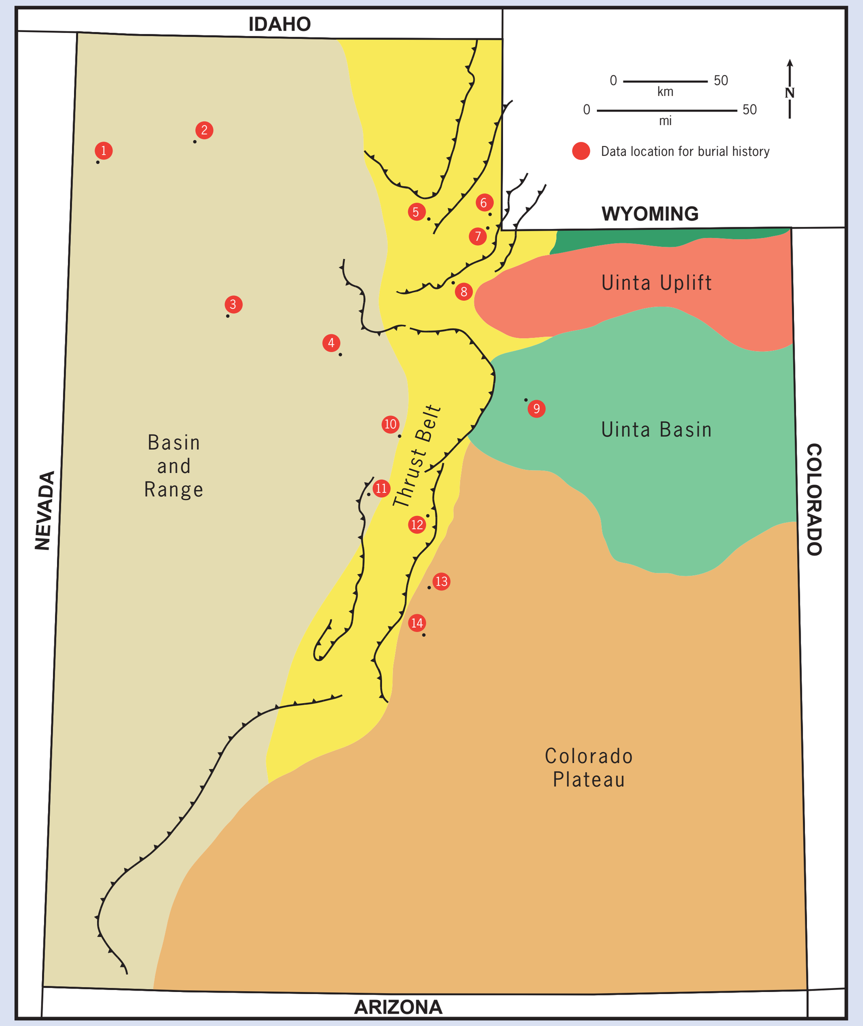
The Mississippian Manning Canyon and Chainman Shales and their equivalents in central and western Utah are potential hydrocarbon source rocks and shale-gas reservoirs. The Utah Geological Survey has constructed burial histories of these strata as an aid to both modeling their thermal maturation histories and understanding their reservoir properties. The Mississippian strata reached maximum burial depths of 18,000–40,000 feet in much of the area, but, as would be expected from the geological diversity of Utah, burial histories vary significantly with location.

In the Basin and Range Province of central Utah, Pennsylvanian-Permian subsidence of the Oquirrh basin dominated the burial histories. Farther west, Pennsylvanian subsidence was less pronounced, possibly due to tectonism identified in eastern Nevada or to development of the West Central Utah Highlands. Maximum depths were probably reached in the Jurassic, but erosion of most of the early Mesozoic section in the Basin and Range hinders reconstruction of this part of the record. Compression during the Sevier orogeny further buried some parts of the Mississippian section beneath foreland basin sediments and thrust sheets, whereas other sections were exhumed on the hanging walls of reverse faults. Locally thick sediments and volcanics contributed to additional burial in Cenozoic extensional basins.

In contrast, the Mississippian of the thrust belt east of the Basin and Range experienced relatively steady and less pronounced subsidence during the late Paleozoic and early Mesozoic. Burial histories of these sections show moderate subsidence in the Late Jurassic, probably related to development of the back-bulge basin of the Nevadan orogeny. Maximum burial depths were reached during pronounced Late Cretaceous and early Cenozoic subsidence of the Sevier foreland basin. As in the Basin and Range, post-orogenic continental deposits locally added to burial depths.



Upper Mississippian—Pennsylvanian Stratigraphy of Northern Utah (from Hintze and Kowallis, 2009).



The data locations for the burial histories stretch from northwestern to central Utah, and include sections in the Basin and Range, the thrust belt, the eastern Uinta Basin, and the eastern Colorado Plateau. Depending on location, the MCS and its equivalents have been affected to various degrees by late Paleozoic subsidence of the Oquirrh basin, the Jurassic Nevadan orogeny, the Cretaceous Sevier orogeny, and late Cenozoic Basin-and-Range extension.

Introduction

This poster presents the initial burial and maturation histories developed as part of the Utah Geological Survey's (UGS) assessment of the Paleozoic shale-gas resources of the Colorado Plateau and eastern Great Basin, Utah. These analyses focus on the Late Mississippian to Early Pennsylvanian Manning Canyon Shale (MCS) and correlative rocks in northwestern and north-central Utah. Later analyses will include the Mississippian Delle Phosphatic Shale and the Pennsylvanian Paradox Formation. The data for the modeled sections are from published descriptions of oil exploration wells and measured stratigraphic sections (pseudo wells). The burial and maturation histories were calculated using Platte River Associates' BasinMod 1-D®.

Deposition of the Upper Mississippian and Lower Pennsylvanian rocks of northern Utah occurred on a low-relief marine shelf that graded westward into the successor foreland basin of the Antler orogeny (Blakey, 1997; Trexler and others, 2004). The thickness of the MCS ranges between 500 and 1500 feet in much of northern Utah, but accurate measurements are scarce owing to the unit acting as a detachment surface for Mesozoic thrust sheets, and to its susceptibility to weathering and slumping in modern outcrops (Hintze and Kowallis, 2009). Total organic content of the MCS ranges from 1% to greater than 8%, and is probably mostly type III kerogen (Laine and others, 2008)

The data locations for the MCS burial histories stretch from northwestern to central Utah, and include sections in the Basin and Range, the thrust belt, the eastern Uinta Basin, and the eastern Colorado Plateau. Depending on location, the MCS and its equivalents have been affected to various degrees by late Paleozoic subsidence of the Oquirrh basin, the Jurassic Nevadan orogeny, the Cretaceous Sevier orogeny, and late Cenozoic Basin-and-Range extension.

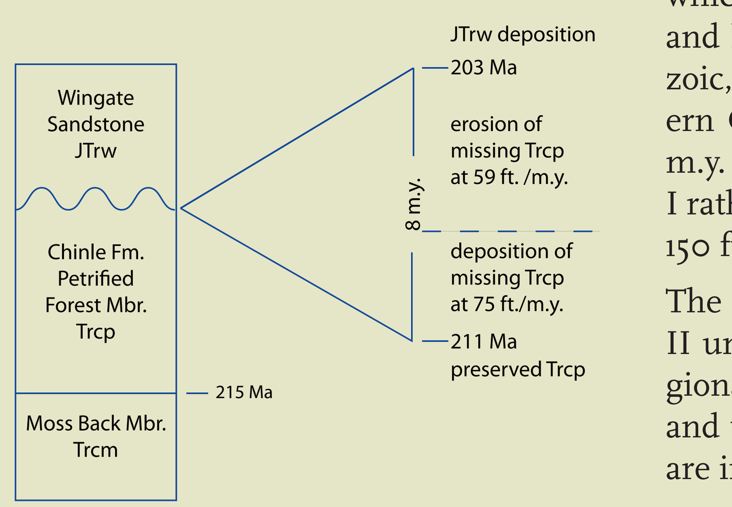
To calculate the burial histories, I usually entered the stratigraphic thicknesses of the MCS and overlying units as presented in the source of the data, but in a few cases I adjusted the thickness of the Phosphoria Formation and the Arapien Shale to reflect post-depositional structural thickening (see Sprinkel, 1994).

I estimated the amounts of section missing across unconformities by classifying two types:

1. Depositional unconformities occurred when relative base-level fall led to relatively brief (~5 to 25 m.y.) intervals of non-deposition and erosion.
2. Tectonic unroofing occurred when structural uplift of the sedimentary section resulted in erosion of the upper plates of thrust sheets. Erosion may have removed anywhere from insignificant amounts to the greater part of the sedimentary section.

Sample calculation of thickness deposited and eroded.

Phillips USA E-1 (#13)
J-0 unconformity

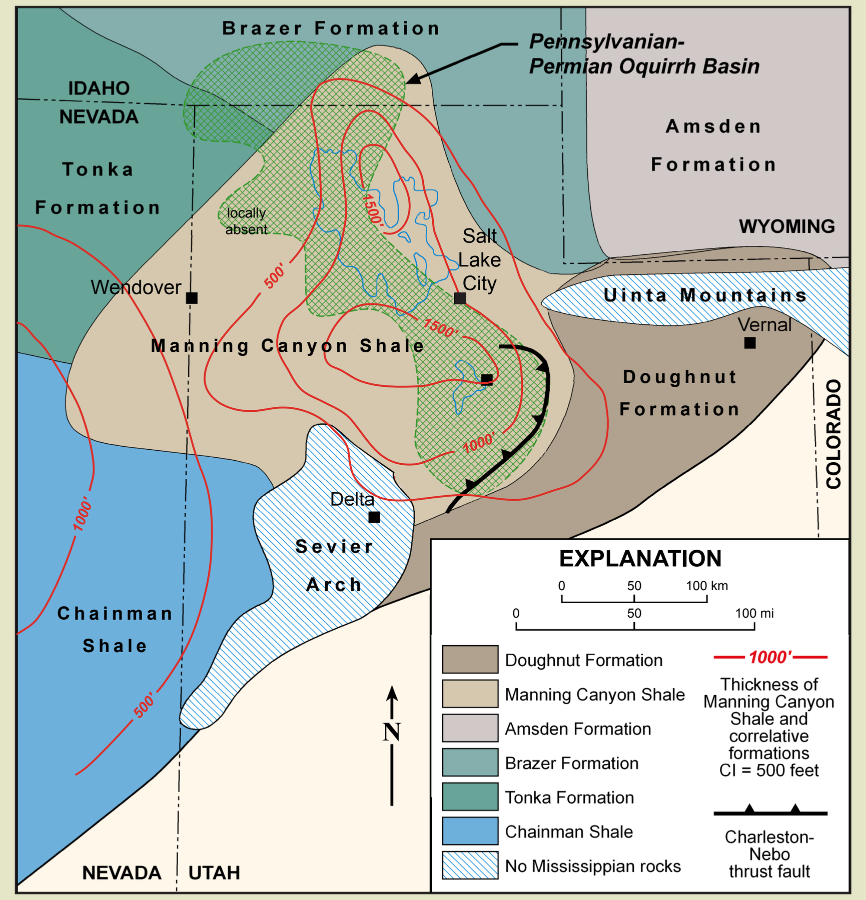


x = time of missing Trcp deposition
8 - x = time of missing Trcp erosion
75x = 59 (8 - x)
75x = 472 - 59x
134x = 472
x = 3.5 m.y.
3.5 m.y.: deposit 264 ft. of missing Trcp
4.5 m.y.: erode 264 of missing Trcp

Thicknesses of rocks removed during type-I unconformities were calculated using the deposition rate of the underlying, preserved unit, and the erosion rate for the relevant time. I determined an erosion rate of 59 ft./m.y. for the Mississippian to the Early Cretaceous by averaging modern denudation rates in major drainage basins of Africa (from Summerfield, 1991), which is a reasonable analogue to the low relief and low paleolatitude of Utah. For the Cenozoic, I used the denudation rate for the modern Colorado River drainage basin of 275 ft./m.y. (Summerfield, 1991). For the Cretaceous, I rather arbitrarily used an intermediate rate of 150 ft./m.y.

The amount of section removed during type-II unconformities was calculated from the regional isopachs I constructed for this project, and which are available on request while they are in development.

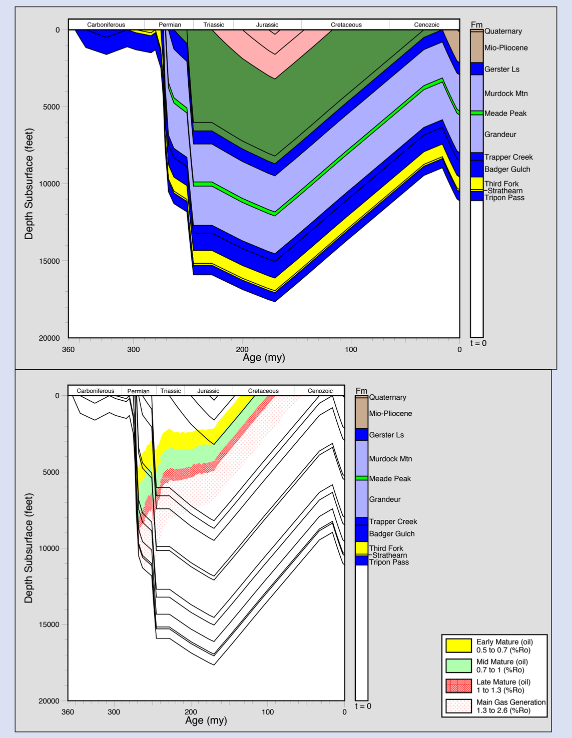
To model organic maturation I used a modern continental average heat flow of 57 mW/m² for the interval from the Late Mississippian to the onset of igneous activity in the area, after which I used the modern heat flows reported by Henrikson and Chapman (2002). The timing of initial igneous activity varied from Late Jurassic in northwest Utah to late Cenozoic in the thrust belt and eastern Basin and Range. However, since the MCS in every section had gone through the gas window before igneous activity began, changing heat flow had no significant effect on the models.



Thickness and Distribution of Manning Canyon Shale in Northern Utah and Correlative Formations in Adjacent Areas. (Modified from Moyle, 1958, and Sprinkel and Chidsey, 2006.)

Burial and Maturation Histories

Section 1 Lucin

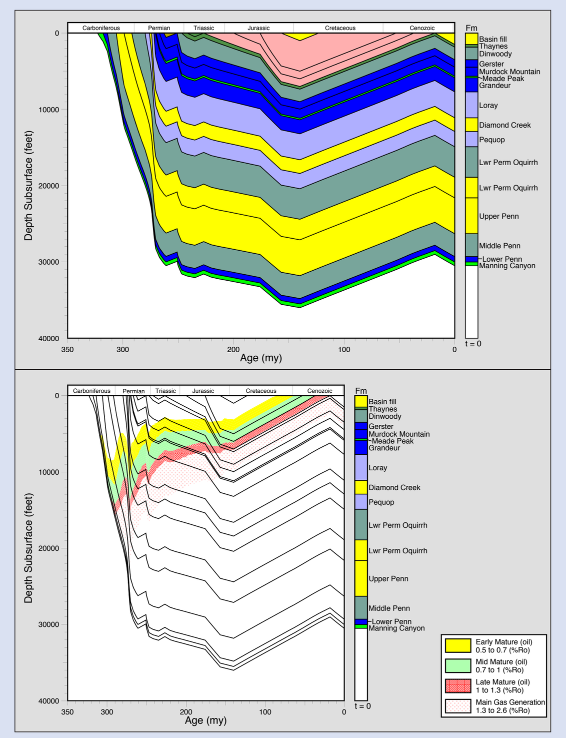


In the Lucin area, rocks tentatively indentified as Upper Pennsylvanian Strathearn Formation unconformably overlie Lower Mississippian Tripon Pass Limestone. The time during which several hundred feet of intervening Mississippian-Pennsylvanian sediments were possibly eroded corresponds to the age of the C3 to P1 unconformities of Trexler and others (2004), and to periodic exposure of the West Central Utah Highlands (Ritter and Robinson, 2009) and the Lucin high (Hintze and Kowallis, 2009).

The thick section of Lower to Middle Permian strata correlates with sections in the Leach and Cassia Mountains of Nevada and Idaho, respectively. Mytton and others (1983) linked these units to development of the Cassia basin at the Wolfcampian-Leonardian boundary, with deep-water conditions evidenced by euxinic shales during Badger Gulch sedimentation, followed by gradual shallowing.

The relatively thick section of Lower Triassic (5000 feet) is based on the section at Goose Creek (Hintze and Kowallis, 2009). The sediment source for this and the Upper Triassic may have been the Golconda thrust of the Sonoma orogeny (Blakey, 1997; Dickinson, 2006). By the Late Jurassic the area was undergoing erosion, coincidental with igneous intrusions from 160 to 150 Ma.

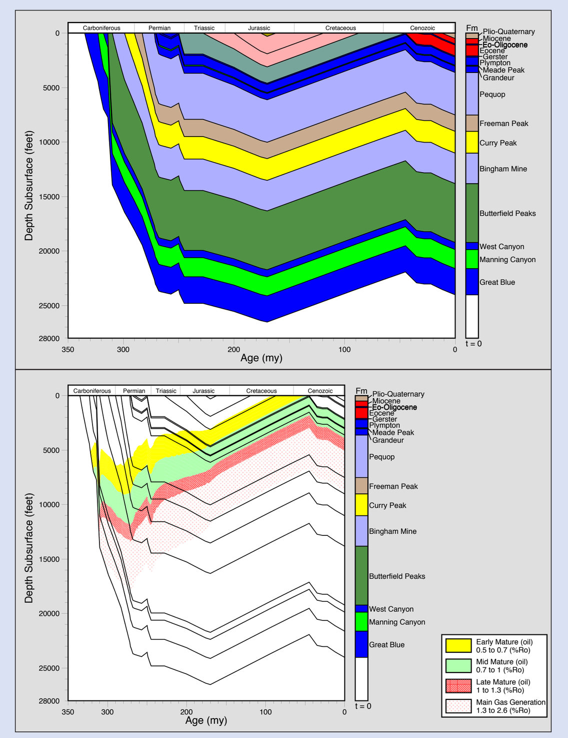
Section 2 Hogup Mountains



The base of the Middle Pennsylvanian is not exposed in the Hogup Mountains so the thickness of this and underlying units was taken from regional isopachs. The extremely thick Pennsylvanian-Permian section, capped by the Gerster Limestone, reflects rapid subsidence and deposition in the Oquirrh basin.

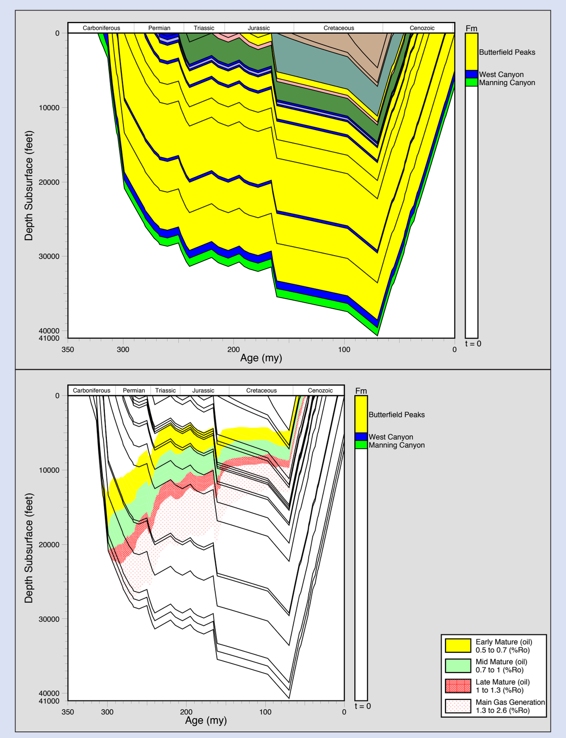
Thicknesses of the missing Triassic and Lower Jurassic Navajo Sandstone equivalent were estimated from isopachs. The missing Middle Jurassic was probably marine mudstone in the foredeep of the Nevadan orogeny (Blakey, 1997; Hintze and Kowallis, 2009). Blakey's paleogeographic reconstructions for the Late Jurassic, Morrison-Formation time, show the foredeep filling and evolving to a terrigenous foreland basin. Deposition probably ended by the middle of the Early Cretaceous, followed by erosion of 7000 feet of Upper Jurassic to Chinle equivalent. The area also contains from 0 to 3000 feet of Miocene to Quaternary Salt Lake Formation and valley fill.

Section 3 Cedar Mountains



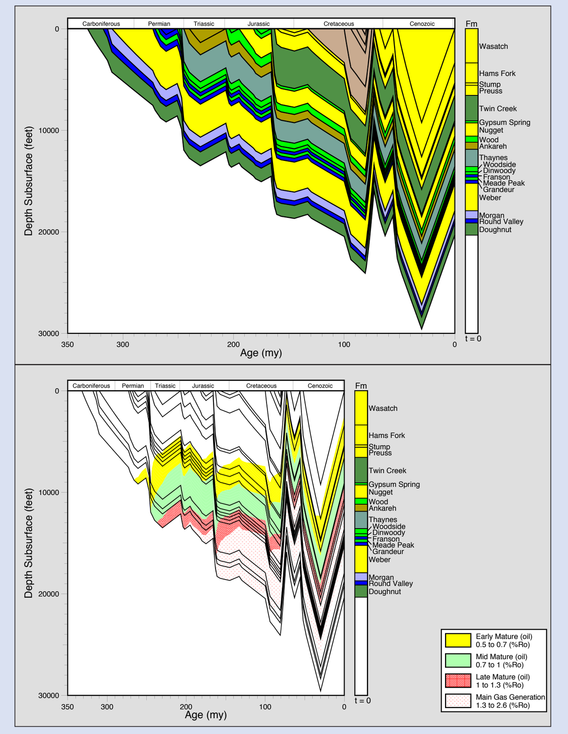
In the southern Cedar Mountains, the MCS consists of 1500 to 2000 feet of gray to black shale with minor quartz sandstone and carbonaceous limestone (Clark and others, 2009). A very thick overlying section of Oquirrh Group and Lower to Middle Permian marine strata records generally continuous deposition in the Oquirrh basin. Approximately 4600 feet of Triassic through Middle Jurassic marine and terrigenous siliciclastics was deposited in the area before uplift and erosion began in the Late Jurassic (Blakey, 1997). Eocene to Miocene volcanic rocks were overlain by variable thicknesses of Neogene valley fill.

Section 4 Cedar Valley



The modeled section corresponds to the Oak Springs syncline in the southern Oquirrh Mountains, Tickville Spring quadrangle (Biek and others, 2005). The MCS is about 1100 feet thick, and contains abundant terrestrial plant and shallow marine invertebrate fossils (Hintze and Kowallis, 2009). As at Section 3, the MCS was overlain by a very thick Pennsylvanian-Permian section of marine rocks of the Oquirrh basin, and by approximately 7500 feet of Triassic through Middle Jurassic marine and terrigenous rocks. Foreland basin deposits of the Jurassic Nevadan orogeny were estimated as 500 feet thick. Cretaceous foreland basin sediments shed from the Sevier orogen may have totaled 6600 feet in thickness (Roberts and Kirschbaum, 1995; Currie, 2002). Post-Cretaceous erosion of the hanging wall of the Beef Hollow thrust removed Upper Pennsylvanian and higher strata and thinned the Butterfield Peaks Formation to 5000 feet.

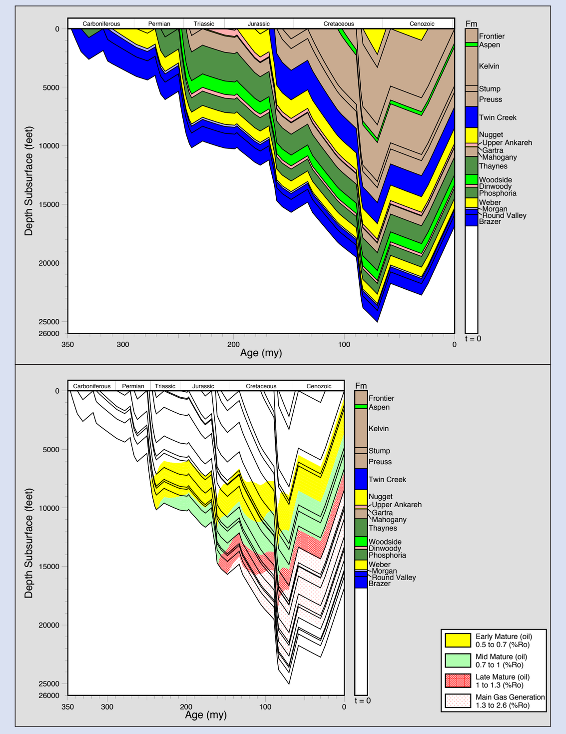
Section 5 Devils Slide



Section 5 is carried on the hanging wall of the Crawford thrust (Yonkee and others, 1997). The section preserved in Weber Canyon records marine platform deposition from the Permian Morgan Formation through the Middle Jurassic Twin Creek Limestone. The Middle and Upper Jurassic Preuss and Stump Formations total an additional 850 to 1400 feet (Hintze and Kowallis, 2009). The eroded Lower and Upper Cretaceous were probably 3000 feet (Hintze and Kowallis, 2009) and 5700 feet (DeCelles, 2004) thick, respectively. Erosion started about the end of emplacement time of the Crawford thrust (84 Ma) and resulted in removal of the Lower and Upper Cretaceous section before deposition of the Hams Fork Member at 73 Ma, for an erosion rate of 745 ft./m.y., comparable to the modern Ganges River basin of Asia.

Following the Paleocene unconformity (63 to 56 Ma), deposition resumed in the late Paleocene and continued to the early Oligocene (~30 Ma), represented by Wasatch Formation sandstone, and overlying Green River and Bridger Formations or equivalents (Franczyk and others, 1992; Smith and others, 2008). The thickness of the missing section is calculated as 9240 feet, based on the depositional rate of the preserved Wasatch (3370 ft./4 m.y. = 840 ft./m.y.) declining at a linear rate for the next 22 m.y. Removing this amount of sediment by the present requires a denudation rate of 308 ft./m.y., slightly greater than that of the modern Colorado River basin.

Section 6 Island Ranching D-1

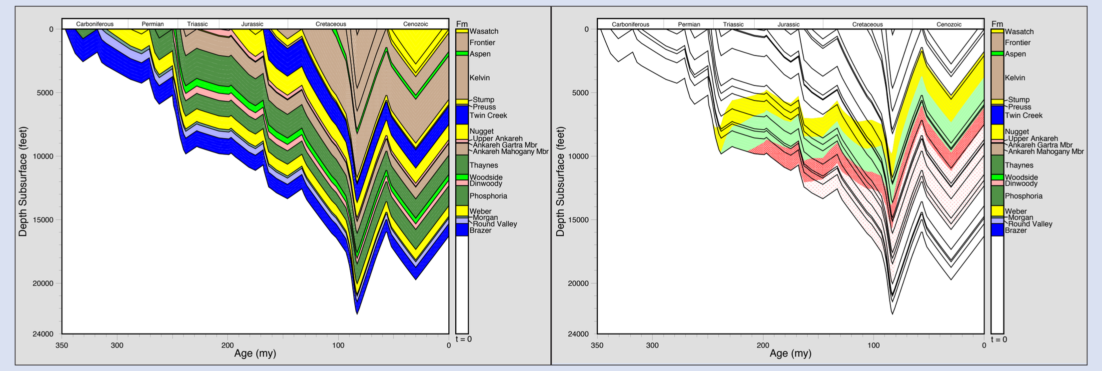


The Anschutz Island Ranching D-1 well is on the hanging wall of the Medicine Butte thrust fault, which was active from the Late Cretaceous to early Cenozoic (Lamerson, 1982). The MCS and the correlative Doughnut Formation are absent in the well, and a 15 to 20 million year hiatus separated deposition of the Brazer Dolomite from the overlying Round Valley Limestone (Sprinkel, 1994). The thickness of the missing MCS equivalent, based on erosion rates and Sprinkel and Chidsey's (2006) isopach, was about 800 feet.

The youngest unit in the well is the Albian-Turonian Frontier Formation. The thickness of the missing Upper Cretaceous units is about 6000 feet for the Coniacian-Santonian Henefer and Echo Canyon Formations, and 2200 feet for the Campanian Indianola Group equivalent (Roberts and Kirschbaum, 1995). Deposition resumed in the late Paleocene (~58 Ma) and continued to the early Oligocene (~30 Ma), represented by Wasatch Formation sandstone (Franczyk and others, 1992).

Burial and Maturation Histories *continued*

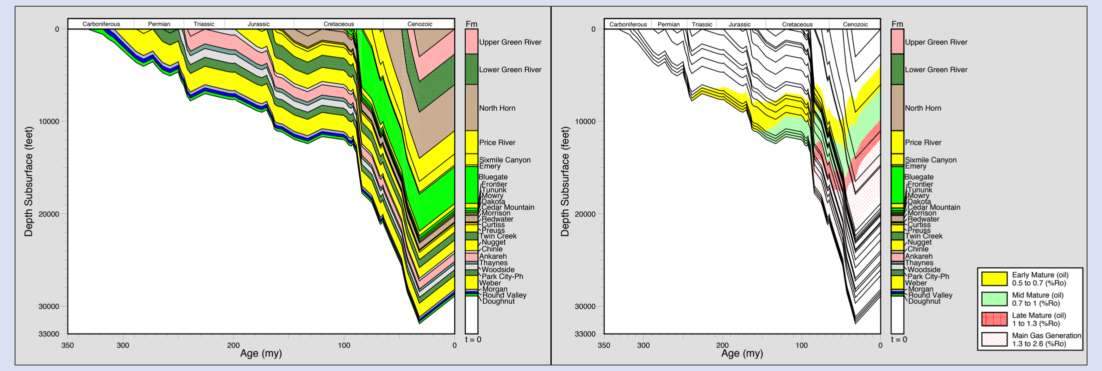
7 *Anschutz Ranch 3-1*



Anschutz Ranch 3-1 is located about three miles south of Section 6 in a similar structural setting. The thickness of the missing MCS is again roughly 800 feet. The well log reported a thickness of 1570 feet for the Permian Phosphoria Formation, but this is probably structurally enhanced. For the model I used a stratigraphic thickness of 910 ft recorded in Section 6, and thickened the unit between 85 to 80 Ma during motion of the Tunp thrust and early movement of the Absaroka thrust (DeCelles, 2004).

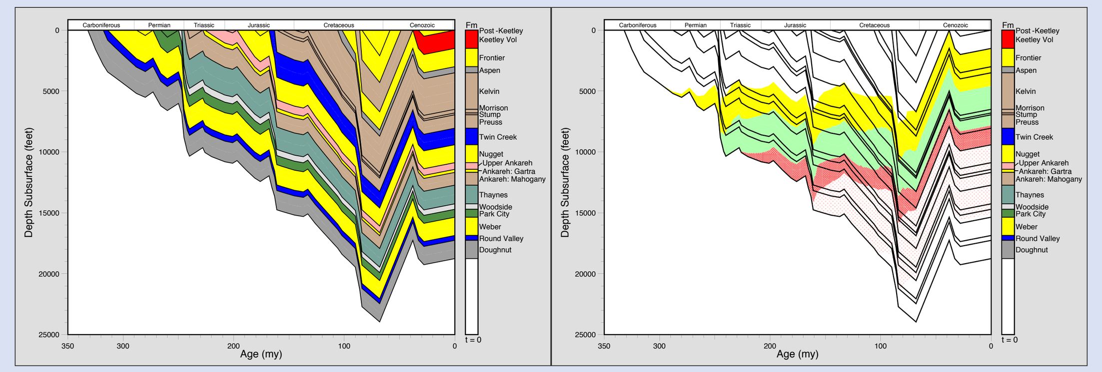
The thickness of the eroded Turonian through Campanian, and the absence of the Maastrichtian are from DeCelles' (2004) isopachs. Erosion of the 6450 feet of missing Turonian-Campanian at a rate of 275 ft./m.y. requires 26 m.y., suggesting erosion began in the early Campanian (~83 Ma). Deposition resumed in the late Paleocene (~57 Ma) and continued to the early Oligocene (~30 Ma) represented by sandstone of the Evanston, Wasatch, and Bridger Formations (Franczyk and others, 1992). The amount of Evanston deposited and eroded is unknown but the unit is 1000 feet thick at Sprinkel's (1994) sections 3 and 4. The preserved thickness of the Wasatch Formation is 300 feet.

9 *Shell 1-16D9 Ute*



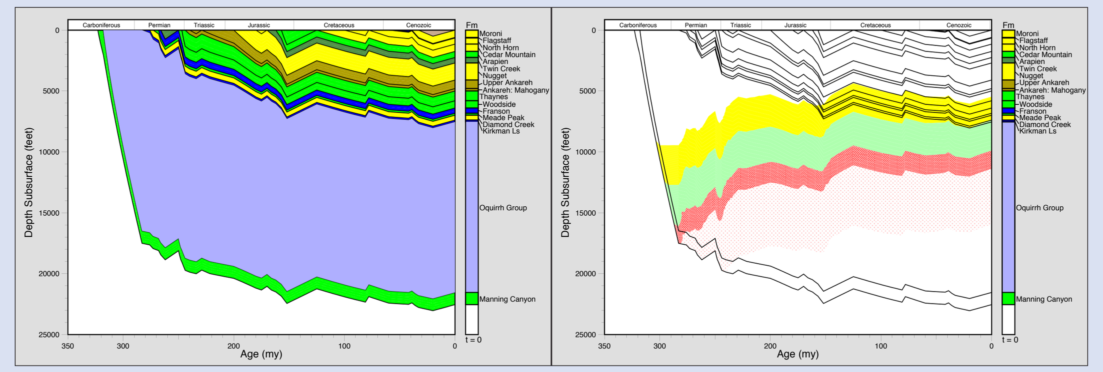
Shell's 1-16D9 Ute well was drilled in the western Uinta Basin approximately 11 miles east of the Charleston-Nebo thrust. Like Section 8, the well records relatively steady deposition and burial of the MCS-equivalent Doughnut Formation from the Late Mississippian to the beginning of the Late Cretaceous. However, the Mississippian through Lower Cretaceous is significantly thinner at Section 9 than at Section 8 (12,000 versus 18,000 feet) reflecting the more cratonward position of Section 9. With the onset of movement of the Charleston-Nebo thrust, this relationship changed, and Section 9 received a very thick foreland-basin detrital wedge during the Late Cretaceous and Paleogene. Being located east of the frontal thrusts of the Sevier orogen, this area was not subjected to uplift and erosion as the thrusts advanced.

8 *Heber*



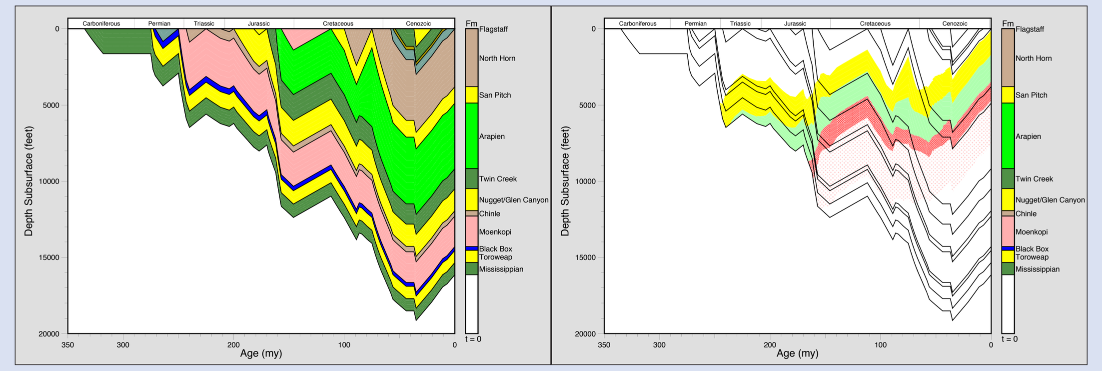
Section 8 is located about 15 miles north of Heber City, Utah. The area experienced relatively constant deposition from the Late Mississippian to the Late Cretaceous, punctuated by several regional unconformities. The youngest preserved Cretaceous unit is the Frontier Formation, deposited from 102 to 90 Ma. The maximum thickness of the missing Henefer Formation (Coniacian), Echo Canyon Formation (Santonian), and Indianola Group (Campanian) is about 6700 feet (Roberts and Kirschbaum, 1995; Hintze and Kowallis, 2009). Deposition probably ceased during the Maastrichtian, and during the Paleocene and Eocene the site was on the edge of the Uinta Mountains non-depositional area (Franczyk and others, 1992). Assuming the combined thickness of the Henefer, Echo Canyon, and Indianola was 6700 feet, and that they were eroded between the middle Maastrichtian (68 Ma) and deposition of the Keetley Volcanics, the rate of erosion would be 223 ft./m.y., comparable to the modern Colorado River drainage basin.

10 *Mount Nebo*



This section contrasts with Section 9 in two respects: it contains thick Pennsylvanian through Permian strata typical of the Oquirrh basin, and it has a relatively thin Cretaceous through Paleogene section as a result of being uplifted on the Charleston-Nebo thrust. The Oquirrh Group in this area has not been divided, but may reach a thickness of 15,000 feet of calcareous sandstone (Hintze and Kowallis, 2009). Movement of the Charleston-Nebo thrust and uplift of the Santaquin culmination began about 100 Ma (DeCelles, 2004). Thin Paleogene sediments of the North Horn and Flagstaff Formations are preserved, but the section was generally outside the area of Paleogene deposition (Franczyk and others, 1992).

11 *Placid Howard 1A*

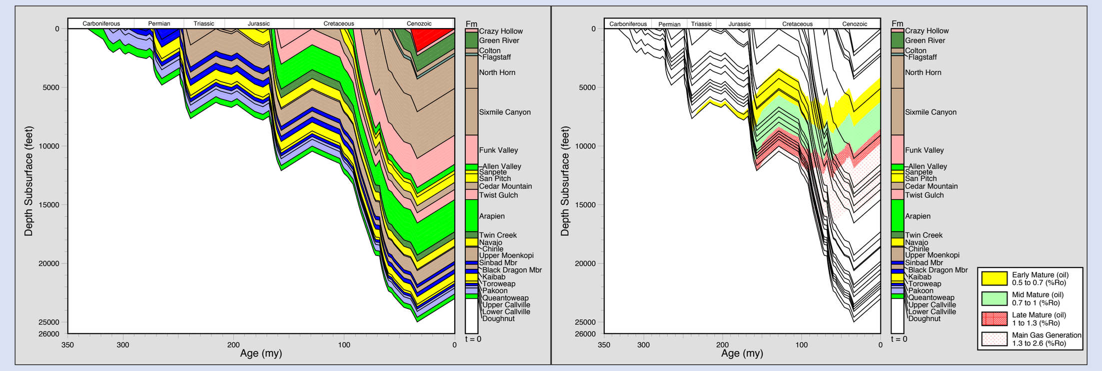


Placid WXC-Howard 1A is located on the southwest margin of the Oquirrh basin and the northeast margin of the Cretaceous Sevier arch, on the hanging wall of the Sage Valley thrust (Schelling and others, 2007). The section lies within the western part of the Emery shelf as shown by Hintze and Kowallis (2009), which received no Pennsylvanian deposits and may have shed sediments to the Oquirrh basin. From the isopach, the MCS or Doughnut equivalent are 700 feet thick if preserved. The Pennsylvanian is modeled as a hiatus since it is uncertain if the area received sediments during sea-level high stands or shed much debris to the Oquirrh basin during low stands.

The well log records 4300 feet of Middle Jurassic Arapien Shale, but the depositional thickness was probably closer to 2000 feet (Sprinkel, 1994). Thickening probably occurred between the end of Paxton thrust motion and the start of movement of the Gunnison thrust (86 to 75 Ma [DeCelles, 2004]). The Upper Jurassic Morrison equivalent was probably deposited in the area (Blakey, 1997). It may have been 1000 feet thick, based on preserved sections to the east, and was eroded during the Early Cretaceous.

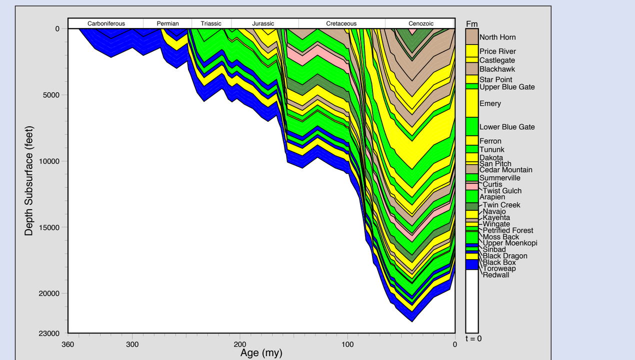
DeCelles' (2004) isopachs suggest ~2400 feet of Indianola Group equivalent was deposited in the Cenomanian and Turonian (100 to 89 Ma) in front of the Pavant and Paxton thrusts. This would have been eroded by 75 Ma and followed by deposition of 3800 feet of North Horn Formation. Hintze and Kowallis' (2009) Sage Valley section suggests 3000 feet of later Paleogene and Neogene rocks were deposited and eroded.

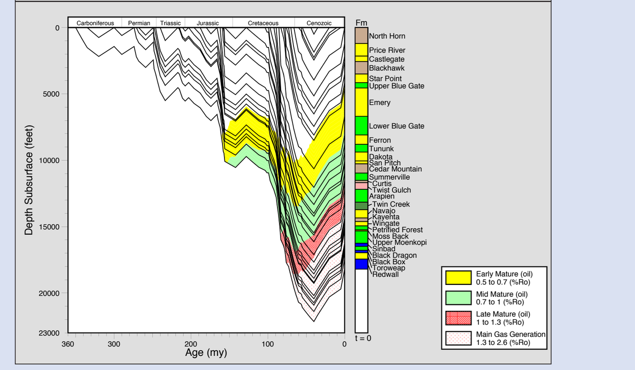
12 *Hanson Moroni-1AX*



The MCS isopach indicates 400 feet of Doughnut Formation was deposited at Hanson Moroni 1AX, drilled in the central Utah thrust belt. The Pennsylvanian-Permian section onlapped the Emery High, probably in numerous transgressive regressive cycles (Johnson and others, 1992) that lack constraints for modeling. Deposition of thick Middle to Upper Jurassic rocks coincided with the Nevadan orogeny, although the Arapien Shale probably had its thickness doubled during the Sevier orogeny. The angular unconformity between the Sixmile Canyon and North Horn Formations probably formed during movement of the Suttons Canyon thrust (late Campanian, 74-71 Ma?). Schelling and others (2007) showed the Gunnison detachment fault cutting the base of the Arapien Shale. Motion probably occurred between Maastrichtian and early Paleocene time (71-64 Ma [DeCelles, 2004]), and thickened the Arapien from 1500 to 2740 feet, coincidental with the onset of North Horn deposition. Thicknesses of the eroded Moroni and Salt Creek Formations are from Hintze and Kowallis' (2009) Moroni chart.

13 *Phillips USA E-1*

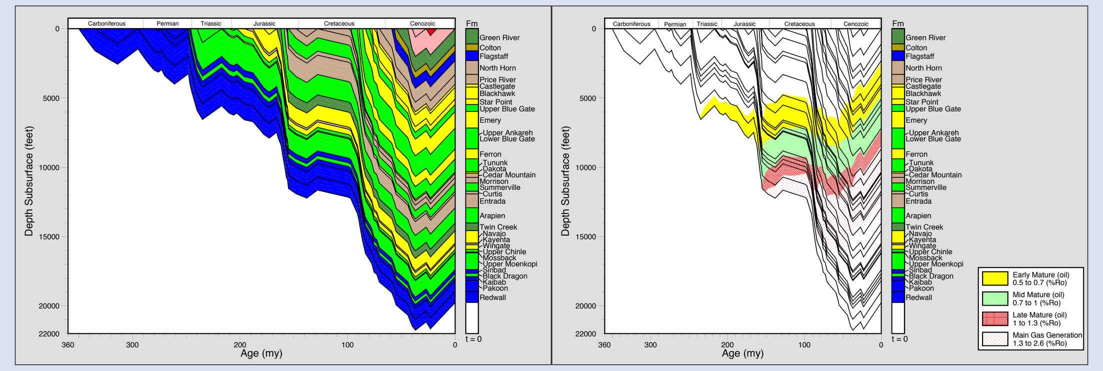




Phillips USA E-1 was drilled in the Colorado Plateau transition zone about eight miles east of the Salina-Gunnison thrust. The Lower Permian Toroweap Formation unconformably overlies Lower to Upper Mississippian Redwall Limestone on the Emery High. The total amount of missing section represents 61 million years, from 335 Ma to 274 Ma, but Blakey's (2005) paleogeographic maps indicate post-Redwall deposition continued until the end of the Mississippian (318-320 Ma). The Emery Uplift was emergent throughout the Pennsylvanian.

As in sections 9 and 12, Phillips USA E-1 shows significant increases in sedimentation rates coincidental with the Nevadan and Sevier orogenies. The thicknesses of the eroded North Horn, Flagstaff, Colton, Green River, and Crazy Hollow Formations was taken from Hanson Moroni 1AX (Section 12).

14 *Upper Salina Canyon*



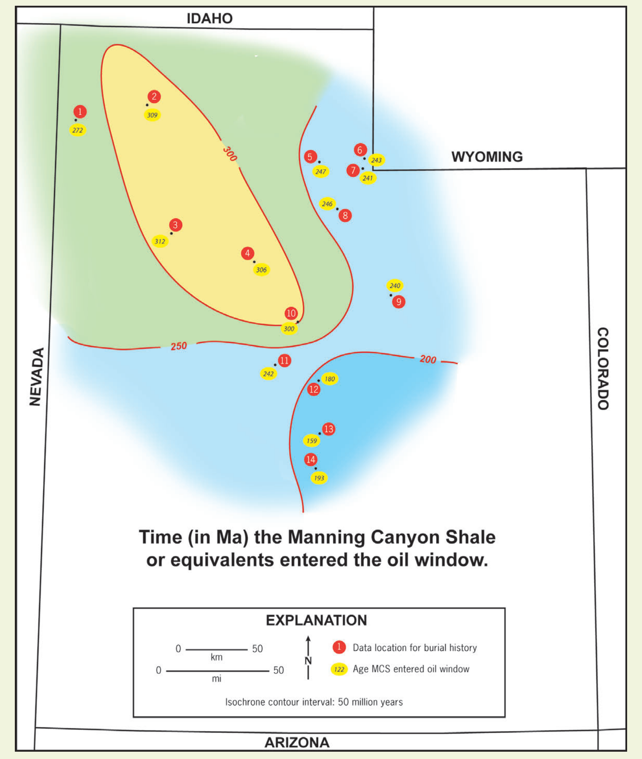
The outcrops at upper Salina Canyon occupy a structural position similar to that at Section 13. Lower Permian Pakoon Dolomite unconformably overlies Lower to Upper Mississippian Redwall Limestone on the Emery High. Although five regional Mesozoic unconformities have been identified in Section 14, only the Middle Triassic event appears to have led to significant erosion. Instead, deposition was relatively uniform into the Early Cretaceous, except for a Late Jurassic increase in sedimentation rate during the Nevadan orogeny. The sedimentation rate then increased markedly in the Late Cretaceous during formation of the Sevier foreland basin. Based on thicknesses in the Salina 7.5 quadrangle (Willis, 1986), 2000 feet of Paleogene were later eroded.

Distribution of Maturation Calculations

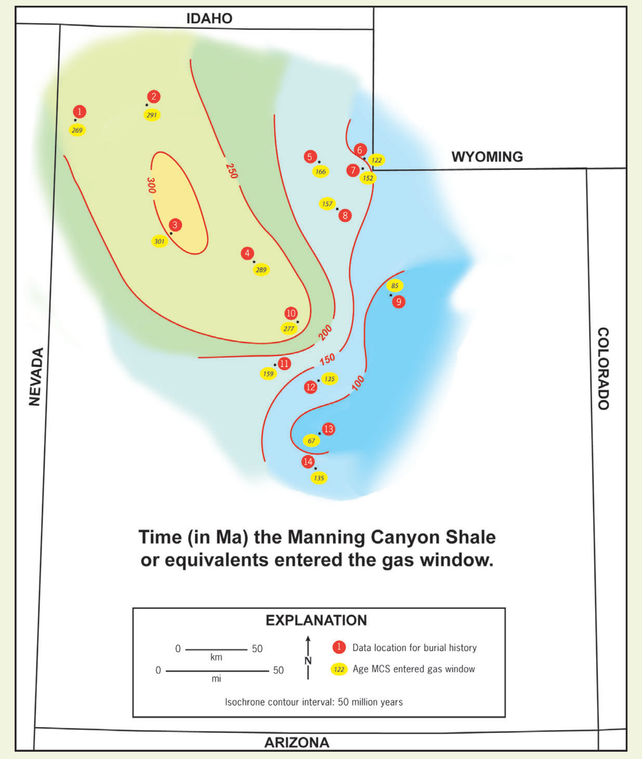
Summary of Burial and Maturation Models

Number	Name	Section type	Maximum MCS burial depth (feet)	Time MCS entered oil window (Ma)	Time MCS entered gas window (Ma)	Reference
1	Lucin	Pseudo well	17,100	272	269	Miller and Schneyer, 1985; Miller and Glick, 1986.
2	Hogup Mountains	Pseudo well	35,600	309	291	Jordan, 1983; Hintze and Kowallis, 2009.
3	Cedar Mountains	Pseudo well	22,400	312	301	Wardlaw and others, 1979; Clark and others, 2009; Hintze and Kowallis, 2009.
4	Cedar Valley	Pseudo well	39,500	306	289	Biek and others, 2005
5	Devils Slide	Pseudo well	28,400	247	166	Yonkee and others, 1997; Hintze and Kowallis, 2009.
6	Anschutz Island Ranching D-1	Well	24,100	243	122	Sprinkel, 1994.
7	Anschutz Ranch 3-1	Well	21,500	241	152	Sprinkel, 1994.
8	Heber	Pseudo well	22,500	246	157	Sprinkel, 1994.
9	Shell 1-16 D9 Ute	Well	31,700	240	85	Sprinkel, 1994.
10	Mt. Nebo	Pseudo well	22,100	300	277	Hintze and Kowallis, 2009
11	Placid WXC Howard 1	Well	18,300	242	159	Sprinkel, 1994; Schelling and others, 2007.
12	Moroni - 1AX	Well	24,700	180	135	Sprinkel, 1994; Schelling and others, 2007.
13	Phillips USA E-1	Well	21,400	159	67	Sprinkel, 1994.
14	Salina Canyon	Pseudo well	21,000	193	135	Hintze and Kowallis, 2009.

A



B



The maps above show the times in Ma, based on the burial histories presented here, that the top of the MCS or its equivalents entered (a) the oil window, and (b) the gas window. Hydrocarbon generation occurred earliest in northwestern Utah where the MCS was rapidly buried in the Oquirrh basin, and latest in the southeast part of the study area where the MCS typically was at relatively shallow burial depths until the mid-Cretaceous and development of the Sevier foreland basin.

Future work on evaluating the hydrocarbon source potential of the MCS will include:

1. Generation of additional burial and maturation histories to determine whether other patterns exist in areas that have tectonic and depositional records different from those shown here; and
2. Calibration of the histories with other thermal maturation data such as vitrinite reflectance and possibly conodont alteration indices.

Acknowledgments

Funding for this project is provided in part by RPSEA through the "Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources" program authorized by the U.S. Energy Policy Act of 2005. RPSEA (www.rpsea.org) is a nonprofit corporation whose mission is to provide a stewardship role in ensuring the focused research, development and deployment of safe and environmentally responsible technology that can effectively deliver hydrocarbons from domestic resources to the citizens of the United States. RPSEA, operating as a consortium of premier U.S. energy research universities, industry, and independent research organizations, manages the program under a contract with the U.S. Department of Energy's National Energy Technology Laboratory.

Partial funding was also provided by the UGS.

I benefited from discussions with Tom Chidsey, Craig Morgan, Doug Sprinkel, and Dave Tabet of the UGS. Richard Austin of the UGS designed and prepared the posters.

For additional information refer to the Utah Geological Survey's project Web page http://geology.utah.gov/emp/shalegas/index.htm.

References

Biek, R.F., Solomon, B.J., Keith, J.D., and Smith, T.W., 2005, Geologic map of the Tickville Spring quadrangle, Salt Lake and Utah Counties, Utah: Utah Geological Survey Map 214, 2 sheets, scale 1:24,000.

Blakey, R.C., 1997, Paleogeographic evolution of the passive-margin to active-margin transition, early Mesozoic, western North America: Geological Society of America Abstracts with Programs v. 29, n. 6, p. 202, accessed May 10, 2010 at http://jan.ucc.nau.edu/rcb7/paleogeogwus.html.

Clark, D.L., Kirby, S.M., and Oviatt, C.G., 2009, Progress report geologic map of the Rush Valley 30' x 60' quadrangle, Tooele, Utah, and Salt Lake Counties, Utah: Utah Geological Survey Open-File Report 555, 60 p. pamphlet, one plate, scale 1:62,500.

Currie, B.S., 2002, Structural configuration of the Early Cretaceous Cordilleran foreland-basin system and Sevier thrust belt, Utah and Colorado: The Journal of Geology, v. 110, p. 697-718.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A.: American Journal of Science, v. 304, p. 105-168.

Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin: Geosphere, v. 2, p. 353-368.

Franczyk, K.J., Fouch, T.D., Johnson, R.C., Molenaar, C.M., and Cobban, W.A., 1992, Cretaceous to Tertiary paleogeographic reconstructions for the Uinta-Piceance basin study area, Colorado and Utah: U.S. Geological Survey Bulletin 1787-Q, 37 p.

Henrikson, A., and Chapman, D.S., 2002, Terrestrial heat flow in Utah: Salt Lake City, University of Utah, Department of Geology and Geophysics, accessed December 29, 2005 at http://geology.utah.gov/emp/geothermal/pdf/terrestrialhf.pdf.

Hintze, L.F., and Kowallis, B.J., 2009, Geologic history of Utah: Brigham Young University Geology Studies, Special Publication 9, 225 p.

Johnson, S.Y., Chan, M.A., and Konopka, E.A., 1992, Pennsylvanian and Early Permian paleogeography of the Uinta-Piceance Basin, northwestern Colorado and northeastern Utah: U.S. Geological Survey Bulletin 1787-CC, 35 p.

Jordan, T.E., 1983, Structural geometry and sequence, Bovine Mountain, northwestern Utah, in Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 215-227.

Laine, M.D., Chidsey, T.C., Jr., and Morgan, C.D., 2008, Potential shale-gas resources in Utah [abs.]: American Association of Petroleum Geologists Annual Convention Abstracts, v. 17, p. 115, accessed May 10, 2010 at http://geology.utah.gov/emp/shalegas/pdf/shalegas_poster0408.pdf.

Lamerson, P.R., 1982, The Fossil Basin and its relationship to the Absaroka thrust system, Wyoming and Utah, in Powers, R.B., editor, Geologic studies of the Cordilleran thrust belt: Denver, Rocky Mountain Association of Geologists, v.1, p. 279-340.

Miller, D.M., and Glick, L.L., 1986, Geologic map of the Lemay Island quadrangle, Box Elder County, Utah: Utah Geological Survey Map 96, 8 p., 2 plates, scale 1:24,000.

Miller, D.M., and Schneyer, J.D., 1985, Geologic map of the Tecoma quadrangle, Box Elder County, Utah, and Elko County, Nevada: Utah Geological Survey Map 77, 8 p. pamphlet, 2 plates, scale 1:24,000.

Moyle, R.W., 1958, Paleoecology of the Manning Canyon Shale in central Utah: Brigham Young University Research Studies, Geology Series, v. 5, n. 7, 86 p.

Mytton, J.W., Morgan, W.A., and Wardlaw, B.R., 1983, Stratigraphic relations of Permian units, Cassia Mountains, Idaho, in Miller, D.M., Todd, V.R., and Howard, K.A., editors, Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 281-303.

Ritter, S.M., and Robinson, T.S., 2009, Sequence stratigraphy and biostratigraphy of Carboniferous-Permian boundary strata in western Utah, in Tripp, B.T., Krahulec, K., and Jordan, J.L., editors, Geology and geologic resources and issues of western Utah: Utah Geological Association Publication 38, p. 27-42.

Roberts, L.N.R., and Kirschbaum, M.A., 1995, Paleogeography of the Late Cretaceous of the western interior of North America—coal distribution and sediment accumulation: U.S.G.S. Professional Paper 1561, 115 p.

Schelling, D.D., Strickland, D.K., Johnson, K.R., and Vrona, J.P., 2007, Structural geology of the central Utah thrust belt, in Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., editors, Central Utah—diverse geology of a dynamic landscape: Utah Geological Association Publication 36, p. 1-30.

Smith, M.E., Carroll, A.R., and Singer, B.S., 2008, Synoptic reconstruction of a major ancient lake system—Eocene Green River Formation, western United States: Geological Society of America Bulletin, v. 120, no. 1/2, p. 54-84, doi: 10.1130/B26073.1.

Sprinkel, D.A., 1994, Stratigraphic and time-stratigraphic cross sections: a north-south transect from near the Uinta Mountain axis across the Basin and Range transition zone to the western margin of the San Rafael Swell, Utah: U.S. Geological Survey Miscellaneous Investigation Series 2184-D, 31 p., 2 plates.

Sprinkel, D.A., and Chidsey, T.C., Jr., 2006, Exploration history and petroleum geology of the central Utah thrust belt: Online, American Association of Petroleum Geologists Search and Discovery Article No. 10103, <http://www.searchanddiscovery.net/documents/2006/06028sprinkel/index.htm>, posted May 13, 2006.

Summerfield, M.A., 1991, Global geomorphology—an introduction to the study of landforms: Harlow, England, 537 p.

Trexler, J.H., Jr., Cashman, P.H., Snyder, W.S., and Davydov, V.I., 2004, Late Paleozoic tectonism in Nevada—timing, kinematics, and tectonic significance: Geological Society of America Bulletin, v. 116, p. 525-538.

Wardlaw, B.R., Collinson, J.W., and Maughan, E.K., 1979, Stratigraphy of Park City Group equivalents (Permian) in southern Idaho, northeastern Nevada, and northwestern Utah, in Wardlaw, B.R., editor, Studies of the Permian Phosphoria Formation and related rocks, Great Basin – Rocky Mountain region: U.S. Geological Survey Professional Paper 1163–C, p. 9–16.

Willis, G.C., 1986, Geologic map of the Salina quadrangle, Sevier County, Utah: Utah Geological and Mineral Survey Map 83, 20 p., 2 plates, scale 1:24,000.

Yonkee, W.A., DeCelles, P.G., and Coogan, J., 1997, Kinematics and synorogenic sedimentation of the eastern frontal part of the Sevier orogenic wedge, northern Utah, in Link, P.K., and Kowallis, B.J., editors, Proterozoic to recent stratigraphy, tectonics, and volcanology – Utah, Nevada, southern Idaho, and central Mexico: Brigham Young University Geology Studies, v. 42, part 1, p. 355-380.