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GEOLOGIC IMPLICATIONS OF DATA FROM THE AMERICAN QUASAR 27-22 HAGENBARTH DRILLHOLE, BEAVERHEAD COUNTY, MONTANA

by

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INTRODUCTION

The American Quasar 27-22 Hagenbarth was drilled to a total depth of 12,048 ft (3,672 m) as a rank-wildcat exploratory test for oil and gas in the south-central part of the McCartney Mountain salient, a second-order salient within the northern part of the southwestern Montana recess of the Cordilleran thrust belt (fig. 1, table 1). The Hagenbarth drillhole is significant for a number of reasons: (1) it reached crystalline basement; (2) it appears to have encountered a thin sequence of Proterozoic Belt sandstone just above crystalline basement and thus appears to help define the southern margin of the Belt embayment in this area; (3) thermal maturation data, analyzed from cuttings of this drillhole, help define the oil and gas potential of the region, and (4) a close comparison of the computed thicknesses of the different units encountered in the drillhole with nearby surface sections help better define paleotectonic features in the area surrounding the McCartney Mountain salient.

The geology of the McCartney Mountain salient was principally studied by Brumbaugh (1973), Brumbaugh and Hendrix (1981), Brandon (1984) and Schmidt and others (1988). Lopez and Schmidt (1985, fig. 7) show an east-west structural section, near the drillhole, based in part on a seismic reflection line. They interpret an east-vergent thrust complex, containing abundant imbricated thrusts of relatively small individual (generally less than 1 km) displacement (Lopez and Schmidt, 1985, fig. 7 ; Schmidt and others, 1988, fig. 23). I measured the length of the Triassic/Permian (Mz/P) contact on their cross section to be 40.8 km over a horizontal distance of 22.3 km. The indicated shortening is thus 18.5 km over an estimated original distance of 40.8 km. The shortening ratio $\Delta l/l_o$, where Δl is the shortening in km and l_o is the calculated original distance in km, is 0.4534 which rounds to 45% shortening. Thus, in spite of the modest amount of shortening represented by any one thrust, the cumulative shortening in the McCartney Mountain salient is quite significant.

A preliminary K/Ar date of 70 ± 1.5 my from a stock that cross-cuts the thrusts, reported by Brumbaugh (1973), has been widely used to date this part of the thrust belt (Ruppel and Lopez, 1984; Schmidt and others, 1988). It should be emphasized that this may be younger than the bulk of the thrusting in the area, but contractional deformation farther east, along the eastern edge of the Helena salient (fig. 1) continued into the late Paleocene and earliest Eocene (Harlan and others, 1988).

ACKNOWLEDGMENTS

I wish to thank officials with the former American Quasar Petroleum Company for providing logs and cuttings from the 27-22 Hagenbarth drillhole; Juanita McKenzie, formerly with USGS, for laboratory preparation and description of cuttings obtained from American Quasar; Jerry L. Clayton, USGS, for providing RockEval results, Alonzo H. Love, USGS, for kerogen color and TAI; Mark J. Pawlewicz, USGS, for vitrinite reflectance measurements, and Charles A. Sandberg, USGS, for conodont age and CAI results as well as helpful suggestions concerning the present report. I also wish to thank J. Michael O'Neill for many helpful comments.

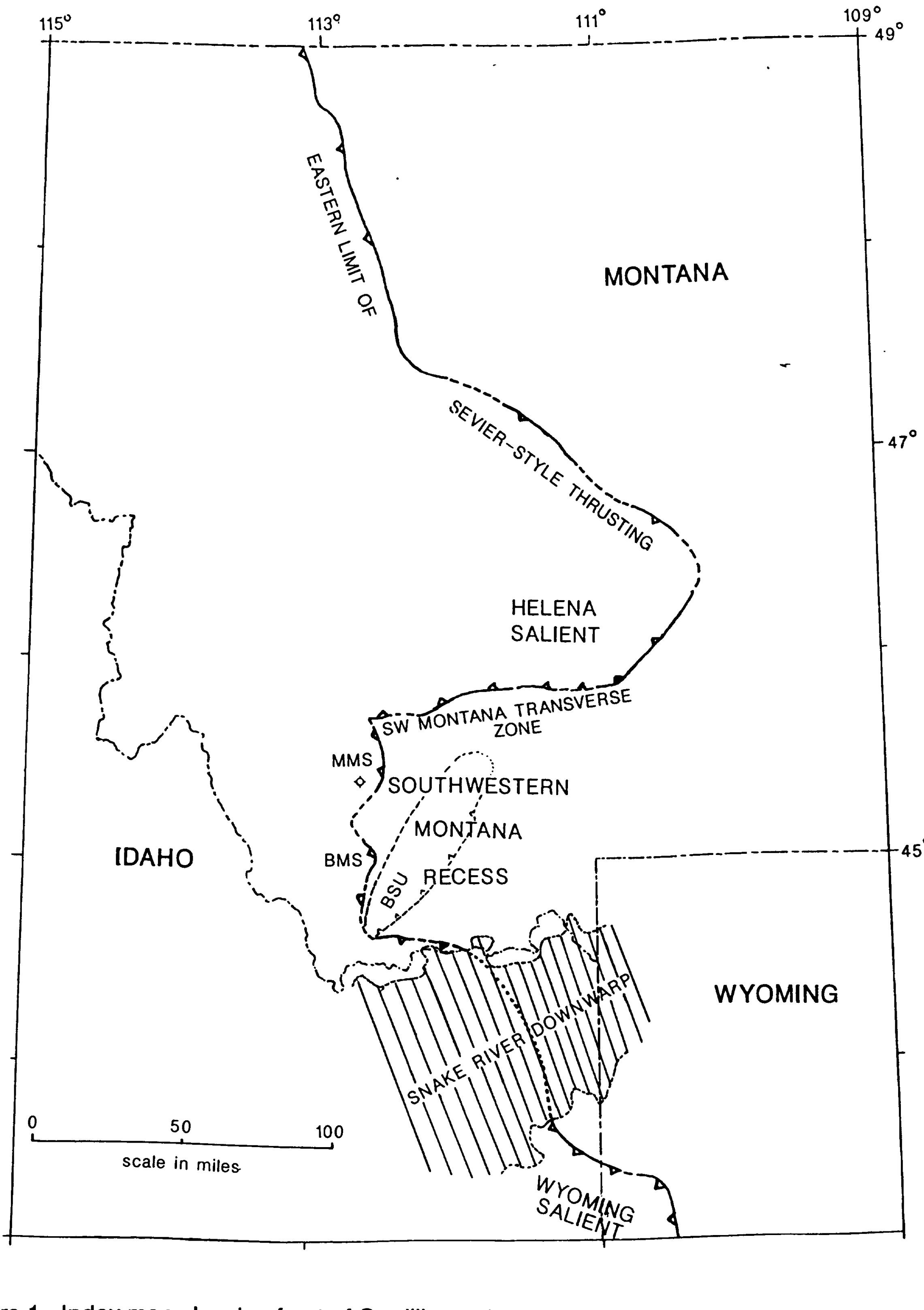

Figure 1. Index map showing front of Cordilleran thrust belt in Montana as well as tectonic features described by Perry and others (1989). Location of 27-22 Hagenbarth drillhole shown by dry hole symbol just below MMS. BMS - Blacktail Mountains salient; BSU - Blacktail Snowcrest uplift; MMS - McCartney Mountain salient.

EXPLANATION OF TABLE 1 **WJP 12/04/97**

Formation and member tops and bases, in the American Quasar 27-22 Hagenbarth drill-holes (table 1) are based primarily on my interpretation of the borehole compensated sonic log, both sonic and gamma ray curves, in conjunction with the formation density log and mudlog record of lithology of returned drill cuttings. I calculated formation thicknesses from drilled intervals (log tops minus log bases) based on the publicly released dipmeter[1] arrow plots (dip azimuth vs. dip magnitude) for the drill-hole interval 1,002 to 7,918 ft. I used an eyeball average for consistent (more than three) nearby readings, eliminating data scatter that is likely due to fractures, cross-stratification, or miscorrelation of resistivity curves:

For Cretaceous rocks at less than 1,810 ft - - - ~12° N
1,810-3,000 ft - - - - - - - - - - - - - - - - - - - ~15° N
3,000-3,960 ft - - - - - - - - - - - - - - - - - - - ~15° NW (based on data from 3,810-3,900 ft)
3,960-4,610 ft - - - - - - - - - - - - - - - - - - - ~17° NW (consistent dips from 3,900-4230 ft range from 10-25° NW)
4,610-5,385 ft - - - - - - - - - - - - - - - - - - ~19° N (consistent dips from 4,900 to 5,000 range from 15-22° N)
5,385-5,570 ft - - - - - - - - - - - - - - - - - - ~20° NW (consistent dips from 5,250-5,500 range from 18-22° NW)
5,570-5,712 ft - - - - - - - - - - - - - - - - - - ~18° NW (consistently 18°NW, 5,550-5,585)
5,712-5,781 ft - - - - - - - - - - - - - - - - - - ~15° NW (consistently 15°NW, 5,690-5,780)
5,781-5,902 ft - - - - - - - - - - - - - - - - - - ~22° NW (consistently 22°NW, 5,825-5,900)
5,902-6,560 ft - - - - - - - - - - - - - - - - - - ~20° NW
6,560-6,782 ft - - - - - - - - - - - - - - - - - - - ~18° NW (consistently 18°NW, 6,560-6,600)
6,782-7,245 ft - - - - - - - - - - - - - - - - - - - ~26° WNW (consistent dips from 6,800-6,960 range from 20-30° WNW)
7,245-7,300 ft - - - - - - - - - - - - - - - - - - ~26° WNW (consistent dips from 7,080-7,250 range from 18-33° WNW)
7,300-7,442 ft - - - - - - - - - - - - - - - - - - ~32° W (consistent dips from 7,300-7,365 range from 28-42°W)[2]
7,880[2]-11,909 ft - - - - - - - - - - - - - - - - ~18° NW (based on consistent dips from 7,884-7,918, ranging from 14-26° NW)

1. The dipmeter HDT logging tool uses "4 pads, 90° apart, mounted on hydraulically actuated arms" which provide focused "micro-resistivity curves" of the adjacent borehole margin, giving deeper and narrower penetration than the older three pad CDM tool (Schlumberger, 1970, Fundamentals of dipmeter interpretation, p. 1). The four resistivity curves are normally matched by computer analysis; the released arrow plot specifies that it was obtained from a "cluster program", computed October 15, 1980.

2. Dip magnitudes decrease from 7,770 to 7,774 ft from 45°NE to 42°NNE in a tight group of three; next reading is @ 7,790 ft: 23°N, followed by 13°NE @ 7,792 and 18°N @ 7,796 and 7,798 ft. Possible thrust fault @ 7,788 ft, based on GR-Sonic log character, is consistent with dip changes. Three relatively consistent attitudes are recorded from 7,802 to 7,814 ft: 56°W, 50°WSW and 58°WSW. Dips drop back to 18°NW at 7,884 ft. Correction as follows: a = (7880-7788) x cos54.66667° = 53.207; b = (9158-7880) x cos18° = 1215.45; a + b = 1268.66; rounds downward to 1268 ft estimated thickness of Mission Canyon.

TABLE 1. American Quasar 27-22 Hagenbarth, drilled in SE NW Sec. 27, T. 5 S., R. 9 W. (Lat. 45.37331°N Long. 112.70201°W), Beaverhead County, MT. This oil and gas test was completed as a dry hole (D&A) December 5, 1980, at a total depth of 12,048 ft. Ground surface elevation at the wellsite was 5,410 ft. KB elevation, the datum for the borehole logs, was 5,431 ft. A dipmeter arrow plot, available from 1,002-7,918 ft, was used to calculate estimated true thickness of drilled intervals.

Stratigraphic unit	Log Tops feet	Drilled thickness feet	True thickness [corrected, for interpreted dip] feet	True thickness [corrected, for interpreted dip] meters
Quaternary valley fill	0	265	265	81
Upper Cretaceous rock	265	2,085(?)	2,039(?)	621(?)
Frontier Formation	265	2,085(?)	2,039(?)	621(?)
Lower Cretaceous rocks	2,350(?)	1,253(?)	1,210(?)	369(?)
Blackleaf Formation	2,350(?)	845(?)	816(?)	157(?)
Vaughan Member	2,350(?)	730(?)	705(?)	215(?)
Flood Member	3,080	115	111	34
Kootenai Formation	3,195	408	394	120
Pryor Conglomerate Mbr.	3,528	75	72	22
Jurassic rocks	3,603	472	456	139
Morrison Formation	3,603	199	192	59
Ellis Group	3,802	273	264	80
Triassic rocks	4,075	1,310	842	257
Thaynes(?) Limestone	4,075	130	124	38
Woodside(?) Formation	4,205	405	387(?)	118
thrust fault or faults	4,610	NA		
Thaynes(?) Limestone	4,610	125	119+	36+
Woodside(?) Formation	4,735	405	383	117
Dinwoodie Formation	5,140	245	232	71
Permian rocks	5,385	517	487	149
Phosphoria Fm.	5,385	517	487	149
Blacktail Shale Member	5,385	185	174	53
Shedhorn Sandstone Mbr.	5,570	142	135	41
Tosi Chert Member	5,712	16	15.5	4.7
Retort Member	5,728	55	53	16
Meade Peak Member	5,860	3	2.8	0.85
Grandeur Member	5,863	39	36	11
Pennsylvanian rocks				
Quadrant Sandstone	5,902	658	618	188
Mississippian rocks	6,560	3,413	3,189	972
Snowcrest Range Group	6,560	882	796	243
Conover Ranch Formation	6,560	222	211	64
Lombard Limestone	6,782	463	416(?)	127
decollement or thrust fault(?)	7,030	NA		
Kibbey Formation (siltstone)	7,245	197	169	52
Madison Group	7,442	2,531	2,407(?)	734(?)
Mission Canyon Formation	7,442	1,716	1,632(?)	497(?)
thrust fault?	7,788	NA	NA	NA
Mission Canyon Formation	7,788	1,370	1,268(?)	387(?)
Lodgepole Formation	9,158	812	775	236
Paine Member	9,495	475	452	138
Cottonwood Canyon Mbr.	9,970	3	2.9	0.87

TABLE 1 (continued).

Devonian rocks	9,973	645	613	187
Three Forks Formation	9,973	155	147	45
Sappington Member	9,973	29	27.6	8.4
Unit 1 (lower Bakken)	9,986	(16)	(15)	5
Trident Shale Member	10,002	28	26.6	8
Logan Gulch Member	10,030	98	93	28
Jefferson Dolomite	10,128	490	466	142
Cambrian rocks	10,618	1,215	1,156	352
Pilgrim Dolomite	10,618	302	287	88
Park Shale	10,920	122	116	35
Meagher Dolomite	11,042	545	518	158
Wolsey Shale	11,587	163	155	47
Flathead Sandstone	11,750	83	79(?)	24(?)
Precambrian? sedimentary rocks (Belt?)	11,833	76(?)	72(?)	22(?)
Precambrian metamorphic rocks	11,909			
Total Depth	12,048			

METHODS

Formation and member tops, in the American Quasar 27-22 Hagenbarth drillhole (table 1), are based primarily on my interpretation of the borehole compensated sonic and gamma ray (BHC/GR) log, in conjunction with the compensated neutron-formation density (FDC/CNL) log and log of lithology of returned drill cuttings, commonly known as a mudlog. These data were then compared with those of other drillholes from southwest Montana (Perry and others, 1981; Perry, 1986) as well as descriptions of stratigraphic units by Lowell (1949, 1963), Pecora (1981), and Hildreth (1981). I calculated formation thickness from drilled intervals, picked on the BHC/GR log, on the basis of publicly released dipmeter arrow plots (dip azimuth vs. dip magnitude) for the drill-hole interval 1,002 to 7,918 ft. I used an eyeball average for consistent (more than three) nearby readings, eliminating data scatter that is likely due to fractures, cross-stratification, or miscorrelation of resistivity curves. As always, the reported depths of drill cuttings need to be adjusted to those of lithology changes indicated by the geophysical borehole log curves (table 1).

One- to 5-pound, cloth-bagged samples of borehole cuttings were obtained from the operator for 10 ft intervals from 9,820-10,270 ft, from the lower Lodgepole through upper Jefferson Formations. Cuttings from the intervals 9,820-50, 9,950-60 and 9,990-10,000 ft were processed for conodonts by C. A. Sandberg. Conodont elements and fragments of elements from all three intervals indicate a CAI of 3 (C.A. Sandberg, 1997, written communication). The bagged cuttings appear to be about 30 ft low at the base of the Lodgepole (9,973 ft, table 1) with respect to the BHC/GR log: well cuttings from the depth interval 9,990-10,000 ft which yielded Kinderhookian (basal Mississippian as well as basal Lodgepole) conodonts, reported by C.A. Sandberg (1997, written communication). Lag (depth of cuttings vs. geophysical borehole depths) appears to vary, as black shale of the Cottonwood Canyon? Member of the Lodgepole Limestone (upper Bakken equivalent?) first appears in the cuttings in the interval 9,980-90 ft (10% shale); the gamma radiation marker on the gamma ray-sonic log places the Cottonwood Canyon at 9,970-9,973 ft. The proportion of black shale to limestone climbs to 95% black shale in the interval 10,000-10 ft and is approximately 90% in the interval 10,010-20 ft. The strong gamma radiation marker for the basal black shale of the Sappington Member of the Three Forks (lower Bakken equivalent?) is from 9,986-10,002 ft (table 1) based on geophysical borehole logs. Here the lag appears to be of the order of 14 to 18 ft, consistent with the organic carbon values reported (table 2). The usual downhole contamination from borehole cavings complicates the story; shales cave much more readily than carbonate rocks.

The interval 9,820-10,100 ft, which spanned expected Lower Mississippian through Upper Devonian potential hydrocarbon source rocks, was analyzed by Rock-Eval pyrolysis (Jerry Clayton, 1981, written communication). Organic carbon (TOC) determinations of these 26 samples were conducted by Rinehart Laboratories, Inc. Both sets of results are summarized in table 2. Rock-Eval pyrolysis is the controlled heating of a rock sample under dry conditions. It is currently the most common laboratory screening technique in hydrocarbon source rock evaluation (Bordenave and others, 1993) and was conducted on 26 samples in conjunction with the present study (table 2). **Tmax** is the temperature in °C (degrees Celsius) recorded for the maximum generation of hydrocarbons from kerogen, the insoluble organic material in the cuttings, during the artificial maturation caused by dry pyrolysis. It is a measure of thermal maturity. The high-temperature end of the oil window in source rocks occurs at a Tmax of about 460°C (Tissot and Welte, 1978, p. 454, fig. V.1.16). More recently, Bordenave and others (1993, fig. 2-17) showed that the oil and gas window varies slightly for different types of organic matter. Highly mature Type III organic matter can give Rock-Eval TOC values as much as 48 percent lower than actual (Bordenave and others, 1993, table 2-4), because 600° combustion does not completely oxidize such material. The boldface values of Tmax (table 2) for samples containing more than 0.9% TOC are believed

Table 2.

Organic carbon (TOC) and Rock-Eval analyses well cuttings - American Quasar 27-22 Hagenbarth drillhole.

DEPTH (ft)	FORMATION	% TOC	S1	S2	S3	Tmax[1]	S1+S2	HI	OI	PI
9,820-30	Lodgepole	0.88	0.049	0.148	0.35	379	0.197	17	40	0.25
9,830-40	-do-	0.88	0.051	0.081	0.37	359	0.132	9	42	0.39
9,850-60	-do-	0.89	0.154	0.091	0.42	355	0.558	45	47	0.28
9,850-60	-do-			0.313		**433**				
9,860-70	-do-	0.85	0.095	0.214	0.32	355	0.366	32	38	0.26
9,860-70	-do-			0.057		**436**				
9,870-80	-do-	0.83	0.056	0.160	0.35	364	0.303	30	42	0.18
9,870-80	-do-			0.087		**439**				
9,880-90	-do-	0.79	0.048	0.101	0.33	356	0.188	18	42	0.26
9,880-90	-do-			0.039		**441**				
9,890-9,900	-do-	0.82	0.269	0.441	0.38	372	0.809	66	46	0.33
9,890-9,900	-do-			0.099		**437**				
9,900-10	-do-	0.36	0.082	0.189	0.31	370	0.314	64	86	0.26
9,900-10	-do-	0.36		0.043		**436**				
9,910-20	-do-	0.83	0.076	0.129	0.34	360	0.262	22	41	0.29
9,910-20	-do-			0.057		**427**				
9,920-30	-do-	0.78	0.071	0.283	0.37	372	0.503	55	47	0.14
9,920-30	-do-			0.149		**442**				
9,930-40	-do-	0.38 0.39	0.054	0.104	0.23	356	0.158	27	60	0.34
9,940-50	-do-	0.77	0.038	0.076	0.35	361	0.146	14	45	0.26
9,940-50	-do-			0.032		**421**				
9,950-60	-do-	0.27	0.046	0.161	0.32	362	0.207	60	119	0.22
9,960-70	-do-	0.29	0.017	0.122	0.36	367	0.139	42	124	0.12
9,970-80	Three Forks	0.16 0.18	0.046	0.030	0.34	339	0.075	17	200	0.61
9,980-90	Sappington	0.54	0.047	0.198	0.45	337	0.245	37	83	0.19
9,990-10,000	-do-	0.60	0.001	0.086	0.25	369	0.087	14	42	0.01
10.000-10	lower Bakken	6.98 7.01	0.157	0.111	0.24	355	0.420	4	34	0.37
10.000-10	lower Bakken			0.152		**522**				
10.010-20	-do-	3.50	0.054	0.098	0.25	360	0.188	4	7	0.29
10.010-20	-do-			0.036		**526**				
10.020-30	Trident Mmbr	0.40	0.062	0.154	0.21	365	0.216	39	53	0.29
10.030-40	Logan Gulch	0.32	0.007	0.027	0.33	357	0.034	8	103	0.21
10.040-50	-do-	0.40	0.047	0.154	0.36	360	0.201	39	90	0.23
10.060-70	-do-	0.55	0.072	0.152	0.26	361	0.224	28	48	0.32
10.070-80	-do-	0.34	0.012	0.071	0.24	358	0.083	21	72	0.15
10.080-90	-do-	0.23	0.057	0.163	0.2	360	0.22	71	84	0.26
10,090-100	-do-	0.40	0.005	0.073	0.18	357	0.107	25	45	0.05
10,090-100	-do-			0.029		**443**				

1. The boldface Tmax values are considered the most reliable; these indicate late postmaturity with respect to oil; dry natural gas is the expected hydrocarbon.

the most reliable. These are well above the oil window. The **S_1** peak (table 2) is a measure of hydrocarbons that exist in a rock sample and "can be used as a tool to detect migrated hydrocarbons" (Bordenave and others, 1993, p. 241). The **S_2** peak represents hydrocarbons produced by heating of kerogen (Types I, II III). It "gives a reasonable evaluation of the current [hydrocarbon generation] potential of a rock sample"; 70-80 percent of Type I, 45-50 percent of Type II, and only 10-25 percent of Type III kerogen are transformed into hydrocarbons during pyrolysis (Bordenave and others, 1993, p. 242). Rocks with $S_2 < 4$ mg/g of sample have low or no hydrocarbon generation potential; S_2 between 4 and 8 indicates fair potential (Bordenave and others, 1993, p. 260). None of our samples had S_2 values as high as 0.5 (table 2). The **S_3** peak is a measure of carbon dioxide generated in the sample during pyrolysis of oxygen-bearing organic compounds. It is recorded below 400°C because of thermal decomposition of some carbonates and other poorly crystallized inorganic crystalline materials occurs at higher temperatures. The accuracy of this peak is low for rocks with low organic content (TOC < 0.5 percent, especially those containing a large amount of siderite), affecting the oxygen index **[OI]**, computed from S_3/TOC. The hydrogen index **[HI]**, computed from S_2/TOC, correlates well with H/C [atomic] ratios of kerogen. HI vs OI diagrams are used in classifying Types I, II, and III kerogen (Bordenave and others, 1993, p. 251). **PI** (table 2), the production index, is the $S_1/(S_1+S_2)$ ratio, which increases mainly due to cracking of the kerogen (Bordenave and others, 1993, p. 252). Values lower than 0.05 indicate immature kerogens; 0.6 or higher values indicate almost all hydrocarbons have formed (Bordenave and others, 1993, p. 252). The low values of both S_1 and S_2 obtained for our samples (table 2) render the PI results suspect.

STRATIGRAPHIC DISCUSSION

Mesozoic rocks. Although thicknesses of post-Triassic rocks in the Hagenbarth drillhole were not readily comparable with those of the nearby Armstead anticline and Blacktail Mountains to the south (fig. 2 and table 3), no obvious thrust faulting was observed from the borehole data above 4,610 ft. The Cretaceous Frontier/Blackleaf contact is obscure. My pick (at about 2,350 ft) is based on a downward increase in abundance of volcaniclastic material, assigned to the Vaughan Member of the Blackleaf Formation, and a downward decrease in gray-green shale and siltstone, typical of the lower Frontier. The underlying Flood Member of the Blackleaf contains interbedded black shale, light-gray siltstone, and sandstone. The underlying Kootenai has a dip-corrected thickness of 394 ft, with the distinctive Pryor (Cloverly) Conglomerate Member at the base (fig. 3). Jurassic rocks have a dip-corrected thickness of about 472 ft (table 1). Repetition of lithologies and log characteristics occurred in the Triassic interval, indicating that a thrust fault was probably encountered at a log depth of 4,610 ft. Average dip appears to increase from 17° NW to 19° NW at this depth (see explanation of table 1); 530 ft of section is repeated. The interval assigned to the Triassic (table 1) is estimated to have been originally slightly more than 840 ft thick, close to the 700-800 ft thickness given by Lowell (1949). On the surface, in the Blacktail Mountains to the south, the entire Triassic section is placed in the Dinwoody Formation (Pecora, 1981). However the Triassic sequence encountered in the Hagenbarth drillhole appears more like that observed south and east of Lima (Perry, 1986): an upper limestone (Thaynes), a thick middle sequence of brick-red shale, light-red calcareous siltstone and minor limestone (Woodside), and a lower gray-brown to medium- to dark- gray limestone (Dinwoody). Regionally the Triassic sequence thickens southward in outcrop, from 430 ft in the Blacktail Mountains to 1,315 ft in the Blacktail Road area in the Snowcrest Range (table 3). However, undivided Triassic rocks are also about 430 ft thick near Melrose north of the drillhole site (J.M. O'Neill, 1997, written communication). The dip-corrected Triassic thickness and likely presence of both Thaynes and Woodside Formations in the Hagenbarth drillhole appears

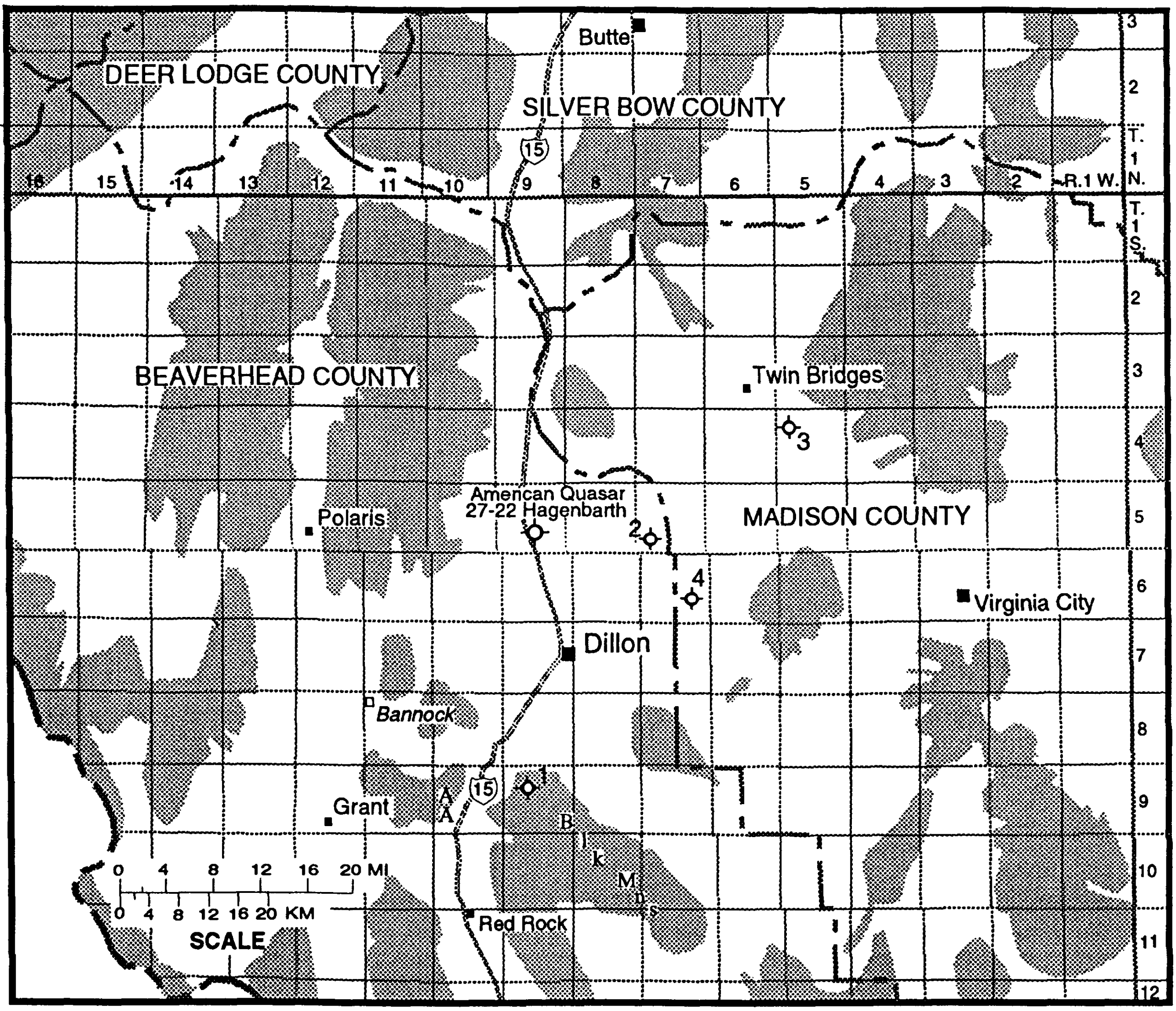

Figure 2. Index map of a portion of southwestern Montana showing the location of the Hagenbarth drillhole and nearby localities: AA - Armstead anticline; Blk Mns - Blacktail Mountains. Highlands are shaded. Drillhole 1 is American Quasar 9-1 May-Federal; 2 is American Quasar Petroleum 29-1 Rebish; 3 is North American Resources 3-8-4-5; 4 is North American Resources 7-23 State.

Table 3.

Thickness Comparisons of Stratigraphic Units

Stratigraphic columns[1]

Age	Formation	27-22 Hagenbarth	Armstead anticl. (Hildreth (1981)	Blacktail Range (Pecora, 1981)	Snowcrest Range (Zeigler, 1954)
Late Cretaceous	Frontier	2,039(?)			
Early Cretaceous	Blackleaf Fm.	816(?)			~500
	Kootenai Fm.	394			241-400
Cretac. & Jurassic	Kootenai+Morrison	866		1,080	
Jurassic, undiv.		472			85-100
Triassic, undiv.		842		430	1,315
Permian	Phosphoria Fm.	487		358	~800
Pennsylvanian	Quadrant Ss.	618	~1,100	725	~1,200 (800 McBride[2])
Mississippian	Conover Ranch	211	~100	88	345 (830 McBride)
	Lombard	416	~450	~696	2023 Byrne[2]
	Kibbey Ss.	169		175	379 (200 Flanagan[2])
	Snowcrest Range Grp	796	~550	959	2,747-3,053
	Mission Canyon Fm.	1,632 (1,268)	1,700	812 (850 Huh[2])	905
	Lodgepole Ls.	775	1,100	753 (990 Huh)	900 (McBride)
Devonian	Three Forks	109	94	60	381 (Gealy[2])
	Jefferson Fm.	466	550	118	269 (Gealy)
Cambrian	Pilgrim Dol.	287	98	122	Unexposed
	Park Shale	116		92	
	Meagher Dol.	518		553	
	Wolsey Shale	155	~100	61	
	Flathead Ss.	79	95	50	
	Total Cambrian	1,155	293	878	~1,000-1,100 (Sheedlo[2])

1. Thicknesses in feet

2. Alternative thicknesses from measured sections by Byrne (1985), Flanagan (1958), Gealy (1953), Huh (1968), McBride (1988), and Scheedlo (1984).

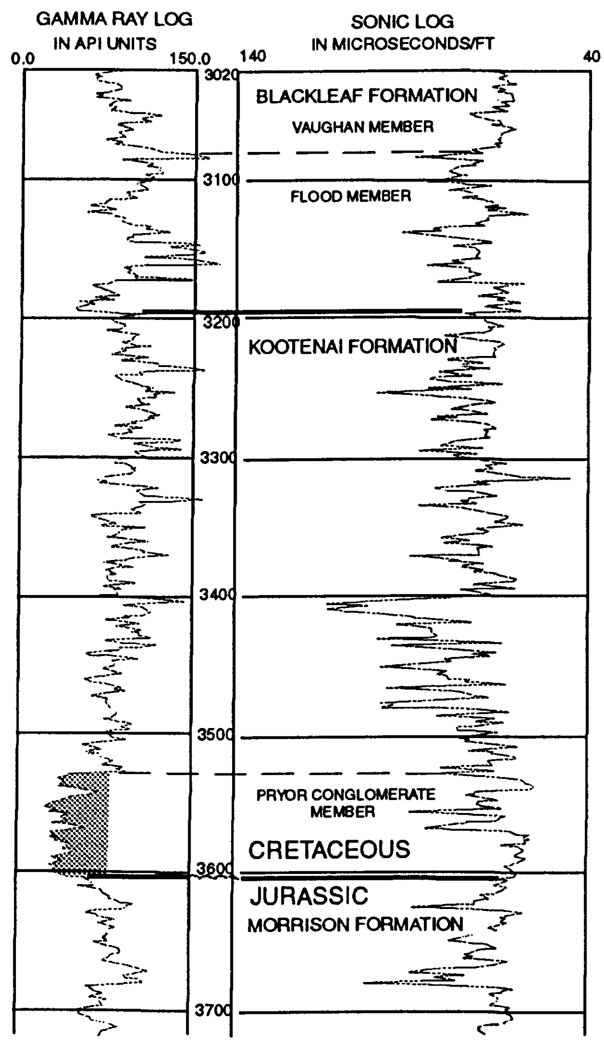

Figure 3. Lower Cretaceous and probable Cretaceous/Jurassic boundary section of BHC/GR log, American Quasar 27-22 Hagenbarth drillhole.

anomalous, based on both the above references and Peterson (1985, fig.15). Possibly, dips get very steep close to the thrust fault, so that my dip corrections may be insufficient; possibly smaller contraction faults exist near the larger thrust fault at 4,610 ft log depth. However, the dip-corrected thickness of Woodside(?) turned out the same both above and below the thrust, 405 ft, suggesting that the total Triassic thickness in the area of the drillhole may indeed exceed 800 ft. Paull and others (1989) report the presence of Thaynes in their nearby incomplete Birch Creek section (SW ¼, sec. 24, T. 5 S., R. 10 W.), where Moritz (1950) earlier reported a total Triassic thickness of 885 ft.

Upper Paleozoic rocks. The dip-corrected thickness of Permian (487 ft), Pennsylvanian (618 ft), and Mississippian strata (3,635 ft) in the Hagenbarth drillhole (table 1) is more consistent than that of the drilled Triassic sequence with reported thicknesses in the region (table 3). The Mississippian assignment of the Conover Ranch (formerly Amsden Formation) follows Wardlaw and Pecora (1985).

The Permian Phosphoria Formation is comprised of from top downward, 142 ft of Shedhorn Sandstone Member, underlain by about 16 ft of the Tosi Chert Member. The underlying Retort Phosphatic Shale Member, is about 53 ft thick, and the Meade Peak, 23 ft farther downhole, is slightly less than 3 ft thick based on gamma ray signature on the BCS/GR-log. The Retort has excellent oil-source-rock potential to the south, in the Blacktail Mountains (Claypool and others, 1978). The basal Grandeur Member (36 ft thick, table 1) is predominately dolomite.

The BCS/GR-log base of continuous sandstone in the Pennsylvanian Quadrant Sandstone occurs at 6,520 ft (based on abrupt increase downward to carbonate velocities at this depth). The interval 6,520-40 ft appears to be predominately dolomite; then lower interval travel times versus low gamma ray response strongly suggests that the basal 20 ft of Quadrant (6,540-6,560 ft) is again sandstone. Drill cuttings show considerable lag here (about 50 ft) with the mudlog base of the Quadrant about 6,610 ft. Dolomite predominates in the cuttings from 6,700 to 6,850 ft, described as silty to argillaceous, with red to dark-gray shale logged from about 6,600 to 6,750 ft, comprising 50% of the cuttings from 6,680-6,700 ft on the mudlog. Based primarily on the BCS/GR log, I interpret the interval 6,560-6,782 ft as Conover Ranch Formation (table 1), formerly the "Alaska Bench" of E. K. Maughan (oral communication, 1982). The interval from 6,782 to 7,245 ft is limestone dominated, with abundant interbedded shale indicated on the gamma ray-sonic log. The limestone is predominantly dark gray to tan, fine grained, and dolomitic in part, according to the mudlog. Velocities are generally higher in this interval than either directly above or below. The basal 150 ft is virtually continuous limestone as in the basal Lombard Formation in the Snowcrest Range to the south. I classify this entire unit (6,782-7,245 ft) as Lombard Limestone.

At 7,300 ft the mudlog lags the gamma ray-sonic log by about 50 ft. The interval 7,245-7,442 ft is predominantly orange siltstone with occasional sandstone and sandy dolostone of the Kibbey Formation as exposed in the Blacktail Mountains and Snowcrest Range (Pecora, 1981; Perry and others, 1988). The interval 6,560-7,442 ft comprises the Snowcrest Range Group of Wardlaw and Pecora (1985). My calculated thicknesses are 796 ft for the group and 211 ft for the Conover Ranch, 416 ft for the Lombard, and 169 ft for the Kibbey (table 1). Based on the regional nature of this interval, tightly folded on the Armstead anticline, and imbricately thrusted in the Blacktail and Tendoy Mountains, it is unwise to trust these computed thicknesses. Additionally, the regional seismic section (Lopez and Schmidt, 1985) requires a decollement in this interval, close to and above the Mission Canyon Formation, possibly at about 7,030 ft, based on comparison of the BCS/GR and other geophysical borehole logs.

The Mission Canyon may be partly repeated by thrusting, with a thrust fault encountered at about 7,788 ft repeating the upper 346 ft drilled interval of Mission Canyon (see footnote 2 to the explanation of table 1). According to descriptions of cuttings on the mudlog, the Mission Canyon is a medium- to dark-gray partly dolomitic micritic limestone which contains abundant calcite-filled fractures. Below 9,000 ft, fossil fragments are logged on the mudlog; I used the gamma ray log break at 9,158 as the top of the Lodgepole (table 1 and fig. 4), but the upper member of the Lodgepole - the Woodhurst Member - is very fossiliferous on the Armstead anticline and in the Highland Mountains northeast of the drillsite. The contact may thus be higher than suggested by the gamma ray log. Below 9,500 ft, the Lodgepole becomes predominantly very dark-gray, very fine-grained, and not visibly fossiliferous limestone, typical lithology of the Paine Member of the Lodgepole, as observed on the east flank of the Armstead anticline. At the base of the Paine Member of the Lodgepole, 9,970 ft by BCS/GR log response, the mudlog lags the gamma ray-sonic log by about 30 ft. Thus the reported depths of cuttings analyzed both for conodonts, TOC, and RockEval (table 2) are off BCS/GR log depth by this amount near the base of the Mississippian. The Cottonwood Canyon Member of the Lodgepole, the "Upper Bakken" equivalent of the oil and gas industry, is represented by an abrupt increase in natural gamma radiation from 9,970-9,973 ft on the BCS/GR log (fig.4). Total thickness of Mississippian rocks penetrated by the Hagenbarth drillhole is about 2,840 ft.

Lower Paleozoic rocks. The Devonian-Mississippian contact is placed at 9,973 ft. All three members of the directly underlying Devonian Three Forks Formation can be recognized by BCS/GR log response (fig.4), although the typical green shale of the Trident member was not recorded on the mudlog. The Three Forks appears to be about 147 ft thick in the Hagenbarth drillhole. The gamma ray intense black shale of unit 1 (lower Bakken) at the base of the Sappington Member is 15 ft thick (table 1 and fig. 4). The recorded TOC of 3.5 to 7% from this interval (table 2) may be low, due to uphole contamination of the cuttings analyzed. First appearance of tan to light-brown Logan Gulch dolostone in the cuttings at 10,060 ft versus the BCS/GR log top at 10,030 ft, indicates that the mudlog tops are 30 ft low with respect to the BCS/GR log, the same lag found at the base of the Mississippian.

The Jefferson Formation, 466 ft thick in the Hagenbarth drillhole, is primarily light- to medium- and dark-gray dolostone, microcrystalline to finely crystalline, with traces of anhydrite. Medium-gray shale in this interval of the mudlog may represent cavings.

The top of the Cambrian was encountered at a depth of about 10,618 ft and is marked by transition to dark gray-brown laminated dolostone. The uppermost Cambrian unit, about 287 feet thick in the Hagenbarth drillhole, is assigned to the Pilgrim Dolomite (after Lowell, 1965, p.1; Pecora, 1981, p.19), although Sandberg (1997, written communication) identified this as Red Lion Formation at an outcrop 12 miles to the northeast. Lag in cuttings vs. BCS/GR log depths is only about 10 ft at the Pilgrim/Park Shale contact. The Park Shale, described as green to gray green and slightly silty on the mudlog, has a calculated thickness of 116 ft. The underlying Meagher Dolomite, about 518 ft thick, consists of predominantly dark-brown to dark gray-brown medium-crystalline to microcrystalline dolostone.

The BCS/GR log top of the Wolsey Shale occurs at a depth of 11,587 ft. Here, there is little if any sample lag as indicated by the mudlog top of the Wolsey at about 11,580 ft. The Wolsey is described as a green waxy to silty shale with interbedded light- to medium-green sandy siltstone. The Wolsey is calculated to be about 155 ft thick. The underlying Flathead Sandstone is 79(?) ft thick with a sharp base on the BCS/GR log at 11,833 ft. Beneath the Flathead is an approximately 72-ft-thick interval logged as quartzitic sandstone, white to pink, very fine to coarse grained, the base of which appears to be at about 11,909 ft on the BCS/GR log. The mudlog places the base of this sandstone at 11,960 ft. This interval

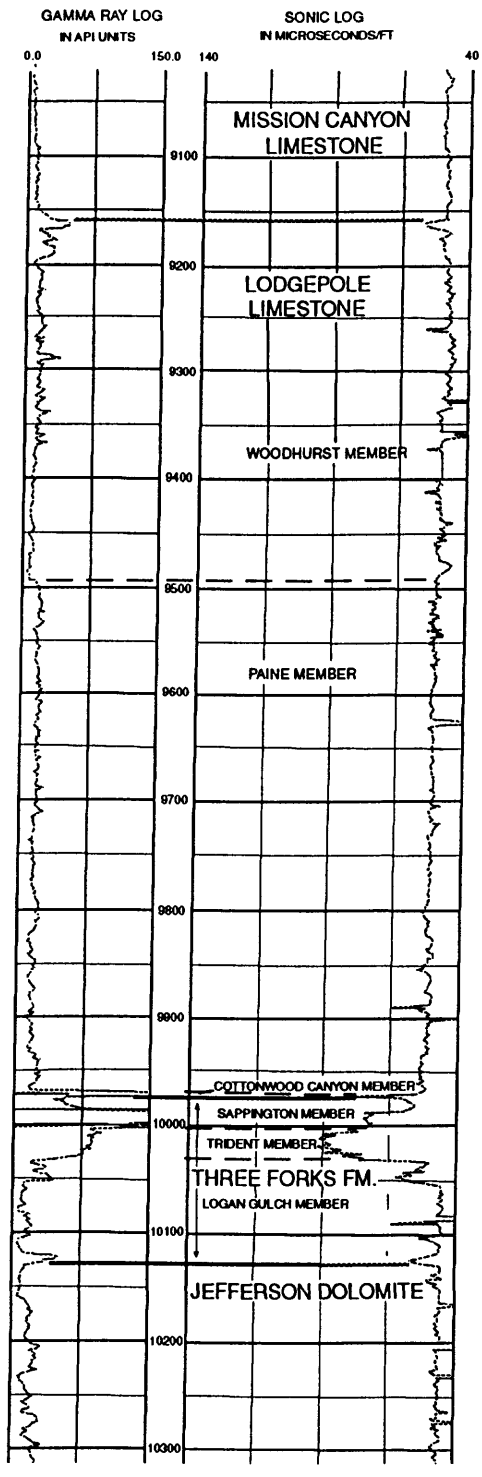

Figure 4. Lower Mississippian and Upper Devonian sections of BHC/GR log, American Quasar 27-22 Hagenbarth drillhole.

is interpreted as possibly a pocket of or near wedge edge of Proterozoic Belt sandstone. Beneath this sandstone the mudlog lists "granite/schist", undoubtedly high-grade metamorphic rocks. Pearson (1996) found 722 ft of possibly equivalent Middle Proterozoic Belt Supergroup, primarily "ferruginous, argillaceous, micaceous, feldspathic quartzite; red and green sandy and silty argillite; and thick-bedded coarse-grained to very coarse-grained feldspathic quartzite" in core from a shallow drillhole in the Argenta mining district about 20 km northwest of Dillon, Montana.

THERMAL MATURATION AND HYDROCARBON POTENTIAL

Thermal maturity indicators obtained from Lower Mississippian and Upper Devonian cuttings from the Hagenbarth drillhole include conodont CAI, vitrinite reflectance, TAI, and Rock-Eval pyrolysis results. Conodont elements and fragments of elements were obtained from cuttings from the intervals 9,820-50, 9,950-60 and 9,990-10,000 ft; all three intervals indicate a CAI of 3 (C.A. Sandberg, 1997, written communication), postmature with respect to oil (fig. 5, Perry and others, 1983). Cuttings from the interval with the highest reported TOC, 10,000-10,100 ft, yielded ordered vitrinite reflectance values ranging from 1.72 to 2.82; the median reflectance of the 57 ordered reflectance values obtained was 2.39; the mean reflectance was 2.36 with a standard deviation of 0.24 (Mark J. Pawlewicz, written communication, 1981), indicating late postmaturity with respect to oil (fig. 5, Perry and others, 1983), a slightly higher thermal maturity than indicated by the conodont CAI. Cuttings from the same interval were processed for kerogen color and TAI by A.H. Love. The dark brown kerogen color and TAI of 4 obtained, are consistent with the vitrinite results. Tmax results from Rock-Eval pyrolysis (in boldface for higher than 1% TOC samples, table 2) reported by J.L. Clayton (written communication, 1981) also indicate late postmaturity with respect to oil. Low S_2 results (table 2) indicate no or very low hydrocarbon generating capacity.

Unfortunately, no Permian cuttings were acquired for source rock analysis. Samples of the Retort (nos. 9-10, Claypool and others, 1978, table 2) from sec. 23, T. 9 S., R. 9 W., in the Blacktail Mountains to the south, ranged from 11.9% to 13.3% organic carbon and contained 16.8 to 18.9 parts/thousand extractable bitumen, excellent oil source rocks. A sample from the Pioneer Mountains to the west (no. 12, Claypool and others, 1978, table 2, sec. 3, T. 6 S., R. 11 W.), contained only 0.5% organic carbon and was supermature with respect to liquid hydrocarbon generation. By extrapolation, the Phosphoria in the Hagenbarth drillhole may also be supermature, but likely generated liquid hydrocarbons during Cretaceous maximum burial and high heat flow associated with magmatic activity.

CONCLUSIONS

The Hagenbarth drillhole appears to have encountered about 72 ft of Middle Proterozoic Belt quartzite beneath the basal Phanerozoic Flathead Sandstone; no Belt rocks are present on the Armstead anticline or Blacktail Mountains (fig. 2). Pearson (1996) shows that Belt rocks thicken rapidly to the north and west of the Hagenbarth drillhole. The encounter in the drillhole is the farthest southeast that Middle Proterozoic rocks have been reported.

The Hagenbarth drillhole provides critical data on the thickness and character of Paleozoic rocks north of Dillon. Cambrian strata are thicker than to the south and west (table 3) in agreement with Peterson (1985). Ordovician through Middle Devonian strata are absent, also in agreement with Peterson (1985). Upper Devonian through lowermost Mississippian Bakkan-equivalent strata contain as much as 7% organic carbon and are supermature with respect to liquid hydrocarbons. The Lower Mississippian Madison Group is probably slightly more than 2,400 ft thick, apparently somewhat thinner than on the Armstead anticline, but thicker than to the southeast (fig. 2; table 3). The presence of Upper Paleozoic Snowcrest Range Group (SRG) at this latitude is in agreement with Peterson (1985). The Kibbey Formation at the base of the SRG is a distinctive orange siltstone, about 170 ft thick in the drillhole, not significantly different than reported by Pecora (1981) in the Blacktail Mountains. The Pennsylvania Quadrant Sandstone is more than 600 ft thick and represents a potential hydrocarbon reservoir rock. The overlying Phosphoria Formation is about 487 ft thick, considerably thicker than the approximately 100 ft shown by Peterson (1985, fig. 14). The Phosphoria contains two black shale members, the Retort about 53 ft thick and the underlying Meade Peak, slightly less than 3 ft thick based on gamma ray signature.

About 842 ft of Triassic and 456 ft of Jurassic rocks are present in the Hagenbarth drillhole. The Triassic sequence is similar to that farther south as discussed above, such that Thaynes, Woodside, and Dinwoodie Formations are all three present. Thickness encountered is similar to that measured by Moritz (1950), nearby, but very different than estimated or measured by others as discussed at length above. The Jurassic sequence encountered consists of about 264 ft of Ellis Group and 192 ft of overlying Morrison Formation. If correct, this aggregate thickness of 456 ft of Jurassic rocks, far in excess of the less than 100 ft reported by Peterson (1985, fig. 16), requires rethinking the presence, location or size of his Jurassic 'Boulder high'. The overlying Lower Cretaceous sequence is subdivided into the Kootenai Formation, about 394 ft thick, and overlying Blackleaf Formation, about 816 ft thick, as discussed above. More than 2,000 ft of Upper Cretaceous Frontier Formation are present in the Hagenbarth drillhole; this siliciclastic formation extends nearly to the surface. Only 265 ft of Quaternary valley fill is present at the drill site. The broad Quaternary valley here is not underlain by Tertiary rocks.

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