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Oil and gas plays of the Las Animas Arch, southeastern Colorado

by

E. A. Merewether[1]

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[1]USGS Denver, Colorado

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INTRODUCTION

On the Las Animas Arch of southeastern Colorado, oil and gas are structurally and stratigraphically entrapped in siliciclastic and carbonate rocks of late Paleozoic age. The arch, as described in this report, occupies a region of about 6,300 sq mi which comprises Cheyenne, Kiowa, Otero, and Bent Counties (fig. 1). Major towns in the region are Cheyenne Wells, in eastern Cheyenne County; La Junta, in northeastern Otero County; and Las Animas, in northwestern Bent County.

Structural setting

The Las Animas Arch is a broad, gently dipping, anticlinal uplift that extends north-northeast from southwestern Bent County through eastern Cheyenne County and into northwestern Kansas. This uplift separates the Denver Basin of northeastern Colorado from the Hugoton Embayment of southeastern Colorado and southwestern Kansas (fig. 2). The southern end of the Las Animas Arch is on the northern flanks of the Apishapa and Sierra Grande uplifts, which trend east-southeast across Las Animas County.

In the region of the arch, folds and faults are recognized on the surface (Tweto, 1979) and in the subsurface (Crouch, 1982). These structural features, and extensive unconformities in the region, reflect deformation mainly during Late Mississippian-Pennsylvanian time and Late Cretaceous-early Tertiary time. The Front Range highland, Apishapa highland, and ancestral Las Animas uplift were forming in the latest Mississippian and Pennsylvanian (Tweto, 1980). The Front Range and Las Animas Arch rose again in the latest Cretaceous-early Tertiary (Tweto, 1980).

Stratigraphy

In the four counties of the Las Animas Arch, the sedimentary rocks range in thickness from about 2,000 ft near the crest of the Apishapa highland to as much as 8,000 ft along the western border of the region (Jensen, 1972). These strata are composed mainly of siliciclastic and carbonate rocks which were deposited in marine and continental environments during the Paleozoic and Mesozoic (Wilson, 1976; fig. 3). Pre-Quaternary strata at the surface of the region are mostly Cretaceous formations but there is a considerable area of Miocene rocks in eastern parts of Kiowa and Cheyenne Counties and a small area of Jurassic rocks near the southern border of Otero and Bent Counties (Tweto, 1979).

In the northern part of the region, in the subsurface, Precambrian rocks are disconformably overlain by an Upper Cambrian sandstone which is probably less than 100 ft thick and was deposited in nearshore-marine environments (Lochman-Balk, 1972; Ross and Tweto, 1980). Dolomite and minor limestone of

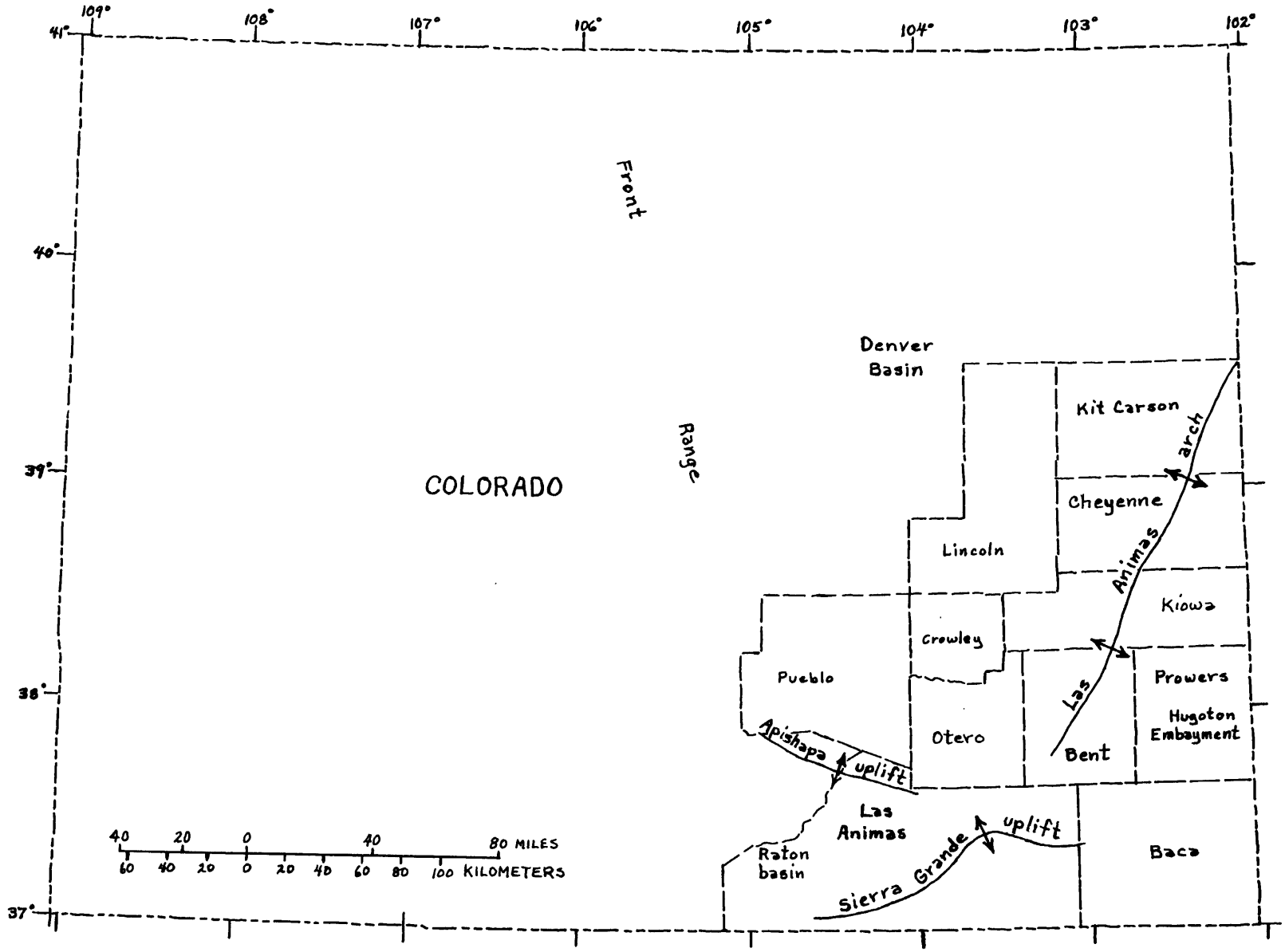

Figure 2. Map of Colorado showing structural features (Scanlon, 1983) and some counties in the region of the Las Animas Arch

ERATHEM	SYSTEM	SERIES	STRATIGRAPHIC UNITS (*-unit contains oil and gas)	DOMINANT LITHOLOGY	THICKNESS (FEET)
CENOZOIC	QUATERNARY	Holocene		Alluvium	
		Pleistocene		Alluvium and eolian deposits	
	TERTIARY	Miocene	Ogallala Formation	Sand and gravel	
MESOZOIC	CRETACEOUS	Upper	Pierre Shale Niobrara Fm. Carlile Shale Greenhorn Ls. Graneros Shale	Shale and limestone	0-3,500
		Lower	Dakota Sandstone	Sandstone and mudstone	0-350
	JURASSIC	Upper	Morrison Fm. Ralston Creek Fm. (part)	Sandstone and mudstone	100-350
		Middle	Ralston Creek Fm. (part) Entrada Ss.		
	TRIASSIC	Upper	Dockum Group	Sandstone, mudstone, limestone, and dolomite	0-500
PALEOZOIC	PERMIAN	Guadalupian	Taloga Formation Day Creek Dol. Whitehorse Ss.	Mudstone, sandstone, conglomerate, and carbonate and evaporitic rocks	1,400-2,000
		Leonardian	Nippewalla Group Sumner Group		
		Wolfcampian	Chase Group Council Grove Group Admire Group		
	PENNSYLVANIAN	Virgilian	Wabaunsee Group Shawnee Group * Douglas Group	Carbonate rocks, shale, sandstone, and conglomerate	1,400-3,000
		Missourian	Lansing Group * Kansas City Group *		
		Desmoinesian	Marmaton Group * Cherokee Group *		
		Atokan	*		
		Morrowan	*		
	MISSISSIPPIAN	Meramecian	Ste. Genevieve Ls. St. Louis Fm. * Salem Fm. * Warsaw Fm. *	Carbonate rocks and mudstone	0-600
		Osagean	Harrison Shale St. Joseph Fm. *		
		Kinderhookian	Gilmore City Ls. equivalent Misener sand		
	ORDOVICIAN	Lower	Arbuckle Group	Dolomite and limestone	150-450
	CAMBRIAN	Upper	Reagan Sandstone	Sandstone	0-100
PRECAMBRIAN			Metamorphic and igneous rocks		

Figure 3. Stratigraphic units and oil and gas-bearing rocks in Bent, Cheyenne, Kiowa, and Otero Counties, Colorado. The wavy lines represent unconformities.

Late Cambrian and Early Ordovician age conformably overlie the Upper Cambrian sandstone in the northern part of the region and unconformably overlie Precambrian rocks in the southern part of the region (Foster, 1972). These carbonate rocks range in thickness from about 150 to 450 ft and are of marine origin.

Disconformably overlying the Ordovician beds are carbonate and siliciclastic rocks of Early and Late Mississippian age, which were deposited in subtidal-marine environments. These rocks are assigned to, from oldest to youngest, the Kinderhookian, Osagean, and Meramecian Series. Disconformities have been recognized at the tops of the Osagean and the Meramecian Series (Ramirez, 1974; De Voto, 1980a). The Mississippian rocks are 500-600 ft thick on the southeastern flank of the arch in eastern Kiowa County, 100-200 ft thick on the northwestern flank of the arch in northwestern Cheyenne County, and absent on the Apishapa highland in southwestern Otero County (Craig, 1972; Volk, 1971; De Voto, 1980a).

Strata of Pennsylvanian age unconformably overlie the Mississippian and older formations in eastern Colorado. The Pennsylvanian formations on the Las Animas Arch are assigned to, in ascending order, the Morrowan, Atokan, Desmoinesian, Missourian, and Virgilian Series. These rocks thicken southwestward from about 1,400 ft thick in northeastern Cheyenne County to about 3,000 ft thick in central Otero County but are absent south of Otero County on the Apishapa highland (Volk, 1971; Mallory, 1972; De Voto, 1980b). The Pennsylvanian formations consist mainly of sandstone, shale, and carbonate rocks which were deposited in continental and marine environments. Most of the rocks in Cheyenne and Kiowa Counties accumulated in offshore-marine environments; those in Otero and Bent Counties accumulated along the northern flank of the Apishapa highland in nearshore-marine and continental environments (Mallory, 1972; De Voto, 1980b).

Permian strata conformably overlie the Pennsylvanian beds on the arch (Rascoe and Baars, 1972) and disconformably overlie pre-Pennsylvanian rocks on the Apishapa highland (Mudge, 1967). The Permian formations comprise, from oldest to youngest, the Wolfcampian, Leonardian, and Guadalupian Series. Beds of the Leonardian Series enclose a widespread disconformity (Maughan, 1980). The Permian strata range in thickness from about 1,400 ft in northern Cheyenne and southwestern Otero Counties to about 2,000 ft in southeastern Kiowa County, and are thicker southeast of Kiowa and Bent Counties (Volk, 1971; Rascoe and Baars, 1972). Permian rocks are mainly red shale, siltstone, and sandstone, which were deposited in deltaic and coastal environments, but include arkosic sandstone and conglomerate of fluvial origin near the Apishapa highland, as well as carbonate and evaporitic rocks of restricted, marine embayments near the Colorado-Kansas border (Rascoe and Baars, 1972).

Strata of Late Triassic age disconformably overlie the Permian formations and range in thickness from about 500 ft in Bent County to a north-northwest-trending featheredge in Kiowa and Cheyenne Counties (MacLachlan, 1972). The Triassic rocks consist of orange-red sandstone, mudstone, limestone, and dolomite and are mainly of continental origin.

Jurassic strata disconformably overlie the Triassic rocks in Otero and Bent Counties and adjoining areas, and disconformably overlie Permian rocks in eastern parts of Kiowa and Cheyenne Counties (Peterson, 1972). The strata are composed of Middle and Upper Jurassic units which are separated by a disconformity (Berman and others, 1980). These beds consist mostly of continental siliciclastic rocks and are 100-350 ft thick.

In the region of the arch, strata of Early Cretaceous age disconformably overlie the Jurassic beds. These Cretaceous strata are 200-350 ft thick and are composed of marine and continental siliciclastic rocks (McGookey and others, 1972) which enclose two disconformities.

Upper Cretaceous beds conformably overlie the Lower Cretaceous strata of the region. The Upper Cretaceous formations consist of siliciclastic and carbonate rocks, most of which were deposited in offshore marine environments. These rocks enclose several disconformities and are as much as 3,500 ft thick; they thin southeastward.

The Upper Cretaceous strata are unconformably overlain by siliciclastic units of Miocene age in eastern parts of Cheyenne and Kiowa Counties. Lower and Upper Cretaceous beds in other parts of the region are unconformably overlain by Pleistocene and Holocene alluvium and eolian deposits.

Source rocks

Many formations in the region contain carbonaceous beds which probably are source rocks for oil and gas. Volk (1971) and MacMillan (1980) report that strata of Mississippian age in southeastern Colorado contain source rocks. Information from MacMillan (1980) and geochemical data from drill cores and outcrops (tables 1 and 2) indicate that source beds occur in strata of Pennsylvanian age. Source rocks also have been identified in two Cretaceous formations and are probably present in others.

Table 1.—Location and description of core and outcrop samples from southeastern Colorado

[Samples 1, 2, 3, 4, and 32 are not located on figure 1]

Core sample	County	Location (Sec.-T.-R.)	Borehole (company, lease)	Depth (ft)	Stratigraphic unit	Lithology
1	Baca	9-29S.-42W.	Anadarko Production Co., Arbuthnot A-1	5,527	Morrowan	shale
2	—do—	—do—	—do—	5,605	—do—	calcareous shale
3	—do—	9-33S.-41W.	TXO Corp., Sloan 1A	3,118	Virgilian	calcareous mudstone
4	—do—	33-33S.-41W.	NRM Petroleum Corp., Kraft 1	4,536	Morrowan	shale
5	Cheyenne	8-14S.-49W.	Tricentrol Resources Co., Wilkerson Sorrento 22-8	5,520	—do—	Do.
6	—do—	23-15S.-46W.	Lewis and Clark Expl. Co., RDD Larson Grouse 1	5,547	Mississippian rocks	dolomite
7	—do—	26-15S.-46W.	Lewis and Clark Expl. Co., Lowe-Arnold Grouse 3	5,527	—do—	calcareous shale
8	—do—	—do—	—do—	5,567	—do—	dolomite
9	—do—	16-16S.-46W.	Lewis and Clark Expl. Co., LKC Schaefer-Colorado 1	4,281	Missourian	calcareous mudstone
10	—do—	—do—	—do—	4,440	Desmoinesian	mudstone
11	Kiowa	6-18S.-52W.	General American Oil Co., Federal 1-6	4,843	Virgilian	calcareous shale
12	—do—	—do—	—do—	5,994	Mississippian rocks	limestone
13	—do—	—do—	—do—	6,100	—do—	calcareous mudstone
14	—do—	31-20S.-42W.	Kirby Exploration Co., L. L. Fenton 2-31	4,288	Missourian	dolomite
15	—do—	—do—	—do—	4,332	Desmoinesian	limestone

Table 1.—Location and description of core and outcrop samples from southeastern Colorado—continued

Core sample	County	Location (Sec.-T.-R.)	Borehole (company, lease)	Depth (ft)	Stratigraphic unit	Lithology
16	Lincoln	33-13S.-52W.	Midwest Oil Corp., UPRR 1	4,148	Permian rocks	calcareous siltstone
17	—do—	13-14S.-57W.	Louisiana Land and Expl. Co.-Western Drilling Co., Jack P. Jones 2	3,923	Cretaceous rocks (Dakota Sandstone)	carbonaceous siltstone
18	Prowers	6-21S.-43W.	Kirby Exploration Co., B.W. Speaker 1-6	3,824	Missourian	limestone
19	—do—	—do—	—do—	3,872	—do—	shale
20	—do—	35-21S.-45W.	Hunt Oil Co., Heckman 1-35	3,841	Desmoinesian	dolomite
21	—do—	—do—	—do—	3,939	—do—	Do.
22	—do—	34-22S.-43W.	Kirby Exploration Co., F. E. Verhoeff 1-34	3,661	Missourian	Do.
23	—do—	—do—	—do—	3,692	—do—	limestone
24	—do—	18-24S.-45W.	Michigan-Wisconsin Pipe Line Co., Neuhold 1-18	4,993	Morrowan	carbonaceous shale
25	—do—	—do—	—do—	5,050	—do—	silty shale
26	—do—	26-25S.-45W.	Michigan-Wisconsin Pipe Line Co., Bailey 1-26	4,874	—do—	mudstone

Table 1.—Location and description of core and outcrop samples from southeastern Colorado—continued

Core sample	County	Location (Sec.-T.-R.)	Borehole (company, lease)	Depth (ft)	Stratigraphic unit	Lithology
27	Pueblo	28-21S.-61W.	General American Oil	6,967	—do—	limestone
28	—do—	—do—	—do—	7,048	Mississippian rocks	dolomite
29	—do—	19-22S.-60W.	General American Oil Co., State 1-19	6,962	—do—	limestone
30	—do—	—do—	—do—	7,108	Cambrian and Ordovician rocks	Do.

Outcrop sample	County	Location (Sec.-T.-R.)	Formation	Member	Lithology	Remarks
31	Crowley	6-22S.-59W.	Pierre Shale	Sharon Springs	shale	from Gautier and others, 1984
32	Las Animas	34-28S.-53W.	Dakota Sandstone		shale	from Flores and others, 1985

Table 2.—Estimated organic composition, hydrocarbon-source potential, and thermal maturity of sampled rocks in southeastern Colorado

[from pyrolysis assays, using the Rock-Eval procedure of Espitalie and others (1977)]

Sample (Described on Table 1)	Organic carbon (wt%)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	$T(S_2)$ (C)	Genetic potential (ppm)	HI (mgHC /gC)	OI ($mgCO_2$ /gC)	Trans-formation ratio (S_1/S_1+S_2)	Hydro-carbon-source potential	R_o, percent (median)	Thermal maturity
1	0.82	0.02	0.54	0.47	569	560	65	57	0.04	poor	1.19?	mature
2	0.13	0.00	0.02	0.18	---	20	15	138	0.00	--do--		probably mature
3	0.31	0.01	0.21	0.46	514+	220	67	148	0.05	--do--		Do.
4	0.43	0.16	0.78	0.19	596	940	181	44	0.17	--do--		mature
5	0.28	0.01	0.39	0.11	462	400	139	39	0.02	--do--		probably mature
6	0.12	0.15	0.05	0.24	---	200	41	200	0.75	--do--		Do.
7	0.16	0.04	0.22	0.10	532	260	137	62	0.15	--do--		mature
8	0.39	0.29	0.30	0.18	440	590	76	46	0.50	--do--		Do.
9	0.59	0.11	0.32	0.14	434	430	54	23	0.26	--do--		Do.
10	0.21	0.02	0.28	0.10	524	300	133	47	0.07	--do--		Do.
11	0.38	0.01	0.08	0.25	491+	90	21	65	0.12	--do--	1.56	Do.
12	0.05	0.00	0.01	0.11	---	10	20	220	0.00	--do--		probably mature
13	0.34	0.03	0.11	0.30	462	140	32	88	0.21	--do--		mature
14	0.35	0.04	0.31	0.29	---	350	88	82	0.12	--do--		probably mature
15	0.20	0.05	0.10	0.09	433	150	50	45	0.36	--do--		mature
16	0.03	0.00	0.02	0.06	---	20	66	200	0.00	--do--		unknown
17	2.40	0.13	4.67	0.24	434	4,800	194	10	0.03	moderate to fair		marginally mature

Table 2.—Estimated organic composition, hydrocarbon-source potential, and thermal maturity of sampled rocks in southeastern Colorado—continued

Sample (Described on Table 1)	Organic carbon (wt%)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	$T(S_2)$ (C)	Genetic potential (ppm)	HI (mgHC /gC)	OI ($mgCO_2$ /gC)	Trans-formation ratio (S_1/S_1+S_2)	Hydro-carbon-source potential	R_o, percent (median)	Thermal maturity
18	0.65	0.06	0.60	0.20	433	660	92	30	0.09	poor		Do.
19	7.56	1.63	27.50	1.25	434	29,130	363	16	0.06	good to excellent	0.32?	Do.
20	0.16	0.01	0.05	0.19	——	60	31	118	0.17	poor		probably mature
21	0.33	0.01	0.11	0.19	528	120	33	57	0.08	--do--		mature
22	0.32	0.02	0.25	0.41	476	270	78	128	0.08	--do--		probably mature
23	0.28	0.05	0.29	0.21	428	340	103	75	0.02	--do--		Do.
24	8.48	1.08	15.66	0.38	454	16,740	184	4	0.06	good to excellent	0.91	mature
25	0.99	0.07	0.83	0.09	455	900	83	9	0.08	poor	0.81	Do.
26	0.39	0.17	0.86	0.25	504	1,030	220	64	0.17	marginal		Do.
27	0.02	0.00	0.01	0.09	——	10	50	450	0.00	poor		possibly mature
28	0.20	0.02	0.04	0.20	——	60	20	100	0.33	--do--		Do.
29	0.05	0.00	0.02	0.16	——	20	40	320	0.00	--do--		probably mature
30	0.16	0.00	0.08	0.30	471	80	50	187	0.00	--do--		Do.
31	3.86	0.14	4.19	2.91	415	4,330	109	75	0.03	moderate to fair		immature
32	1.99	0.02	2.04	0.61	430	2,060	102	30	0.01	--do--	0.49	Do.

Samples of outcrops and of cores from boreholes in southeastern Colorado (table 1) were analyzed for organic carbon content and for pyrolytic hydrocarbon yield by T.A. Daws of the U.S. Geological Survey. Results of these analyses are shown in table 2. Source rocks for oil and gas contain at least 0.5 percent organic carbon (Dickey and Hunt, 1972). Source rocks for oil and possibly gas have a generating capacity or genetic potential of at least 2,000 ppm (Tissot and Welte, 1978). Several samples of core from the Pennsylvanian Morrowan and Missourian Series contain more than 0.5 percent organic carbon (samples 1, 9, 18, 19, 24, and 25). However, only samples 19 and 24 have sufficient genetic potential; they represent good to excellent source beds for hydrocarbons. Core and outcrop samples of Cretaceous rocks (samples 17, 31, and 32) have values for organic carbon and genetic potential which indicate moderate to fair source beds for hydrocarbons.

Burial history, thermal maturity, and timing of migration

In the region of the arch, the Phanerozoic rocks record deposition as well as erosion and they are as much as 8,000 ft thick near the Apishapa highland (fig. 2). The Paleozoic strata are as much as 5,500 ft thick and the Triassic, Jurassic, and Lower Cretaceous strata are about 800 ft thick along the north flank of the highland. Upper Cretaceous rocks in that area formerly were at least 3,000 ft thick. At the end of Mesozoic time, strata at least 9,300 ft thick had accumulated near the highland in Otero County. Rocks of Tertiary age in that region formerly were 1,000 - 5,000 ft thick.

The thermal maturity of the sedimentary rocks in southeastern Colorado was determined by the analysis of samples from cores and outcrops (table 1) and from information provided by MacMillan (1980). Data (table 2) from pyrolysis assays (using the procedure of Espitalie and others, 1977), expressed as the transformation ratio or production index and as the temperature of maximum pyrolytic yield [$T(S_2)$], indicate the thermal maturity of organic matter in the sampled strata. The thermal maturity required for the generation of oil is reflected by a transformation ratio of at least 0.1 or a temperature of maximum pyrolytic yield of at least 435 °C. The maturity of samples is also determined from measurements of the reflectance of component vitrinite particles. Median vitrinite-reflectance values of 0.6 and 1.3 percent generally define the maturity of rocks that have generated oil (Waples, 1980). Reflectance values of more than 0.7 percent characterize rocks that have generated thermogenic gas.

The interpretations of the analytical data (table 2) are not conclusive but they imply that some beds of Mississippian and Pennsylvanian age at depths of about 3,900 - 6,100 ft are thermally mature. Pennsylvanian and Cretaceous rocks considered marginally mature are at depths of about 3,800 - 3,900 ft. MacMillan (1980) indicated that beds in northeastern Baca County (fig. 2) are thermally mature at depths greater than about 4,000 ft. The samples of outcropping Cretaceous formations are immature. In the four counties of the Las Animas Arch, the source rocks for oil and gas at depths greater than about 3,800 ft apparently are thermally mature (fig. 4, table 3) and probably have generated petroleum.

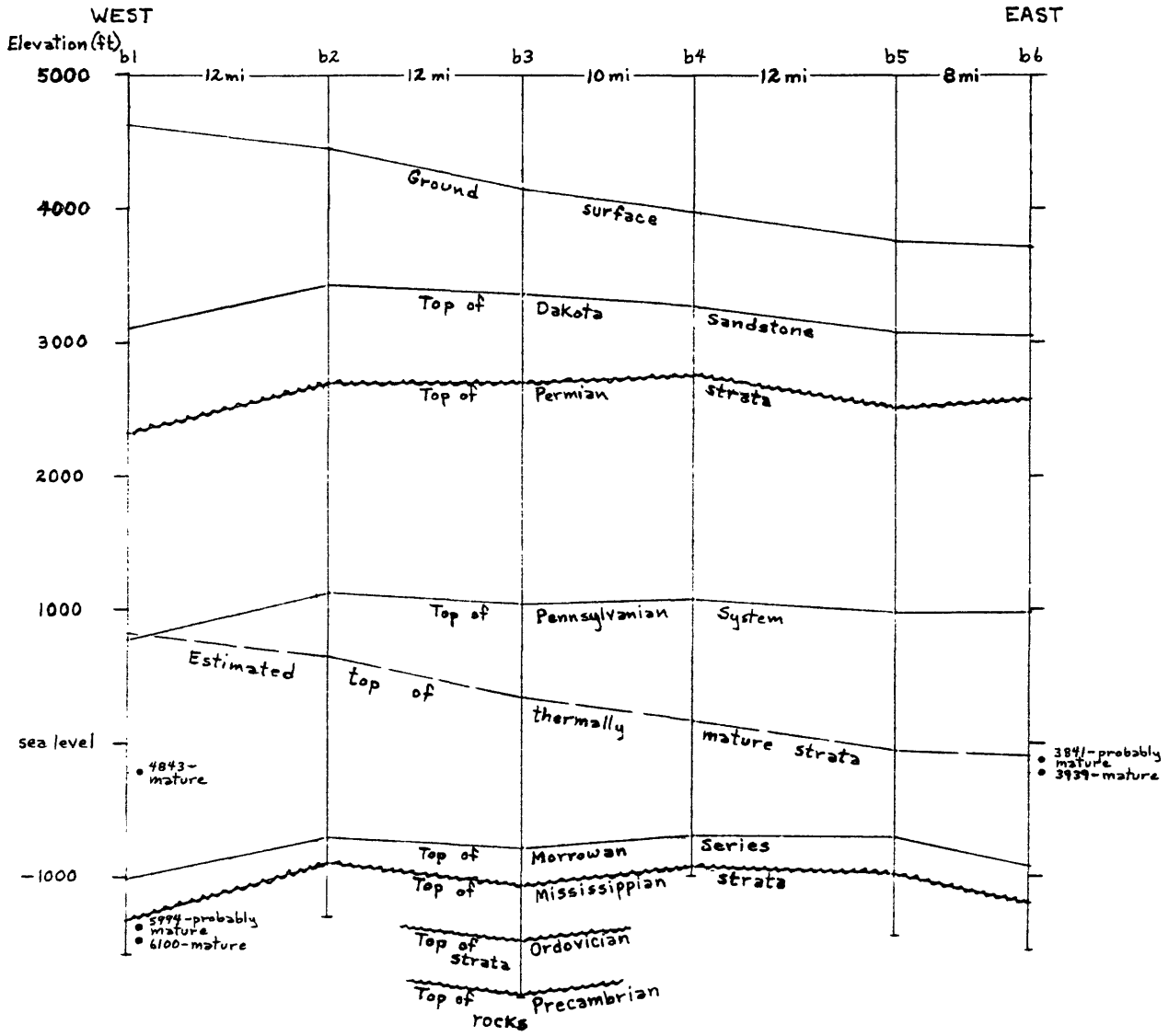

Figure 4. Cross section of the Las Animas Arch, derived from logs of boreholes in Kiowa and Prowers Counties, Colorado, showing the depth (ft) and thermal maturity of sampled beds as well as the estimated depth of the thermally mature strata. Locations of boreholes shown on figure 1 and table 3. Wavy lines represent unconformities.

Table 3.—Boreholes used for cross section (fig. 4) in southeastern Colorado

Borehole	Operator	Name	County	Sec.	T.	R.
b1	General American Oil Company of Texas	Federal 1-6	Kiowa	6	18S.	52W.
b2	Samson Oil Company	State-Frazee 1-36	—do—	36	18S.	51W.
b3	The Superior Oil Company	Weisenberger 65-23	—do—	23	19S.	49W.
b4	Texas Oil and Gas Corporation	Richards 1	—do—	25	20S.	48W.
b5	Inexco Oil Company	State-Root 1-36	—do—	36	20S.	46W.
b6	Hunt Oil Company	Heckman 1-35	Prowers	35	21S.	45W.

MacMillan (1980) investigated the strata and geothermal gradient in a borehole in northeastern Baca County, southeast of the Las Animas Arch. He concluded that hydrocarbons were generated in Paleozoic source rocks and that the migration of the hydrocarbons began in early Paleocene time, prior to maximum burial in the Eocene. MacMillan (1980) also proposed that the source rocks of mid-Cretaceous age were not at the required temperature long enough to generate hydrocarbons. Paleozoic source rocks in the basins adjoining the Las Animas Arch generated oil and gas, some of which might have migrated into the arch through porous beds in the Mississippian formations.

Hydrocarbon occurrence

On the Las Animas Arch, oil and gas are structurally and stratigraphically entrapped in Mississippian and Pennsylvanian formations at depths of about 3,600-5,700 ft. The oil in Mississippian strata is produced from porous, carbonate rocks on gently dipping anticlines, many of which are faulted. However, the areal extent of some reservoir beds is controlled by changes in depositional textures and in the associated porosity and permeability. Most of the oil and gas in the Pennsylvanian formations is stratigraphically entrapped in sandstone and carbonate rocks.

The oil and gas plays for the Las Animas Arch are defined by the areal extent of strata that contain reservoir beds, as well as by faults and anticlines. The hydrocarbon-bearing carbonate rocks are commonly vuggy or fractured and occur in the subsurface mainly near the crests of anticlines. Sandstone reservoirs represent local fluvial and shallow-marine depositional environments.

The region includes three principal plays, which are areas of: (1) Mississippian carbonate beds, (2) Lower Pennsylvanian (Morrowan) siliciclastic strata, and (3) Middle and Upper Pennsylvanian (Desmoinesian, Missourian, and Virgilian) siliciclastic and carbonate beds. Criteria used to delineate these plays are: (1) the areal distribution of accumulations of oil and gas, (2) the location of structural features, and (3) the probable lateral extent of potential reservoir strata. Other plays in the region might be within the Cambrian and Ordovician carbonate beds, the Pennsylvanian siliciclastic and carbonate rocks of the Atokan Series, the Permian siliciclastic rocks, and the mid-Cretaceous carbonate and siliciclastic beds.

PRINCIPAL PLAYS

A Mississippian structural play

In the Mississippian strata of the region, a demonstrated play (fig. 5) is outlined by the areal distribution of oil-bearing beds and by structure contours that define the Las Animas Arch. The strata consist of carbonate rocks, which locally are porous and permeable, and include sparse oil reservoirs. In major fields, the reservoirs have proven areas of about 500-3,000 acres; average productive thicknesses range from 3 to 50 ft. The porosity of the reservoirs is inter-crystalline or vugular, or caused by fracturing. Porosity values are highly variable but commonly are about 5-15 percent. The permeability of the reservoirs is also variable and is as much as 300 millidarcies. Oil and gas apparently have not been found in Mississippian beds in the southern part of the region near Federal land (fig. 1).

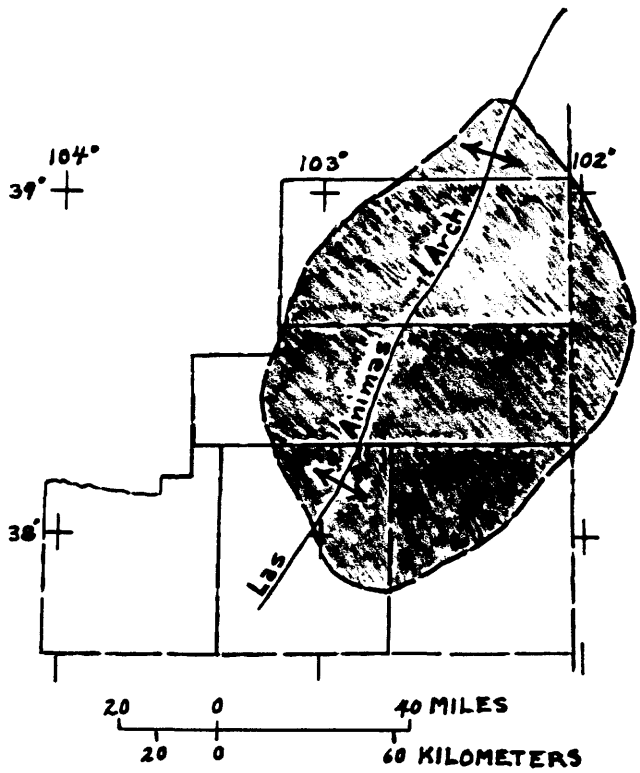

Figure 5. Map showing Mississippian play (shaded) in region of Las Animas Arch

The oil in the Mississippian strata is structurally entrapped in gently dipping anticlines, although local reductions in the porosity of the beds limit the lateral extent of some pools. Seals for the reservoirs consist mainly of dense dolomite and limestone. Water-drive causes reservoir pressure.

Volk (1971) and MacMillan (1980) indicated that the Mississippian formations contain source rocks for petroleum, although none were identified by the analysis of core samples (tables 1 and 2). Source rocks of Early Pennsylvanian age might also have contributed hydrocarbons to Mississippian reservoirs (as a consequence of the unusually low pressures in the Mississippian formations and the higher pressures in the Pennsylvanian rocks). The thermogenic generation and migration of the hydrocarbons probably occurred in early Paleocene time (MacMillan, 1980), after the Late Mississippian-Pennsylvanian orogeny and during the Late Cretaceous-early Tertiary orogeny.

Reservoirs of Mississippian age in the region are at depths of about 4,700-5,500 ft, near the crest of the Las Animas Arch in eastern Cheyenne and eastern Kiowa Counties, and at a depth of about 5,700 ft on the northwestern flank of the arch in northwestern Cheyenne County. These rocks have been explored for oil and gas since 1964, when oil was discovered in Lower Mississippian beds in Prowers County (Volk, 1972). In 1965, oil was found in Lower Mississippian rocks on the southeastern flank of the arch in eastern Kiowa County. In the following years, the Mississippian formations were major targets for exploration.

Oil and gas are produced from Mississippian strata in at least 14 fields in the region of the Las Animas Arch. The cumulative production, as of January 1, 1985, is about 18 million barrels of oil and about 367 million cubic feet of associated gas (Colorado Oil and Gas Conservation Commission, 1986). For nine major fields in the region, the proved reserves in Mississippian formations, as of July 31, 1986, are about 2.7 million barrels of oil and about 704 million cubic ft of gas.

The Mississippian rocks have been lightly to moderately explored on the arch and are practically unexplored in Federally owned areas. Mississippian reservoirs are defined by structural closure, fractures, and reductions in porosity. The crests of most anticlines have been explored. Stratigraphic traps on anticlines have been recognized in the region. Stratigraphic traps not associated with the crests of anticlines probably remain undiscovered.

An Early Pennsylvanian stratigraphic play

The four counties of the Las Animas Arch comprise a demonstrated play in the Morrowan Series of Early Pennsylvanian age. Oil and gas are produced from the Morrowan in fields which are scattered throughout the northeastern part of the arch. Oil and gas have not been reported in the southwestern part of the region, in the area of Federal land (fig. 1). The Morrowan is commonly 100-500 ft thick and is composed mainly of fluvial sandstone and shale and overlying marine shale. Reservoirs in the series consist of sandstone units

which were deposited as point bars in rivers that drained the ancestral Rocky Mountains, the Apishapa highland, and a lowland in western Nebraska and western Kansas. The geographic location of these rivers has not been completely established.

In fields of the region, Morrowan reservoirs have productive areas of 640-33,250 acres and average thicknesses of 6-50 ft. Porosities and permeabilities of the reservoirs commonly are 11-19 percent and 0.5-2.0 millidarcies, respectively.

The oil and gas in the Morrowan Series is stratigraphically entrapped in discontinuous bodies of fluvial sandstone. These reservoirs are sealed mainly by units of shale; those beds at the top of the series were deposited in marine environments. The pressures in some reservoirs are maintained by water-drive.

Volk (1971) and MacMillan (1980) suggest that the Morrowan includes source rocks for oil and gas. Analyses of samples of cores (tables 1 and 2) indicate that some mudrocks in the Morrowan are marginal to excellent sources for hydrocarbons. Thermal generation and migration of the hydrocarbons probably began in the early Tertiary (MacMillan, 1980), during the Laramide orogeny.

The depths of the reservoirs in the Morrowan are about 4,600-5,300 ft near the crest of the Las Animas Arch in Cheyenne, Kiowa, and Bent Counties and about 5,600 ft on the northwestern flank of the arch in western Cheyenne County. Hydrocarbons in the Morrowan were first discovered in 1951 by Continental Oil Company near the crest of the arch in south-central Kiowa County, (Volk, 1972). Other major discoveries, during the years 1968-1979, are scattered throughout the northeastern part of the region. The locations of the pools were determined from studies of borehole logs and from seismic surveys.

Oil and gas are produced from the Morrowan Series in about 20 fields on the Las Animas Arch. The cumulative production, as of January 1, 1985, is about 4 million barrels of oil and about 61 billion cubic feet of gas (Colorado Oil and Gas Conservation Commission, 1986). Proven reserves in the series for four major fields in the region, as of July 31, 1986, are about 3.8 million barrels of oil, 909 thousand barrels of natural gas liquids, and about 28.8 billion cubic feet of associated and nonassociated free gas.

Strata of the Morrowan Series have been moderately explored near the crest of the arch but have been lightly explored in most of the region. The resources of the Morrowan are limited by the number and size of the enclosed reservoirs, which are generally small, lenticular bodies of sandstone and are confined to a few Early Pennsylvanian river valleys.

A Middle and Late Pennsylvanian stratigraphic play

The Desmoinesian, Missourian, and Virgilian Series of the Pennsylvanian System in Cheyenne County and in parts of Kiowa and Bent Counties contain oil and gas and comprise a demonstrated play (fig. 6). Oil and gas have not been found in Otero County, in the area of Federal land (fig. 1). The series consist of continental and marine siliciclastic and carbonate rocks, which

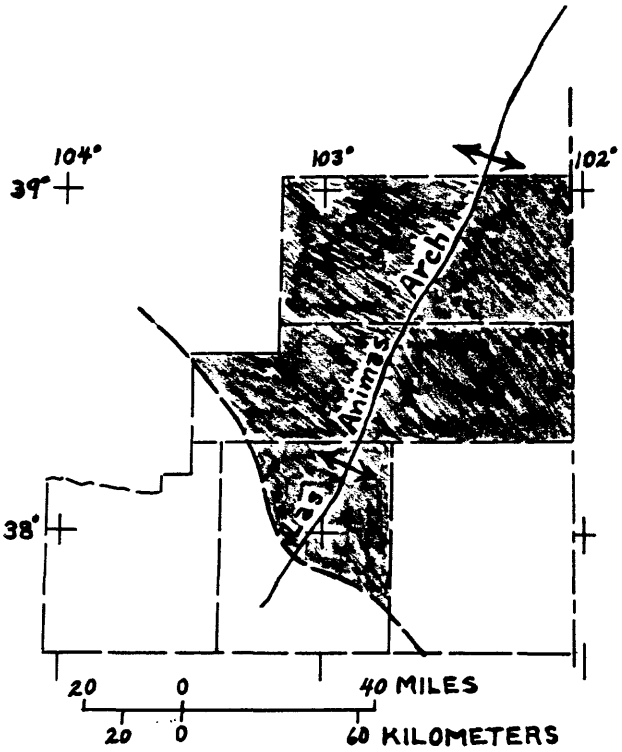

Figure 6. Map showing Middle and Late Pennsylvanian play (shaded) in region of Las Animas Arch

include scattered bodies of oil and gas-bearing sandstone, limestone, and dolomite. Many reservoirs in the series have producing areas of 40-80 acres; their average productive thicknesses range from 4 ft to 31 ft. The few reported porosity values for the sandstone and carbonate rocks range from 9 to 25 percent; the permeability of these rocks is unknown.

Most of the oil and gas in the Middle and Upper Pennsylvanian Series are stratigraphically entrapped, only a few reservoirs are on the crests of anticlines. The seals for the pools include shale and dense carbonate rocks. Water-drive is commonly the cause of reservoir pressure.

Potential source beds for hydrocarbons are abundant in these series (Volk, 1971; MacMillan, 1980) and probably consist of shale and carbonate rocks. Analyses of core samples from the region (tables 1 and 2) indicate that one unit of shale, in the Missourian Series, is a good to excellent source rock. MacMillan (1980) concludes that the generation and migration of the oil and gas in the region occurred in the early Paleocene, during the Laramide orogeny.

Many of the pools in the Desmoinesian, Missourian, and Virgilian Series are at average depths of about 3,600-4,500 ft. Oil was first discovered on the Las Animas Arch in 1933, in Pennsylvanian strata in northwestern Prowers County (Volk, 1972). However, most of the oil and gas in the Middle and Upper Pennsylvanian Series of Bent, Cheyenne, and Kiowa Counties was discovered during the period of 1955-1981.

The Des Moinesian, Missourian, and Virgilian Series yield oil and gas at about 20 fields in Cheyenne, Kiowa, Otero, and Bent Counties. The cumulative production, as of January 1, 1985, is about 1.3 million barrels of oil and 314.5 million cubic feet of associated gas (Colorado Oil and Gas Conservation Commission, 1986). No pools having reserves larger than 0.5 million barrels of oil or equivalent gas occur in these strata in the region. Quantities of proven reserves have not been reported.

These Pennsylvanian rocks have been moderately to intensively explored near the crest of the arch and lightly to moderately explored in other parts of the region. Reservoirs of the series are generally small and are composed mainly of marine carbonate rocks. The carbonate reservoirs are limited to locally porous beds in units that are widespread in Cheyenne and Kiowa Counties, in the northeastern part of the region.

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