UNITED STATES DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

An Initial Resource Assessment of the Upper Devonian Antrim Shale in the Michigan basin

by
Gordon L. Dolton and John C Quinn

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

U.S. Geological Survey, MS 934, Box 25046, Denver Federal Center, Denver CO, 80225

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Introduction:

An assessment of oil and gas resources of the United States was completed by the United States Geological Survey (USGS) in 1994 and published in 1995 (U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1995; Gautier and others, 1995; Dolton, 1995). As part of this assessment and for the first time, the USGS assessed recoverable resources from unconventional or continuous-type deposits nationally. These deposits, commonly treated as unconventional, have an important place in the nation's energy future. At the same time, they possess unique geologic, technologic and economic aspects which set them apart from conventional types of oil and gas resources. The purpose of this report is to lay out the assumptions and results of the initial resource assessment of the Antrim Shale, and indicate directions of research to improve future assessments.

ANTRIM SHALE GAS PLAYS

The Antrim Shale plays, 6319 and 6320 (fig. 1) consist of gas accumulations within fractured Antrim shales of Late Devonian age (fig. 2), whose stratigraphic setting has been described by various workers including Azeez (1969), Harrell and others (1991), Gutschick and Sandberg (1991a, 1991b), Ells (1979), Reszka (1991), and Matthews (1993). Besides the Antrim Shale, proper, the play includes parts of the Upper Devonian Ellsworth Shale in western Michigan and upper Devonian Bedford Shale in eastern Michigan (fig. 2). The plays appear to be partially bounded to the west by the low organic content of the Ellsworth Shale and the loss of thick organic-rich Antrim Shale tongues (Ells, 1979; Curtis and others, 1991; Gutschick and Sandberg, 1991a, 1991b). Trapping the gas may be controlled, in part, by hydrodynamic flow and water block at the subcrop (Maness and others, 1993). At the time of the assessment, the gas was considered to be primarily generated during early catagenesis (Dellapenna, 1990, 1991; Decker and others, 1993). Organic thermal maturity within the formation appears sufficient to have generated hydrocarbons within deeper parts of the central Michigan basin (Cercone, 1984; Pollack and Cercone, 1989, and Cercone and Pollack, 1991), however, more recent work by Walter (1994) and Martini and others (1994b) suggests a biogenic origin for much of the gas. Production appears feasible only where the shales are sufficiently fractured (Decker and others, 1992) and is mostly confined to the black shale facies (Lachine and Norwood Members) of the Lower Antrim (fig. 2), with principal development (Play 6319) in Antrim, Otsego, and Montmorency Counties and to a lesser extent, Kalkaska, Crawford, and Oscoda Counties. Black shale facies of the Antrim outside this general area that were virtually nonproductive constituted the undeveloped area (Play 6320). The overall plays collectively cover approximately 39,000 square miles.

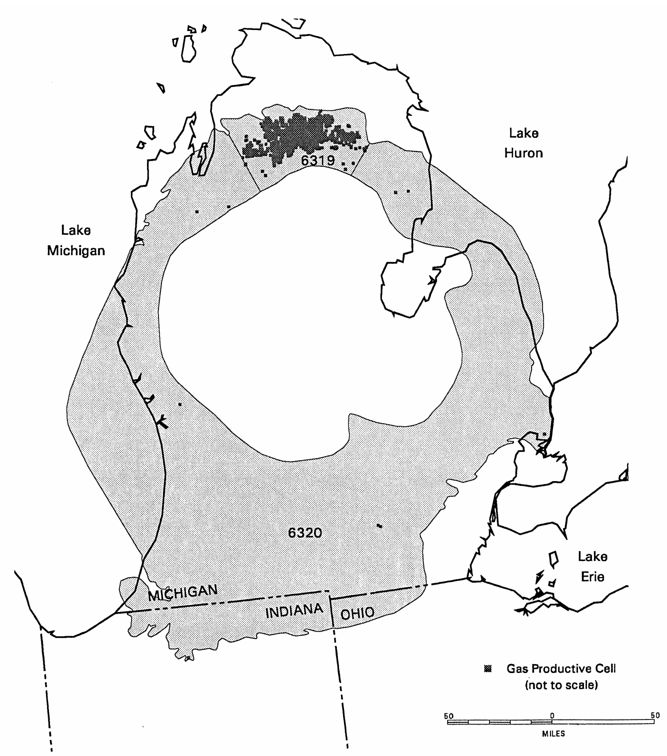


Figure 1. Index map showing limits of Antrim Shale plays as assessed. The up-dip limits of the plays (the outer perimeter) are defined by the extent of the Antrim Shale subcrop beneath the Pleistocene glacial drift. The downdip limit is represented by the approximate 2000 ft depth to top Antrim Shale.

Reservoirs: The formation is up to 800 feet thick and fractured shales provide reservoirs and conduits for production. Gas is also adsorbed within the shale, dissolved in the bitumen, and stored in matrix porosity, but production appears feasible only where the shales are sufficiently fractured and is mostly confined to the black shale facies (Lachine and Norwood Members) of the Lower Antrim (Curtis and others 1991; Manger and Curtis, 1991; Manger and Oliver, 1991; Nicol and Oliver, 1991).

Source Rocks: The “black fades” of the organic-rich Antrim Shale has a total organic content (TOC) ranging from less than one to 25 weight percent, averaging approximately 8 percent. The kerogen is hydrogen rich and oil prone. Thermal maturity of the shale is sufficient to have generated hydrocarbons peripheral to and within deeper parts of the central Michigan basin (Cercone, 1984; Pollack and Cercone, 1989; Cercone and Pollack, 1991; Dellapenna, 1991).

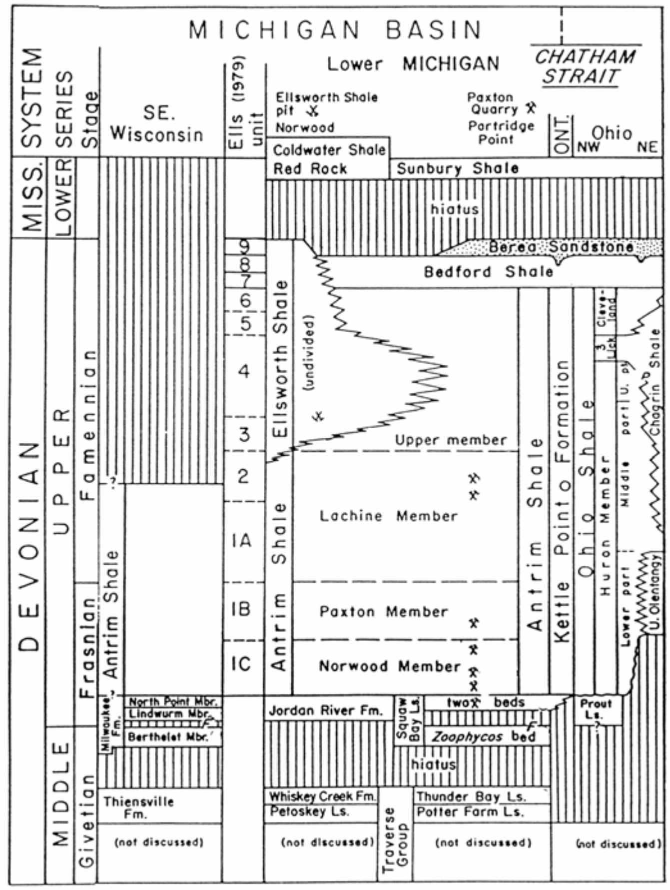


Figure 2. Correlation chart showing Upper Devonian and adjacent strata in Michigan Basin, gamma ray units of Ells (1979), and correlations with northern Ohio (modified from Gutschick and Sandberg, 1991a).

Timing and Migration: Generation of hydrocarbons from the Antrim Shale may have begun in central parts of the basin during subsidence of the basin. Both oil and gas are found in the Antrim reservoirs. As originally modelled, the gas was believed to represent an early stage of catagensis, however, recent work by Walter (1994) and Martini and others (1994a, b), suggests that the gas may be largely biogenic in the shallow areas of Antrim production and of Pleistocene and younger origin. The shale appears within the oil generative window at depths greater than about 2500 feet based on data reported by Cercone and Pollack (1991) and suggests removal of 3,000 to 4,000 feet of strata since the Pemian. Opportunity for oil recovery may exist below 2500 feet and, at the same time, may place an effective floor on the gas play, even though associated gas may be present.

Trap: Gas is trapped within fractures in the Antrim sequence and is adsorbed by clays and organic matter in the shale (Decker, 1993; Decker and others, 1992, 1993). The regional structural setting of the Antrim Shale appears relatively uncomplicated as expressed by the structure of the Middle Devonian Traverse Limestone which underlies it (fig. 3). Trapping may be controlled in part by hydrodynamic flow and water block at the subcrop of the formation (Maness and others, 1993). Controls of fracturing are not well understood and have been attributed to tectonism, flexuring over underlying Silurian reefs, differential loading by glacial drift, and fracture dilation due to glacial unloading. Economic recovery of gas is mostly confined to the organic-rich 'Upper Black' and 'Lower Black' (Lachine and Norwood Member) shale facies of the Lower Antrim, capped by Upper Antrim and 'Middle gray' (Paxton Member) beds, respectively.

Exploration Status: Depth of gas production generally ranges between 1200 and 2000 feet, but is reported at almost 2600 feet in Crawford County and at 3200 feet in Missaukee County. An approximation of drilling depths to the base of the Antrim may be obtained by reference to the Traverse Limestone structure map (fig. 3), which may be adjusted using a 600 to 1000 foot surface elevation in most areas. Production at Otsego Field dates back to 1940, but intensive development in the play has taken hold only since 1986. Principal exploration and development activity and discoveries have been in Antrim, Otsego, and Montmorency Counties but include, to a lesser extent, Kalkaska, Crawford, and Oscoda Counties. Well production typically ranges from 25-150 thousand cubic feet of gas per day. Scattered gas wells have been recorded in Missaukee, Wexford and Jackson Counties. Outside of these areas, the formation has not been successfully produced, although it commonly contains sufficiently high organic matter content for hydrocarbons. Adequacy of fracturing appears to control production.

RESOURCE ASSESSMENT

The assessed area was defined updip by the subcrop limits of the Antrim Shale beneath the glacial drift and was somewhat arbitrarily cut-off downdip, where the incidence of open fractures was believed to be less frequent and where there is some indication that oil may be the predominant hydrocarbon phase. This limit is represented approximately by the 2000 ft depth to the top of the formation. Within this assessed area, two plays were recognized, a developed area (Play 6319) and an undeveloped area (Play 6320). The assessment deals only with those parts of the plays in these two areas that have not yet been tested, hence excludes those resources which, at the time of assessment, have been defined by productive wells.

Methodology:

The Antrim Shale plays include a large in-place hydrocarbon volume, a low recovery factor, and a heterogeneous "hit or miss" character for production rates and ultimate recoveries of wells. The distinction between undiscovered resources and inferred reserves is blurred. Location of the gas bearing unit is reasonably well known and future additions of productive areas can be viewed as additions through growth to currently producing areas (implying inferred reserves), but hydrocarbon estimates of such uncertain additions are broadly dependent on geologic knowledge and theory (implying undiscovered resources). The existence of production in the play causes assignment of no risk as to play success.

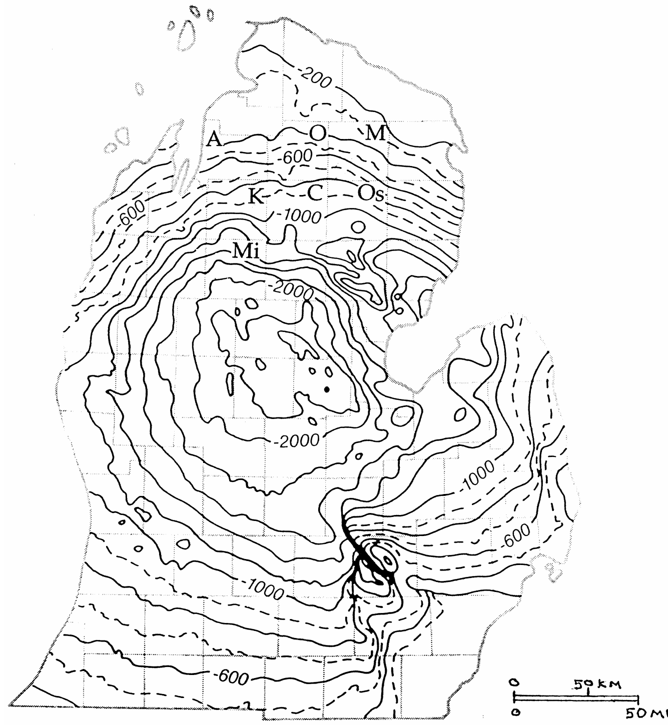


Figure 3. Structure Map of the Middle Devonian Traverse Limestone (*P. A. Catacosinos, P.A. Daniels, Jr. and W.B. Harrison, III*, reprinted by permission of the *American Association of Petroleum Geologists*), (Courtesy of *Aangstrom Precision Corp*.). Contour interval = 200ft (100ft where less than -1000ft). An approximation of drilling depths to the base of the overlying Antrim may be obtained by assuming a 600 to 1000 foot surface elevation in most areas. Counties identified: A=Antrim, C=Crawford; K=Kalkaska; M=Montmorency; Mi=Missaukee; 0=Otsego; Os=Oscoda.

It is advantageous to envision the hydrocarbons of a continuous-type accumulation as residing areally in cells (Schmoker, 1995). As noted by Schmoker, "A play then is regarded as a collection of cells. The cell area or size is equal to the median spacing, as dictated by drainage area, expected for wells of the play. Virtually all cells in a continuous type accumulation are capable of producing some hydrocarbons. For purposes of this assessment, however, a productive cell is one for which production from the play is formally reported.

An untested cell is one in which the play in question has not been evaluated by a well." In the Antrim, cells which have been incidentally drilled in the course of exploration of deeper horizons, without directly evaluating the Antrim, are considered untested.

"The second step of the assessment procedure is to estimate the number of untested cells in a play and the fraction of untested cells expected to become productive (success ratio). Realistic consideration of the uncertainties associated with the number of untested cells in a play usually leads to a substantial range between the minimum and maximum number of untested cells. Therefore, the number of untested cells is treated as a probability distribution."

"The third step of the assessment procedure is to establish a probability distribution for estimated ultimate recovery (EUR) for untested cells of the play that are expected to become productive. This distribution provides a reference model for production from cells yet to be drilled. Of course this statistical model provides no insight as to which untested cells are expected to become productive."

Finally, the combination of play probability, success ratio, number of untested cells, and EUR probability distribution yields the potential additions to reserves expected for the continuous type play. The in-place hydrocarbon volume is not used in this assessment procedure. Current recovery technology is assumed, but no economics are incorporated directly into the model.

Developed (explored) Area (Play 6319):

Within the general area of development activity at the time of assessment, we estimated that cells beyond those now producing would likely be drilled on a 40 acre basis, and the play was modeled on this assumption. Cells which were indicated as currently productive were considered as proven and not part of the additional resource estimated.

Estimated ultimate gas recovery per well was derived from the Petroleum Information (PI) CD-ROM production file (Petroleum Information, 1994). Data from the file represent production from multiwell units of varied spacing, each reported as one producing entity. Information used was limited to those units of relatively stable number of producing wells which had a sufficient production history to establish a production decline curve for EUR calculation. These particular units were, for the most part, developed on 40 acre spacing. The data were normalized on a per-well basis, so that the EUR figures (Table 1) represent average well performance for each of the 12 producing units used and, therefore, do not express the more extreme range of production that actually exists on a per well basis. Drainage areas of wells were not definitively established, however, production analysis indicates interference in some cases with a 40 acre spacing.

Within the developed area play, the authors estimated that considerable uncertainty existed concerning the area in which the formation might ultimately be productive, especially downdip and in areas farther removed from existing production. Within the overall area of production, however, it was estimated that individual well success would be very high, and the reported historic completion success rate of 99% was assumed (fig. 6).

Table 1. Producing units analysed, showing drainage areas and estimated ultimate recovery (EUR) calcuated per well, in billions of cubic feet gas (BCFG). All units are in Otsego County, Michigan.

No.	Operator and Unit name	Production start date	Drainage area (Acres) per well	EUR (BCFG)
1	ADC, Bradford Lake	4/30/88	138	0.203
2	ADC, E-Z	6/30/89	164	0.243
3	ADC, Dodge Lake	8/31/90	98	0.161
12	Terra Energy Ltd., NADV -1	4/1/89	231	0.201
13	Terra Energy Ltd., NADV -3	8/31/89	304	0.185
14	Terra Energy Ltd., Luck 16	10/31/89	72	0.060
16	Terra Energy Ltd., Chester 31	10/31/89	206	0.470
21	Terra Energy Ltd., Bagley 110	7/31/92	106	0.281
26	Ward Lake Energy, Charleton 31	12/31/89	154	0.430
32	Mack Oil Corp., State Hayes	11/30/88	62	0.104
37	Muskegon Dev., Horicon 15	7/31/90	216	0.236
42	Muskegon Dev., Otsego Lake	5/31/90	353	0.751

*ADC = Antrim Development Corporation.

Undeveloped Area (Play 6320):

Within the undeveloped area in the rest of the basin, defined as that part of the Antrim beyond the broad limits of production as defined at the time of assessment (fig. 1), it was estimated that cells possibly would be drilled on an 80 acre spacing, and the play was modeled on this assumption.

Estimated ultimate well recovery was derived from production files from the producing area. Information used was limited to those units of relatively stable number of producing wells which had a sufficient productive history to establish a production decline curve for EUR calculation. The data were normalized on a per-well basis, so that the EUR figures (Table 1) represent average well performance for each of the 12 producing units used, even though these particular units were, for the most part, developed on 40 acre spacing. Although different EUR's were anticipated for different well spacings, available information was insufficient to determine any clear relationship. Actual drainage areas of wells were not clearly established. Literature reports and production history plots indicate interference in some cases at less than 80 acre spacing (Kuuskraa and others, 1992) and is also apparent in our analysis (Table 1). Lacking more definitive data, the per-well EUR's from the productive areas were used without modification.

Within the play area, the authors estimated that considerable uncertainty existed concerning the overall inclusive area(s) in which the formation might ultimately be productive. Within this variable area, however, it was estimated that success would be high, and a completion success rate for cells of 80% was assumed.

EUR Analysis:

Gas production in the Antrim Shale is reported from units rather than from individual wells. The standard practice is to drill several wells, equip them and simultaneously connect the wells to the pipeline for production as a unit. Because of this unitization, any analysis of the production data must be done for the unit or apportioned by the number of wells for individual graphing. This makes it impossible to determine if the wells are interfering with their neighboring wells. The production graph (fig. 4) in the depletion phase, however, appears to reflect an interference pattern but this pattern could be caused by some other source. A more in depth study is necessary to draw definitive conclusions. Nevertheless, the results of our study indicate that some drainage areas extend beyond the well spacing (see Table 1). This may be because the wells are producing from reservoir areas above and/or below the perforated interval, because the fractures intersected by the well are highly directional and draw from an area in one direction which extends past but not connecting with adjoining wells, or because gas is actively biogenerating and recharging the reservoir with free gas as production occurs. Reservoir and engineering data used in this analysis were drawn in part from McGuire (1991), Kuuskraa and others (1992), and Zuber and others (1994).

The analysis process was as follows.

1. Production data were surveyed and all production units which had reached a state of production decline were selected for further examination. Most of the units exhibit a production rate vs. time graph which resembles that of a coalbed methane well (Holditch, S., and Zuber, M., 1992). This probably is due to the similarity of the dewatering process necessary to both but could also be indicating a higher degree of adsorption than is currently accepted in the shale wells.

2. The production history for each of the twelve units was evaluated and a production forecast was prepared. The evaluation and forecast was performed on the MIDA Fetkovich-type curve computer program (Fetkovich, 1980; Mannon, 1990). Most of the units reached the maximum number of wells early in their production life and all reached the maximum number before production decline began. An example of the production forecast and Fetkovich curves for an average well in one of these units is shown in figs. 4 and 5.

3. Production histories for 12 units which had stable well populations were apportioned to a “per well” basis by arithmetic average. These wells were assigned reservoir parameters and analyzed with the MIDA program to estimate drainage area for a typical well in each unit.

4. Evaluation of remaining reserves and drainage areas (Table 1) per well was made using the Fetkovich-type curve method MIDA software by Mannon and Associates, Inc. (Santa Barbara, CA), which performs the curve matching and by introduction of reservoir parameters calculates drainage area. Due to a lack of well or unit information available to USGS at the time of this evaluation, some assumptions of formation parameters were made, such as gas saturation of pore space and formation compressibility.

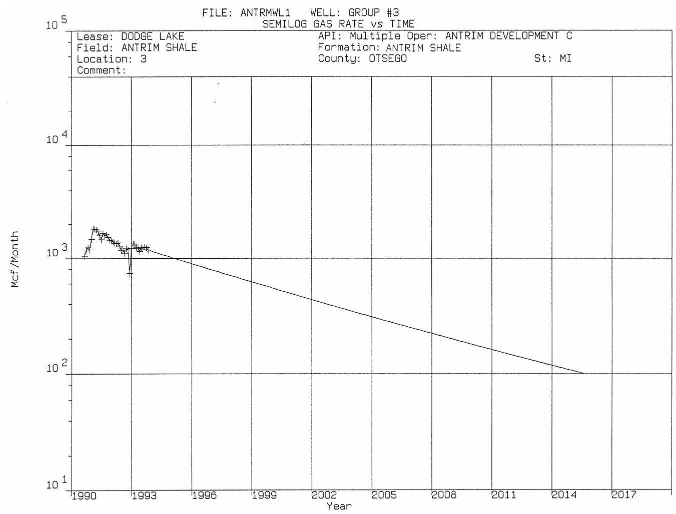


Figure 4. Example of a production forecast curve for an average well within an Antrim Shale unit.

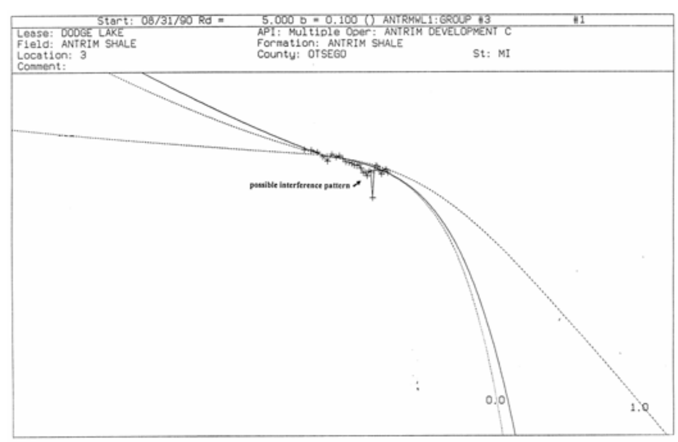


Figure 5. Example of a Fetkovich curve analysis for the forecasted well in fig 4. Note the suggested interference pattern. Arps depletion equation exponent values shown for the boundary curves.

Play Input:

The estimated range in average EUR, derived from the preceding analysis, is shown graphically in fig. 6, each point showing the average EUR per well in the units analysed. Data input for the assessment of the two plays is summarized in figs. 7 and 8. It should be noted that assumptions of well spacing, ultimate areal size of the play, and success rate, have a particularly large effect upon resources calculated, and on any subsequent economic analysis.

Results:

Results of the assessment are shown in tabular and graphic form (table 2 and fig. 9). As shown, great uncertainty exists concerning the amount of undiscovered gas resource contained within the Antrim Shale. This reflects not just the general uncertainty associated with assessment of the unknown but, in particular, the uncertainty surrrounding some of the critical geologic and geochemical elements controlling gas distribution and producibliity, including gas origin and the areal distribution and variation of fracturing within the formation. Estimated EUR's and assumptions indicated in the input section all have large effect upon resources calculated and require further investigation for refinement of gas assessments. The included resource estimates provide the basis for studies of economic recoverability, which are presented in other reports

Recommendations:

1) Recent work by Walter (1994) suggests that the gas in the Antrim Shale is primarily of biogenic origin, associated with water recharge from the Pleistocene glacial drift. Investigations to confirm this concept, particularly in other parts of the basin, has critical significance in defining more precisely the distribution of producible gas in the formation, and assessment of the gas resource.

2) Additional work is required, as more data become available, to better quantify the producing characteristics of the formation, including area of influence of drainage, and better establish the range of estimated per well ultimate recovery (EUR).

3) Better quantification of the distribution of organic content in the formation as related to its internal stratigraphy and geographic distribution is required.

4) Investigation into the specific controls on fracture distribution, orientation and intensity, and its quantification and prediction is required (eg. Apotria and others, 1994; Caramanica and Hill, 1994).

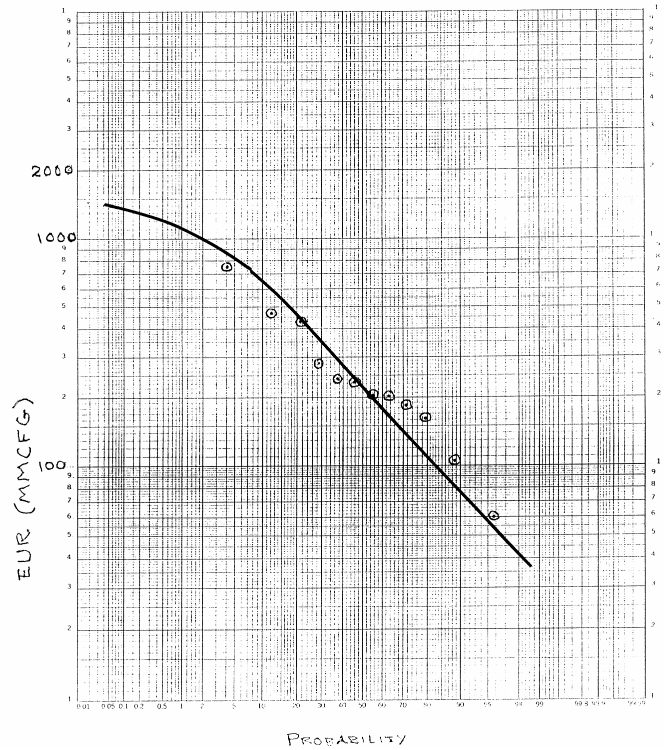


Figure 6. Probability plot of EUR's for the Antrim Shale, showing values calculated as a per well average in 12 different units.

1995 NATIONAL ASSESSMENT
DATA FORM FOR ASSESSMENT OF CONTINUOUS-TYPE ACCUMULATIONS

Province Geologist: G.L. Dolton Province Name, No.: Michigan Basin (063)

Date: ________ Play Name, No.: Antrim Shale Gas, Developed Area 6319
(codes in parenthesis, such as III B, refer to Appendix A)

Play type: ☐ Oil or ☒ Gas (I C) ☒ Confirmed or ☐ Hypothetical (I D)

Geologic scenario (I E):

Play probability (0-1.0) (II A): 1.0 *Stop here if play probability does not exceed 0.10 (II B).*

Cells (III): Cell size (III A1): 40 acres; .0625 mi² (acres/640)

Area of play (III A2): 1963 mi² Total no. of cells (III A3): 31,408

No. of productive cells (III B): 2765 No. of nonproductive cells (III C): 4

No. of untested cells (III D): 15703 50th fractile

Minimum possible number of untested cells (III E1): 2768 100th fractile

Maximum possible number of untested cells (III E2): 28639 0th fractile

Success ratio (0-1.0) (IV): 0.99

EUR probability distribution (V)*:

Fractile:	Minimum 100th	(95th)	(75th)	Median 50th	(25th)	(5th)	Maximum 0th
EUR (BO or MMCF)	20	(60)	(110)	220	(410)	(800)	1500

Data to assess co-products (VI):
☐ Oil play - expected GOR: ________ CF/BO
or ☒ Gas play - expected liquids/gas ratio: 0 BO/MMCF

*100th, 50th, 0th fractiles are required. Other fractiles should be supplied if sufficient data are available.

Selected ancillary data (VII):
Depth (ft) of untested cells (VII A): median 1430; minimum 150;
maximum 2300

Fraction (0-1.0) of untested cells that will be tested by wells originally targeted for (VII B): the play____; deeper horizon____; shallower horizon____

API gravity of liquids (VII C): NA. degrees

Fraction (0-1.0) of play with "tight" FERC designation (VII D): 0

Fraction (0-1.0) of new wells that will be stimulated (VII E): .50

Figure 7. Assessment form showing input for Play 6319.

1995 NATIONAL ASSESSMENT
DATA FORM FOR ASSESSMENT OF CONTINUOUS-TYPE ACCUMULATIONS

Province Geologist: G. L. DOLTON Province Name, No.: MICHIGAN BASIN (063)

Date: __________ Play Name, No.: ANTRIM SHALE GAS UNDEVELOPED AREA 632.
(codes in parenthesis, such as III B, refer to Appendix A)
Play type: ☐ Oil or ☒ Gas (I C) ☐ Confirmed or ☒ Hypothetical (I D)

Geologic scenario (I E):

Play probability (0-1.0) (II A): 1.0 *Stop here if play probability does not exceed 0.10 (II B).*

Cells (III): Cell size (III A1): 80 acres; 0.125 mi² (acres/640)

Area of play (III A2): 26,551 mi² Total no. of cells (III A3): 212,408

No. of productive cells (III B): 10 No. of nonproductive cells (III C): 10

No. of untested cells (III D): 30,000 50th fractile

Minimum possible number of untested cells (III E1): 2500 100th fractile

Maximum possible number of untested cells (III E2): 212,388 0th fractile

Success ratio (0-1.0) (IV): 0.80

EUR probability distribution (V)*:

	Minimum			Median			Maximum
Fractile:	100th	(95th)	(75th)	50th	(25th)	(5th)	0th
EUR (BO or MMCF)	>0	(60)	(110)	220	(410)	(800)	1500

Data to assess co-products (VI):
☐ Oil play - expected GOR: ________ CF/BO
or ☒ Gas play - expected liquids/gas ratio: 0 BO/MMCF

*100th, 50th, 0th fractiles are required. Other fractiles should be supplied if sufficient data are available.

Selected ancillary data (VII):
Depth (ft) of untested cells (VII A): median 1500; minimum 150;
maximum 2300

Fraction (0-1.0) of untested cells that will be tested by wells originally targeted for (VII B): the play______; deeper horizon______; shallower horizon______

API gravity of liquids (VII C): NA. degrees

Fraction (0-1.0) of play with "tight" FERC designation (VII D): 0

Fraction (0-1.0) of new wells that will be stimulated (VII E): .50

Figure 8. Assessment form showing input for Play 6320.

Table 2. Undiscovered gas resources of the Antrim Shale. Potential reserve additions of gas and NGL (Natural gas liquids) are shown for Plays 6319 and 6320 resulting from input parameters shown in figs. 6 and 7. Gas in billions of cubic feet. Natural gas liquids are not considered to be present. Estimates are expressed as a range of values, each value with an associated probability of occurrence (that is, of that amount being met or exceeded). For example, the F5 indicates amount associated with the 1 in 20 chance of being met or exceeded, and the F95 indicates the amount associated with the 19 in 20 chance.

Play: 6319 *Antrim Shale Gas, Developed Area*
Province: 63 Michigan Basin — **Play Type:** continuous-type gas
Geologist: Dolton, G.L. — **Status:** confirmed

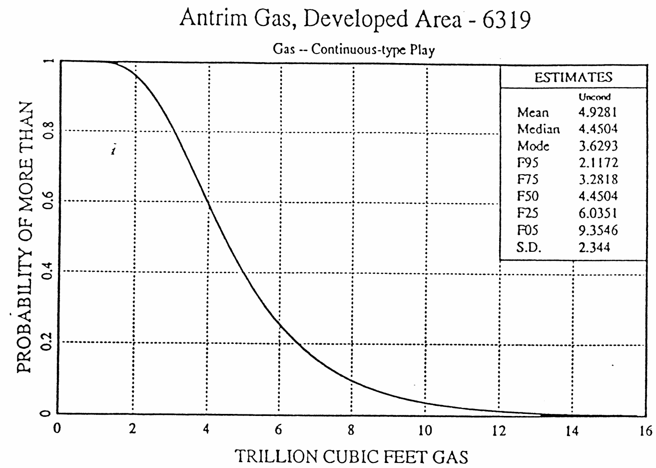
Potential Reserve Additions:

	F95	F75	F50	F25	F5	mean	s.d.
NGL (MMBNGL)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas (BCFG)	2,117.23	3,281.77	4,450.36	6,035.08	9,354.56	4,928.11	2,343.96

Play: 6320 *Antrim Shale Gas, Undeveloped Area*
Province: 63 Michigan Basin — **Play Type:** continuous-type gas
Geologist: Dolton, G.L. — **Status:** hypothetical

Potential Reserve Additions:

	F95	F75	F50	F25	F5	mean	s.d.
NGL (MMBNGL)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas (BCFG)	3,060.29	6,340.43	10,519.30	17,452.40	36,158.60	13,941.90	12,126.90



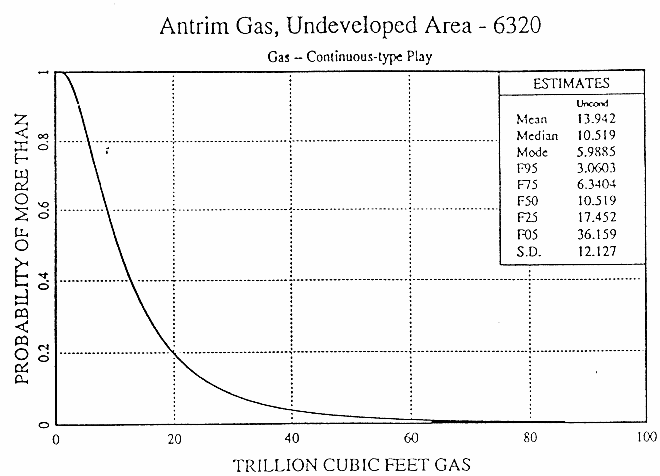


Figure 9. Potential additions of technically recoverable resources. Cumulative probability distribution of gas resources estimated in Play 6319 and Play 6320. Note the difference in scale for the horizontal axis for the two graphs. Insets list selected parameters of unconditional probability distribution, including 95th, 75th, 50th, 25th, and 5th fractiles, and standard deviation. Parameter units are those of graph's horizontal axis (from Schmoker, Crovelli, and Balay, 1995).

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