These concepts and the measurement of joint bearings at local outcrops and in local quarries suggest that the density of vertical joints in the thinly bedded, stiff layers in the Cuyahoga, Ohio, and Bedford shales is much greater than the density of vertical joints in the Sharon and Berea sandstones. This inference was borne out during examination of the borehole videotapes taken in 22 residential water wells in the investigation area and 2 residential water wells outside the investigation area, as presented in the following subsection.

Borehole Videotapes

After examining the data compiled early in the investigation regarding the causes and impacts of the subsurface gas invasions in Bainbridge Township, which were reported in the 2008 DMRM report, the expert panel recognized that making borehole videos is the only direct means of observing the presence of fugitive gas and at what depth(s) gas enters a well. The borehole videos also provide a way to calculate the pressure of the gas entering the wellbore. The most useful and most diagnostic aspect of making borehole videos is in observing changes in the depth(s) where gas entered a well and changes in gas pressure. The DMRM staff was highly trained and experienced in the use of borehole cameras, making high-quality videotapes, and had recently purchased a new, smaller diameter camera. As part of its initial investigation following the house explosion on English Drive, the DMRM staff had the foresight to take seven borehole videos in six of the impacted wells in January and March 2008. The 2008 borehole videos were extremely valuable to the expert panel because they provided baseline information about the depth, thickness, and areal extent of the fugitive gas zone.

Figure 3-27 shows the typical set-up of borehole video equipment, which includes the camera seen in Figure 3-28, digital recorder, cable reel, LED monitor, color TV monitor, water-level probe, tripod with guide wheel, a boatload of skill, and a smidge of luck.

Figure 3-27. Cable reel, LED monitor, and other equipment used to take borehole videotape in the Johnson well (17926 Kingswood Dr).

Figure 3-28. Camera assembly including recessed lens and deeply recessed LED lights.

In late May 2008, the expert panel requested DMRM to take repeat borehole videos in the wells it had already videotaped 15 months earlier and to take several more borehole videos in residential wells in the investigation area and, as a background control, to take borehole videos in one or two residential wells beyond the investigation area. As the expert panel carried out its work in the second half of 2009, it became clear that the information from the borehole videotapes was critical to evaluating the incongruent hypotheses proposed by DMRM and E&A regarding the manner in which the fugitive gas reached residential water wells and the likely duration of the invasive gas problem. Between June 2009 and April 2010, 27 more borehole videotapes were taken. Six of these were taken in the same water wells videotaped in 2008, 25 were taken in water wells in the investigation area, and 2 were taken in water wells in Chester Township, more than 10 miles from the investigation area.

Making borehole videos was a labor intensive effort. The camera and equipment were operated by two DMRM staff members, observations and notes were taken by Dr. Bair, and a well service contractor was always present to remove the pump, reinstall it, and change fittings on pipes. Other professionals sampled and analyzed the well water discharged during videotaping. LEL, pH, specific conductance, and TDS measurements were taken as the borehole videos were being recorded. The organization of people and coordination of equipment during the 14 days spent in the field making the borehole videos was extraordinary.

While taking the borehole video in the new (1973) well on the former Payne property (17975 English Dr), DMRM staff uncovered the older (1956) well on the property located about 8 feet from the back wall of the house. The existence of an older, deeper well was known from the driller's log on file at ODNR and DMRM staff had always considered the old well to be a potential pathway for gas to invade the Payne house. It was found with the aid of a metal detector. The old well was in a pit covered with plywood and buried under several inches of soil. Figures 3-29 and 3-30 are pictures of the well and pit taken on December 1, 2009, the day it was discovered.

Figure 3-29. Wellhead of 1956 well at former Payne property showing disconnected steel pipeline (yellow arrow) into basement and still open tunnel into basement (red arrow) for plastic pipeline from 1973 well.

The old, abandoned well was not sealed or grouted shut, enabling a borehole video to be taken in it that afternoon. As described later, the information obtained from the borehole video taken in the old well helped explain how fugitive gas entered the well, invaded the basement, and caused the explosion on December 15, 2007. The construction details of the old well observed on the borehole videotape also helped explain the local gas migration patterns immediately following the house explosion.

Types of Information Obtained from Analysis of Borehole Videos

The borehole videos made in wells along Bainbridge Road, English Drive, Scotland Drive, and Kingswood Drive provided the expert panel with information about the:

- length of steel or PVC casing
- degree of corrosion and presence of holes in steel casings
- presence of bacterial slimes and/or colonies growing on casing, borehole walls, wiring, discharge pipe
- lithology of rock layers exposed below casing
- depth of geologic contacts (e.g. Cuyahoga Shale and Berea Sandstone)
- depth of prominent bedding planes and joints
- presence of natural gas (bubbles)
- depth of gas source zones where bubbles emanate from bedding planes and joints in exposed in uncased borehole walls

Given below is the sequence of steps generally followed when making the borehole videos.

1. Disconnect discharge pipe and remove pump from well
2. Measure static water level in well
3. Set-up camera and recording equipment
4. Set depth counter to zero while camera hangs at ground level
5. Take notes on features observed in well as camera is slowly lowered in
6. Take camera as deep into well as possible
7. Remove camera from well
8. Re-install pump in well, connect discharge line
9. Re-set camera and recording equipment
10. Start pump and estimate well discharge
11. Slowly lower camera into well and take notes on new features observed in well while it is pumping
12. Take periodic water samples, LEL readings, measure water quality parameters
13. Move camera up and down to get detailed video of important features
14. Take camera to greatest depth possible
15. Examine important features again as camera is removed from well
16. Clean-up

The video taken the first time the camera is run down the well usually has the clearest images. This run is used to identify casing problems, bacteria, and geologic features. The water is less clear during the second camera run because the pump is operating and sediment and bacteria loosened from the casing and borehole walls during the first camera run become suspended in the water column. The purpose of operating the pump during the second run is to reduce the hydrostatic pressure of the water column, which enables gas to migrate more easily along bedding planes and joints intersecting wellbore making it easier to identify the depths of gas source zones. This is particularly true for gas sufficiently dissipated in pressure that it is near pressure equilibrium under non-pumping hydrostatic pressure conditions. Pumping the well also enables videotapes to be taken under the same conditions that exist when the wells are used to provide water for the homeowners.

Several videoclips extracted from the borehole videos taken in the residential water wells can be downloaded from the DMRM website at www.ohiodnr.com/mineral. The videoclips show a variety of features including gas emanating from source zones along bedding planes, rusted casing spalling off into the well, cascading water, roiling gas bubbles, rising gas bubbles, gobs of bacterial colonies, vertical joints, and prominent bedding planes.

The next eight pages show still images captured from the borehole videos. The images illustrate the types of conditions and features seen in the wells. The figure captions explain the types of observations made during analysis of the videotapes. While examining the images, keep in mind that the camera has a fixed focus about four inches in front of the lens and that the lens has a depth of field of about six inches. As a result, features further down the borehole and at the top of each image are not in fine focus. Also keep in mind that the inside diameter of most water wells is 5⅝ inches, even though the diameter looks much larger near the top of the images and much smaller near the bottom. As a consequence of this distortion, gas bubbles, bacteria, and other features appear larger at the top of an image and smaller at the bottom.

Figure 3-30. Severely corroded casing, threaded joint (blue arrows) between casing lengths at 11.7 feet, Adams well (17820 English Dr).

Figure 3-31. Hundreds of colonies of bacteria (white mounds and ridges) amour borehole walls, wires, and pipe at 56.7 feet, Mowery well (7915 Scotland Dr).

Figure 3-32. Prolific bacterial growth (white mounds and armoring) covering borehole walls, discharge pipe at 27.1 feet, Stover well (17860 English Dr).

Figure 3-33. Large, atypical bacterial colony attached to borehole wall at 257.7 feet, Adams well (17820 English Dr).

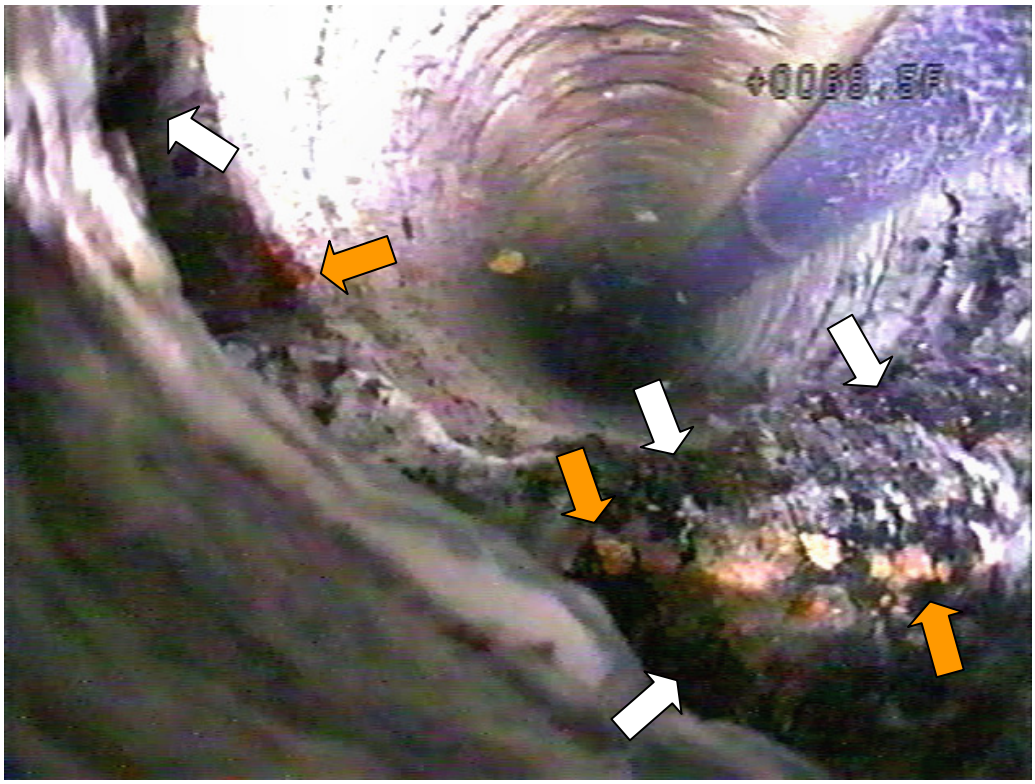

Figure 3-34. Rust particles (orange arrows) from corroded casing, black bacteria (white arrows) on bedding plane/joint intersection at 69.5 feet, Bastifell well (7981 Scotland Dr).

Figure 3-35. Black bacteria on bedding plane at 82.8 feet, Kobella well (one of two background wells in Chester Township).

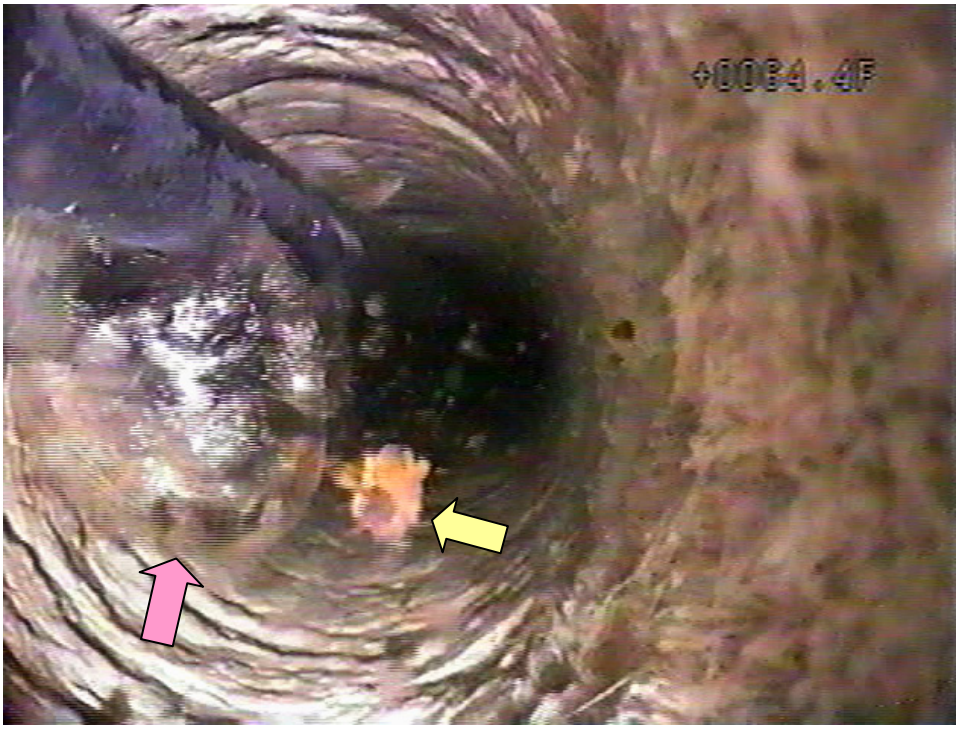

Figure 3-36. Large gas bubble (red arrow) rising from deeper source zone, dislodged bacterial colony (yellow arrow) at 64.4 feet, Bastifell well (7981 Scotland Dr).

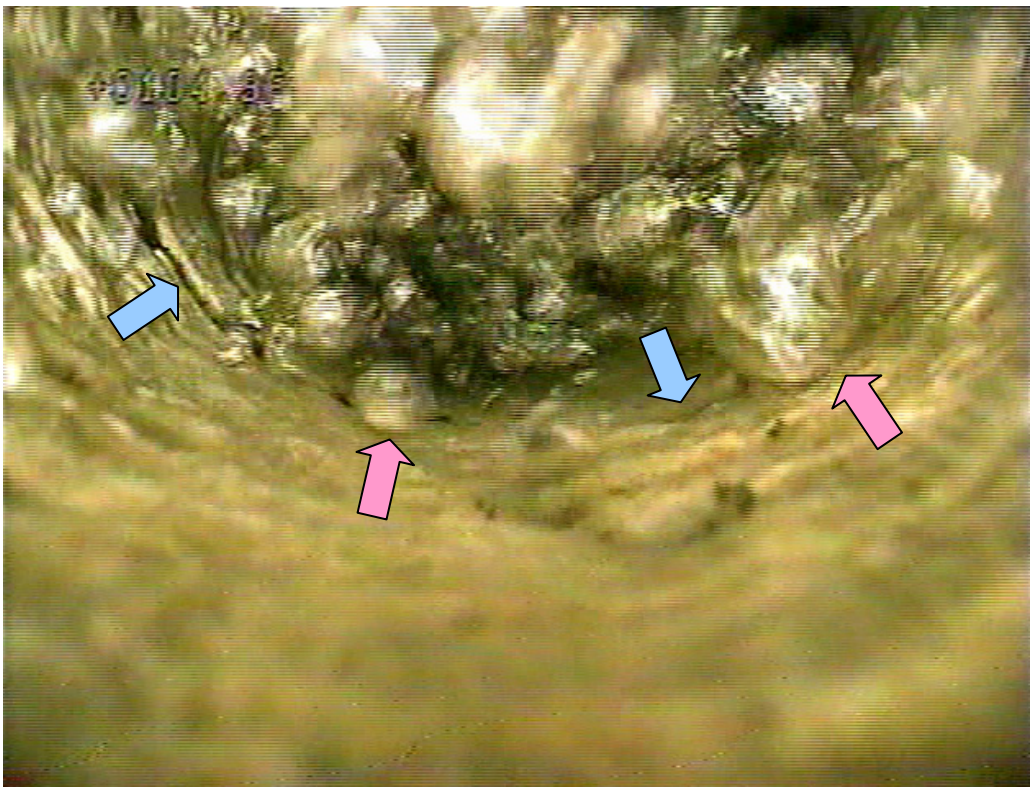

Figure 3-37. Gas bubbles (red arrows) emanating from source zone (bedding plane) at 104.9 feet (blue arrows) mixing with bubbles rising from deeper gas source, Cloninger well (7780 Bainbridge Rd).

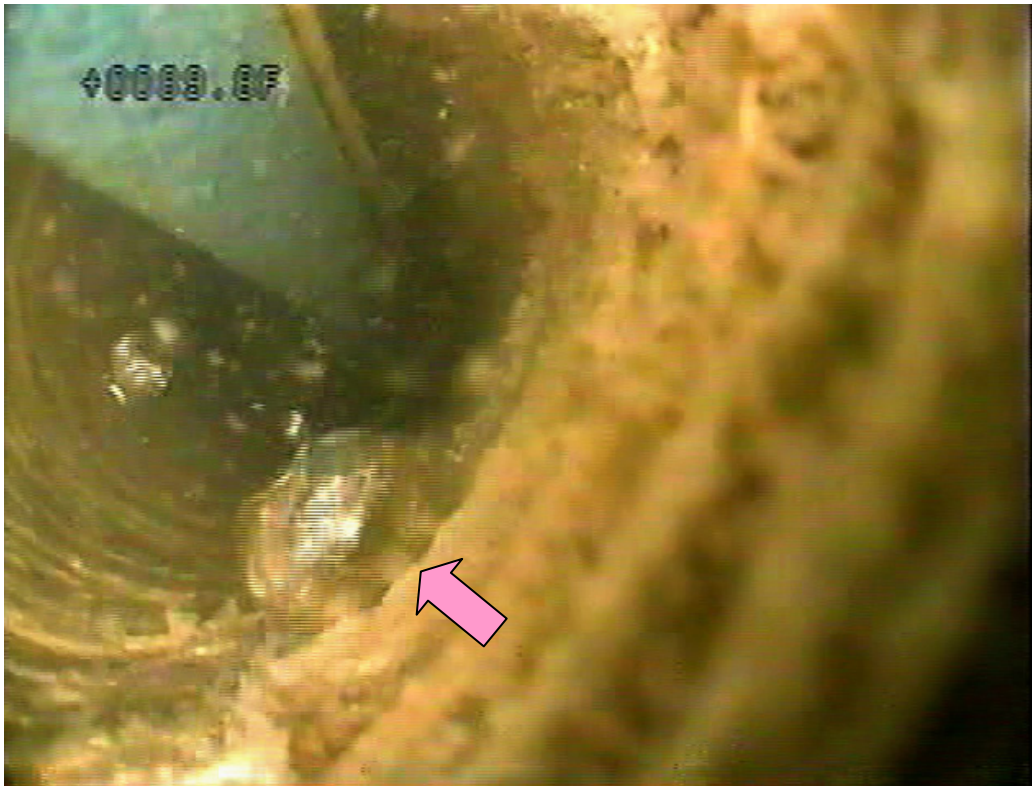

Figure 3-38. Gas bubble (red arrow) emanating from source zone (bedding plane parting) in borehole wall at 89.8 feet, Buddenhagen well (7897 Scotland Dr).

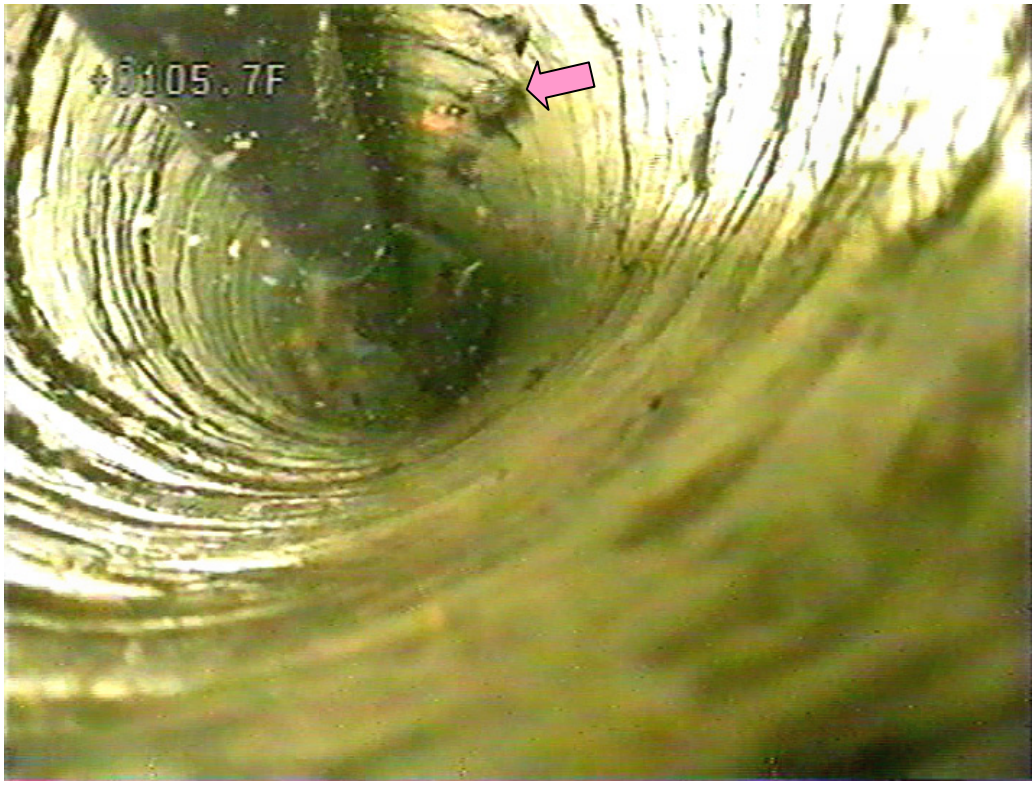

Figure 3-39. Gas bubble (red arrow) emanating from source zone (bedding plane parting) in borehole wall at 105.7 feet, Kukoleck well (7969 Scotland Dr).

Figure 3-40. Large gas bubble (red arrow) emanating from source zone (wide bedding plane parting) at 93 feet, Jordan well (17990 English Dr).

Figure 3-41. Gas bubbles (red arrows) emanating from source zone (bedding plane parting) at 120.7 feet, de Gaetano well (17971 Kingswood Dr).

Figure 3-42. Roiling gas bubbles at water surface while pumping, prominent bedding plane at 104 feet, Calo well (17969 Kingswood Dr).

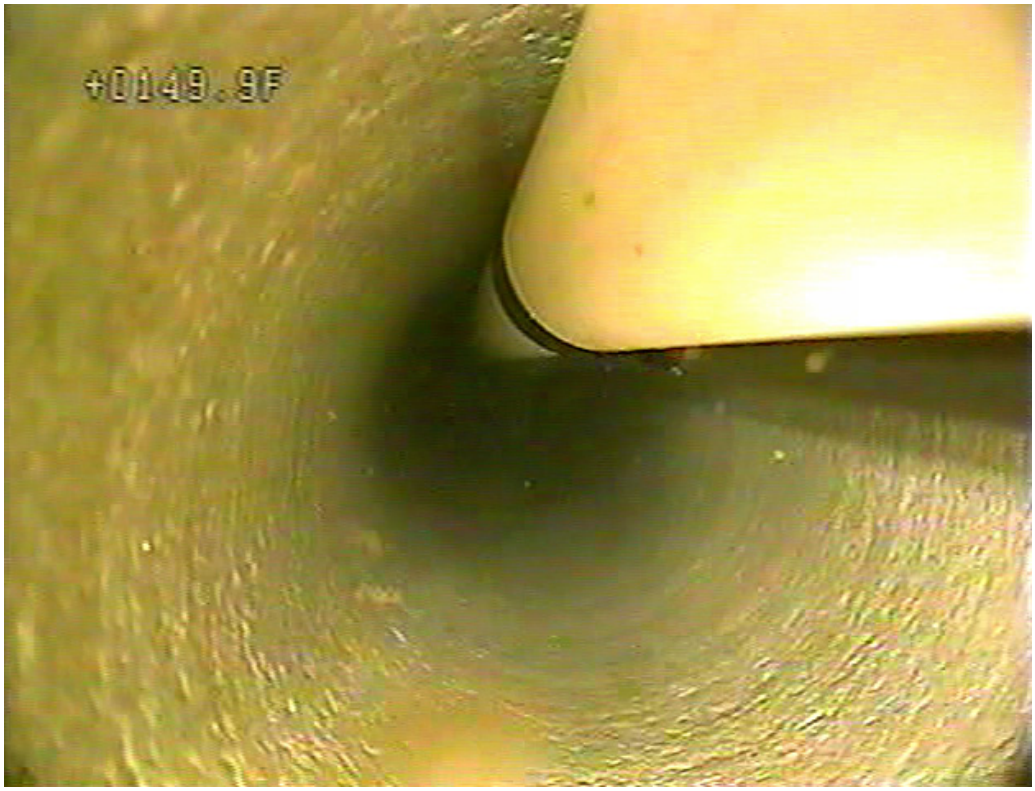

Figure 3-43. Typical shallow pitted texture and cream white color of Berea Sandstone at 149.9 feet, Komocki well (7950 Scotland Dr).

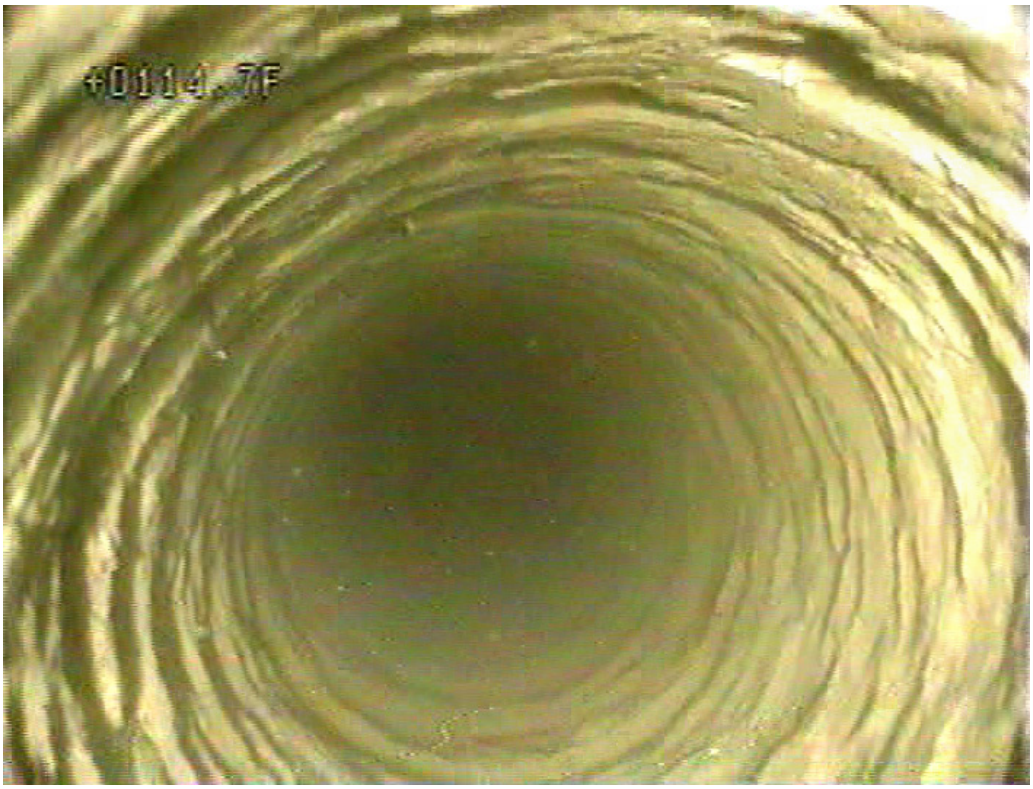

Figure 3-44. Typical ribbed texture of thin shale beds in Cuyahoga Shale at 114.7 feet, old Payne well (17975 English Dr).

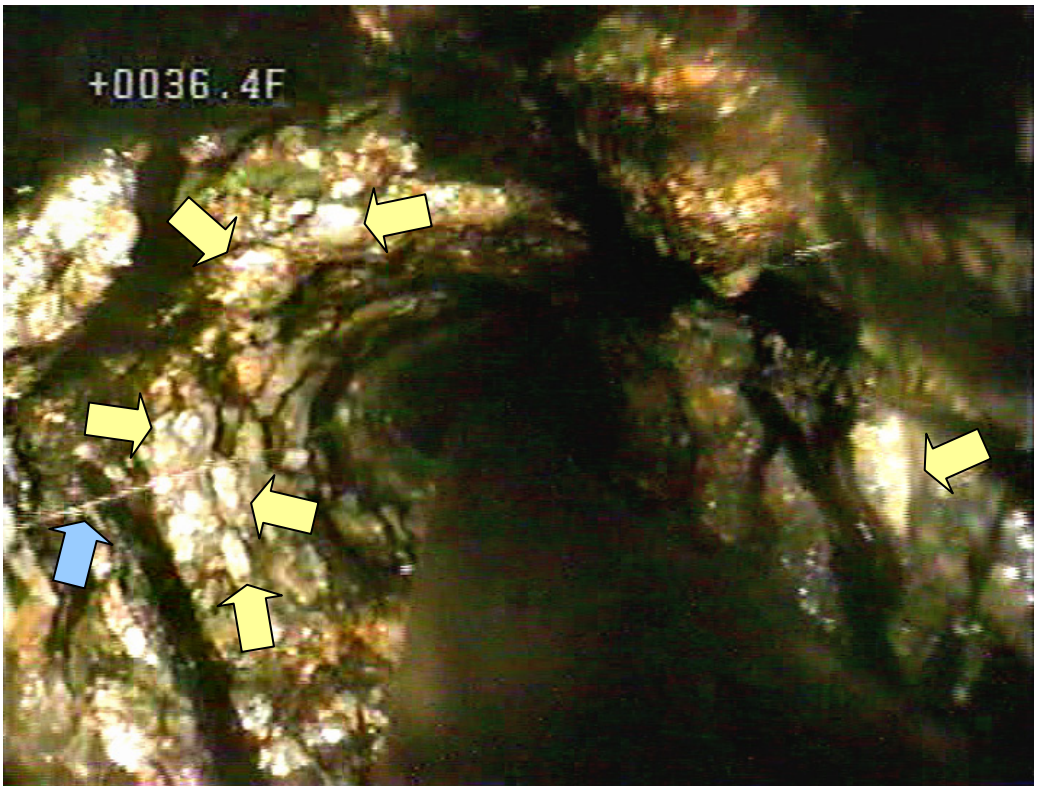

Figure 3-45. Sharon Sandstone containing abundant large quartz pebbles (yellow arrows), cascading water (blue arrow) at 36.4, old Payne well (17975 English Dr).

Analysis of Joints from Borehole Videos

Identifying joints in a borehole video takes an appreciation of how a planar surface (joint plane) looks when it is intercepted by a hollow cylinder. A good analogy is imaging what slices made with a very sharp knife would look like on the inner cardboard tube from a roll of paper towels. Figure 3-46 shows what joint planes at three different angles would look like on the walls of a hollow cylinder that is silt lengthwise and spread out. The joint plane cutting across the cylinder (wellbore) at a low angle (green lines) makes a sine wave with a low amplitude. The joint plane with an intermediate angle (red lines) of intersection with the cylinder also makes a sine wave but its amplitude is slightly larger than that of the low angle joint plane. The joint plane intersecting the cylinder at a high angle (blue lines) makes a large amplitude sine wave.

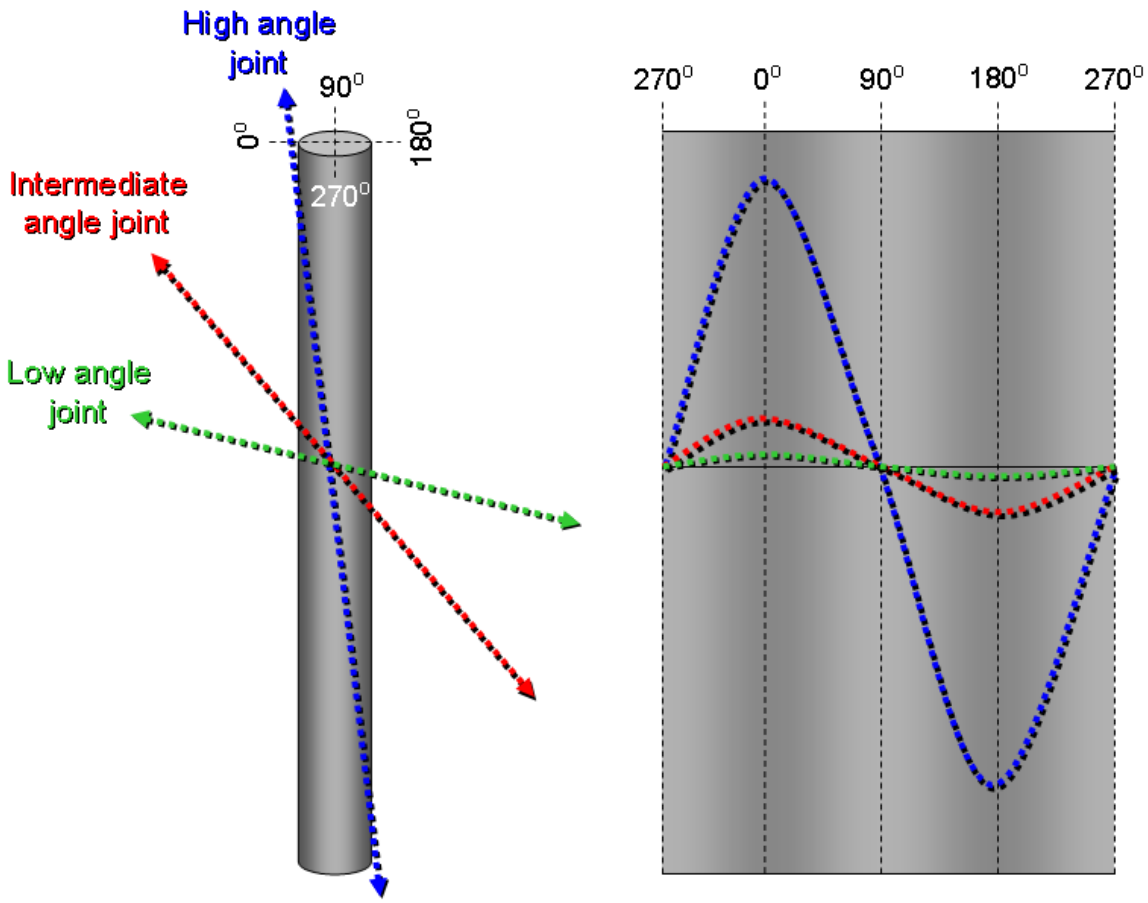

Figure 3-46. Diagram demonstrating geometric relationships created when a plane intersects a cylinder at different angles.

Boreholes that intersect vertical joints, like those in gas fields that occur in the Fractured Devonian Shales and Siltstones Play, as described by Boswell (1996) and Milici (1996), and as seen in outcrops and quarries in and near Geauga County, will appear as high amplitude sine waves in borehole videos. Bedding planes, which are usually horizontal or nearly so in the flat-lying sedimentary rocks in northeast Ohio, will appear in borehole videos as circular rings. Figures 3-47 through 3-53 show images of joint planes seen in the borehole videos taken in residential wells in the area impacted and in a background residential well in Chester Township more than 10 miles from the investigation area.

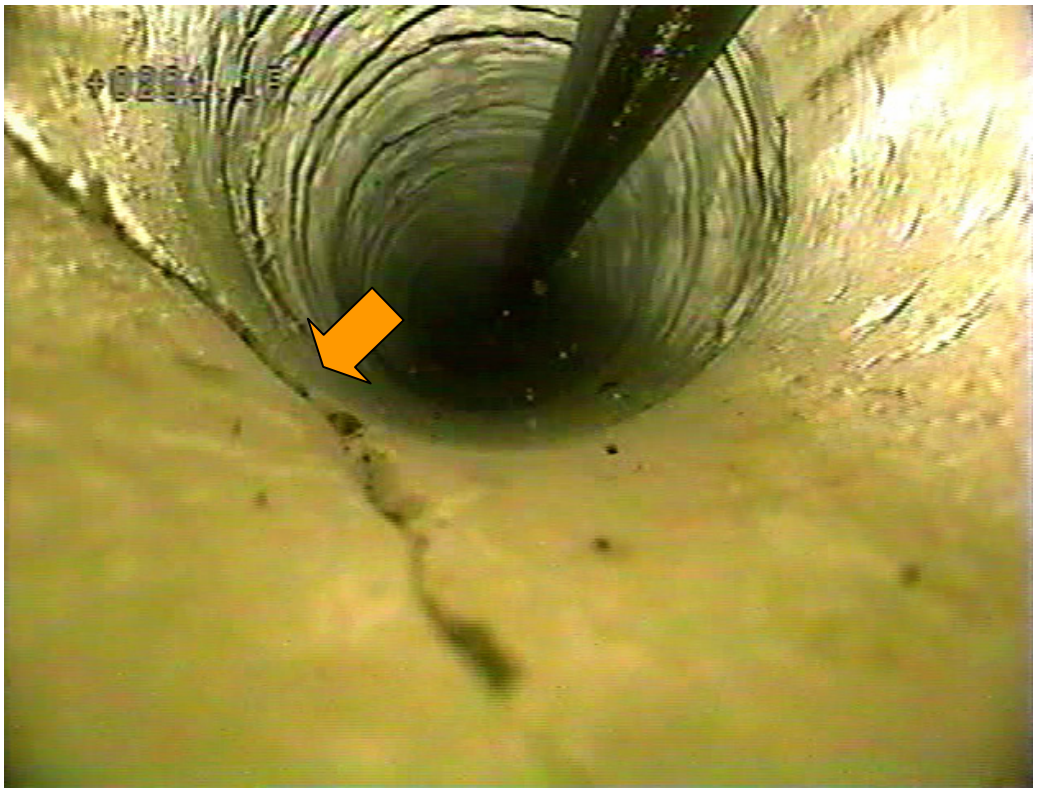

Figure 3-47. Near vertical joint (orange arrow) intersecting borehole at 201.1 feet, several deeper bedding planes, de Gaetano well (17971 Kingswood Dr).

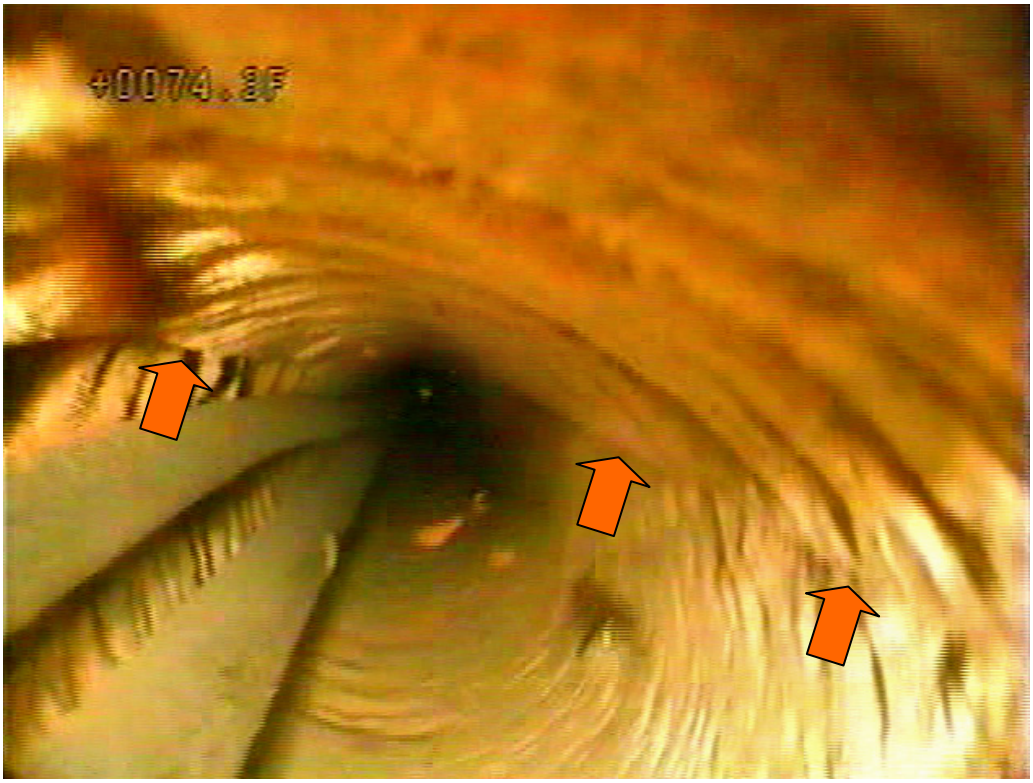

Figure 3-48. Vertical joint (orange arrows) cutting across borehole at 74.3 feet, Jordan well (17990 English Dr).

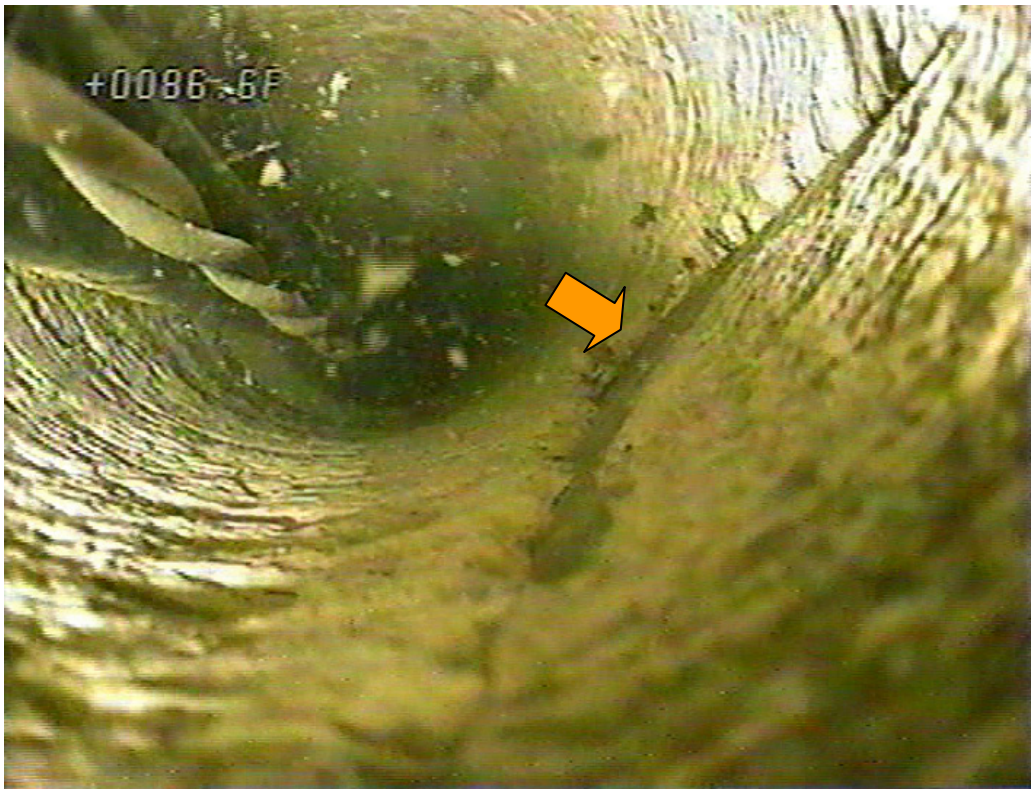

Figure 3-49. Vertical joint (orange arrow) intersecting borehole at 86.6 feet, Kukoleck well (7969 Scotland Dr).

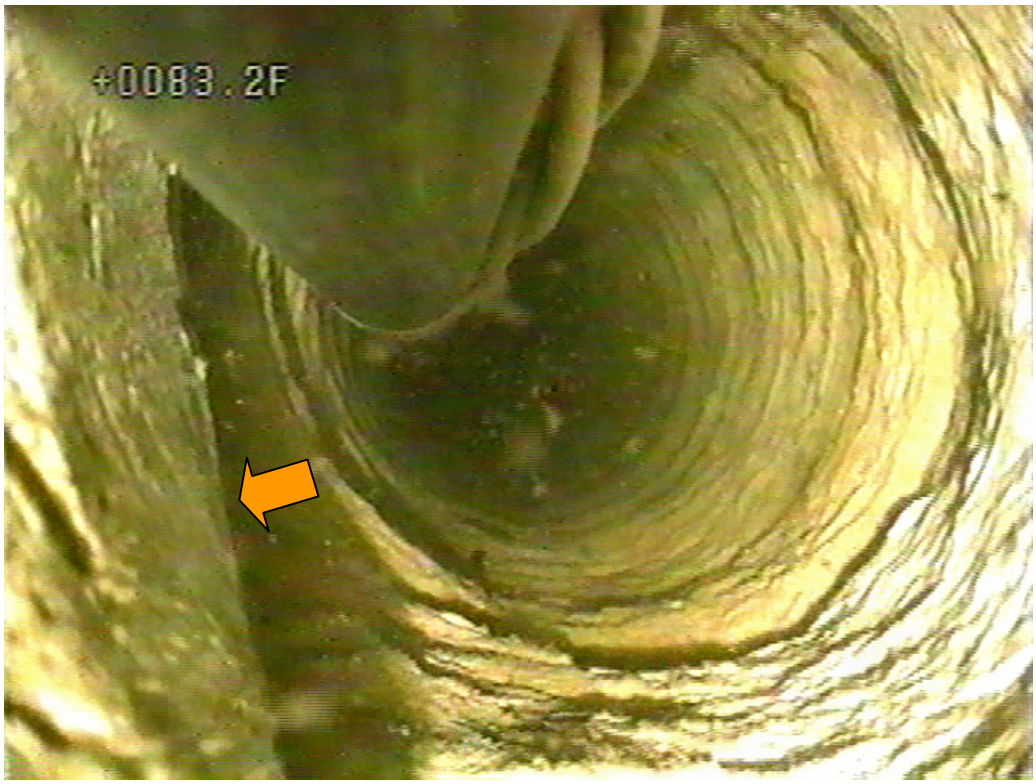

Figure 3-50. Vertical joint (orange arrow) intersecting borehole at 83.2 feet showing ribbed texture of Cuyahoga Shale, Kukoleck well (7969 Scotland Dr).

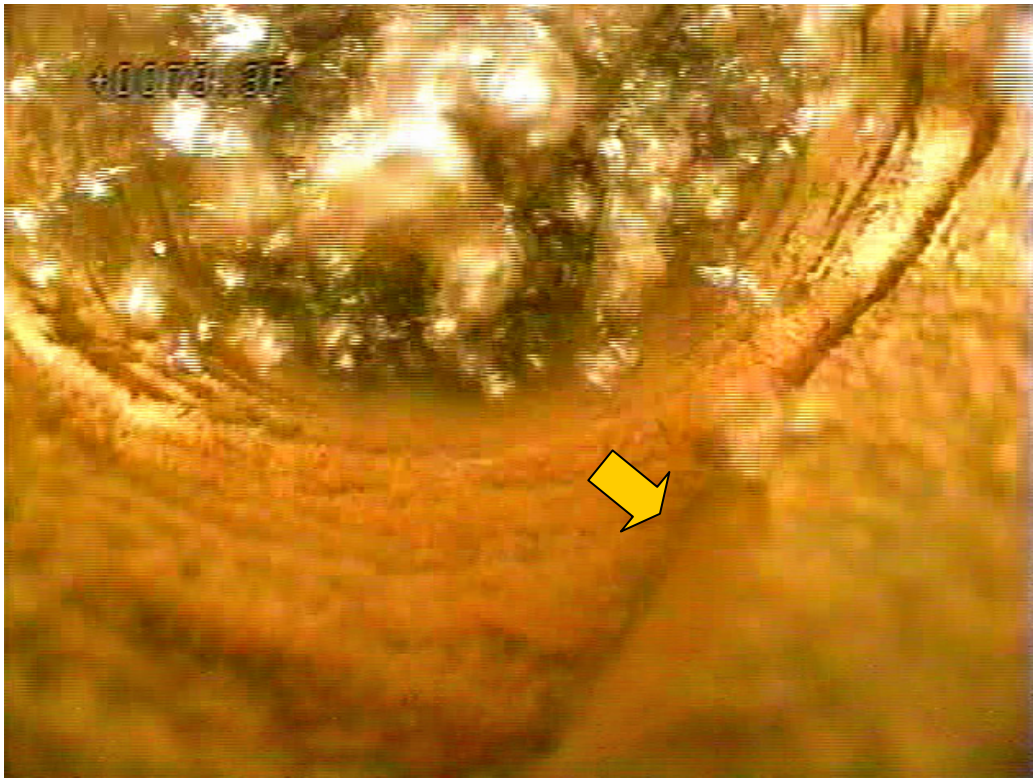

Figure 3-51. Vertical joint (orange arrow) intersecting borehole at 79.3 feet, gas bubbles rising from deeper gas source zone, Jordan well (17990 English Dr).

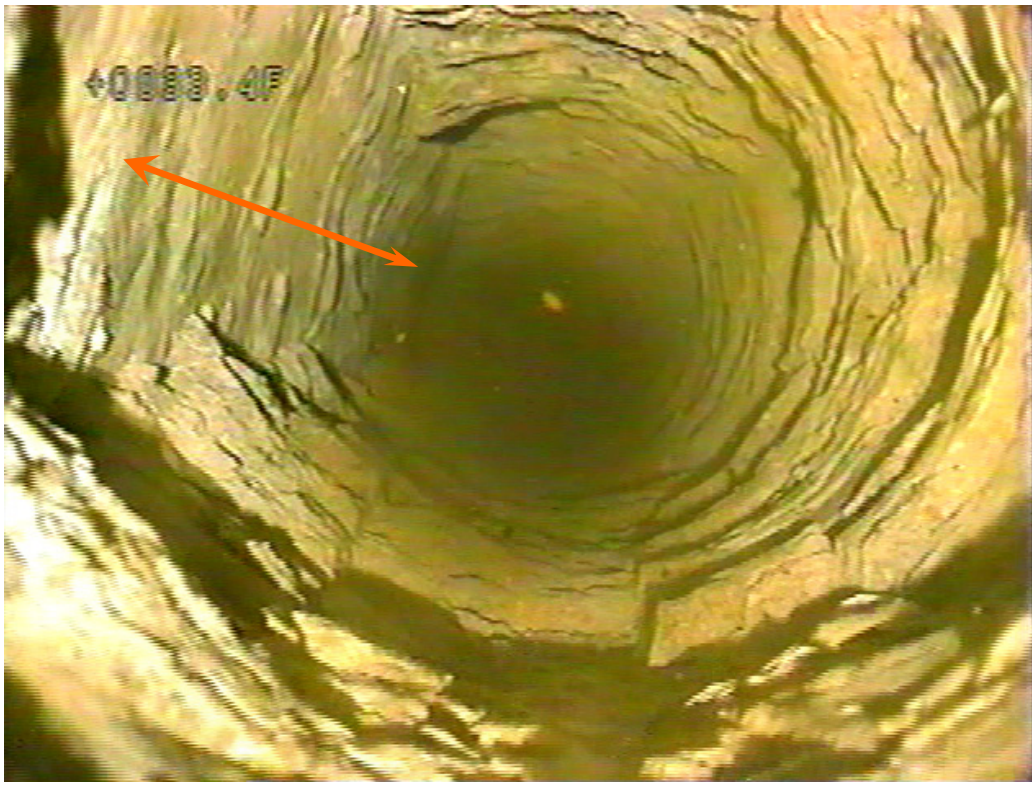

Figure 3-52. Vertical joint surface in borehole wall (orange arrow) at 33.4 feet, Cooper well (17974 English Dr).

Figure 3-53. Vertical joint plane (orange arrows) cutting across borehole at 144.3 feet, Roller well (one of two background wells in Chester Township, Geauga County).

Figure 3-54. Two vertical joint planes (orange arrows) intersecting borehole at 38.4 feet in Sharon Sandstone, old Payne well (17975 English Dr).

Videotapes in Chester Township Background Wells

In addition to the 32 borehole videos taken in 23 water wells proximate to the English #1 Gas Well, two borehole videos were taken in water wells more than 10 miles away from the English #1 Gas Well to provide subsurface background information outside the area impacted by the subsurface gas invasion in Bainbridge Township. These two videotapes were taken in the Roller well and in the Kobella well off route 322 in Chester Township. The features seen in these two wells show the same features seen in the 23 wells in the investigation area. The Kobella well (7174 Sherman Road) contains bacteria and natural gas emanating as tiny bubbles from the Berea Sandstone. The steel casing in the Kobella well is deeply rusted. The video shows several pieces spalling off and falling down through the water column. The Roller well (12803 South Woodside Drive) is uncased through the Cuyahoga Shale and contains an abundance of vertical joints and bedding planes. The thin beds of siltstone at the base of the Cuyahoga Shale (Szmuc, 1970) can be identified as well as several ledges in the borehole wall collecting black particles that fall down through the water column.

Observation Logs of Borehole Videos

Digital copies were made of all the original borehole videotapes. In total, these files use more than 100 gigabytes of memory. The files for one borehole video typically require 3 gigabytes of memory. Consequently, the digital copies of the borehole videos are too large to post on the DMRM website. (Copies of specific borehole videos can be obtained from DMRM by special request.) As previously mentioned, videoclips of several borehole videos can be downloaded from the DMRM website at www.ohiodnr.com/mineral.

Using the public domain VLC multimedia player to view the mpeg files created from the original borehole videotapes, Dr. Bair spent 70 hours examining all the borehole videos, making observation logs recording the depths to important features, and taking screen captures of important features. An important distinction is made on the borehole observation logs between gas bubbles that are rising in the water column, which implies they entered the borehole from a source zone below the camera, and gas bubbles that are emanating from a bedding plane parting or joint opening, which represent the specific geologic feature enabling gas to enter the borehole. Detection of gas bubbles in a well is very important to the homeowner. Identifying the depth and geologic unit where gas enters the well is priceless and critical to determining present and future impacts of the invasive gas. To make this assessment, it is necessary to identify (1) where gas migrated vertically across the various geologic units, (2) where gas migrated laterally across the investigation area, and (3) to identify when the gas reached specific locations. For these reasons, it is important to determine the depth and location of the source zones that permit gas migrating in joints and along bedding planes to enter the water wells. The distinction between gas bubbles and gas source beds is denoted on the observation logs by the symbols **gb** or **gbs** for gas bubbles rising in the water column and the symbol **GS** for identifying the depth of a gas source zone where gas bubbles enter the wellbore.

Figures 3-55 and 3-56 show the observation log from the borehole video taken in the Kukoleck well (7969 Scotland Dr) on December 1, 2009. All of the observation logs are presented in Appendix C. The information recorded on the observation logs was analyzed and used by the expert panel in the testing of the dissimilar hypotheses presented by DMRM and E&A regarding the causes and impacts of the subsurface gas invasions in Bainbridge Township.

Borehole Videotape Observation Log Date: 12/1/09 Page 1 of 2

Address: 7969 Scotland	**Property owner:** Kukoleck
~~City~~ / Township: Bainbridge	**County:** Geauga
Latitude:	**Longitude:**

Camera: (new) | old
Camera operators: TB & TT
Video interpreter: ~~ES~~ Bair
Video datum: ground | top of tripod | other

Type of casing: (steel) | PVC
Diameter of casing (in):
Depth to pitless adapter (ft): 2.9
Depth to water (ft): 59.7
Condition of casing: good | (bad) | ugly
Length of casing (ft): 34.5
Centralizers / torque arrestors: (yes) | no
Depth to pump (ft): 108 (?)
Depth of videotape (ft): 107
Reach borehole bottom: yes | (no)

ODNR well log number:	125132	691212
County well log number:		
Reported casing length (ft):	38	36
Reported depth of well (ft):	80	140
Other:	2 wells (1954)	(1989)

Comments:
- Open part of borehole total in shale
- uncertain about GS @ 86'
- certain of GS @ 106-107'
- certain about GS below centralizer @ 108'
- Pumped from 33:40 to 6:20 (27 min 20 seconds) @ 13 gpm for a total of ~ 360 gals and 1-foot of drawdown → Berea Ss. must be exposed in borehole below 108'

Elev = 1036'

Trip # 1 Pumping rate, when pump on (gpm): 13

Depth (ft)	Time (min)	Feature	Comments
34.5			bottom of casing
36.4		BP	Shale
37.8		BP	shale
59.7	5:45	WL	lots of bacteria
	6:20	WL	Pump on, japanese beetle on WL
60.5	6:50	WL	bacteria colonies (white bumps)
60.6		gbs	railing, camera under WL
64.7		BP V	
68.1	8:00	gbs	
70.5		V gbs	
71.5		V gbs	
74.3		BP gbs	
76.7		V gbs	

BP = prominent bedding plane V = prominent vertical joint gb = gas bubbles from greater depth GS = gas source opening
Sh = shale Ss = sandstone St = siltstone WL = water level in well

Figure 3-55. Page 1 of observation log from borehole video taken in Kukoleck well (7969 Scotland Dr), December 1, 2009.

Page 2 of 2

Trip # 1 Pumping rate when pump on (gpm): 13

Depth (ft)	Time (min)	Feature	Comments
78	8:50	BP gbs	Shale
82.6		V BP gbs	
86.3		V	
88	9:35	no gbs	
88.6	10:15	no gbs	
87.7		1 gbs	– deeper source
85.2		1 gbs	– " "
~~[illegible]~~		~~[illegible]~~	
85.4	11:53	gbs	many
86.4	12:15	V	
87.9	12:25	gbs	
89.2	12:45	gbs	shale
90.5		V gbs	
93		BP gbs	
94.3		BP gbs	
98			shale
100.4	14:35	gbs	
100.8		BP gbs	
102.3		BP	
105.7+	15:35	GS BP	upper right side
106.7+	16:06	GS BP	lower left side, immediately above
106.2	16:45	GS BP	centralizer, shale
106.8	17:08	GS	GS deeper than centralizer, gbs
			getting past centralizer at 9:00
107.5	17:30	gbs	trying get past centralizer, shale
105.8	19:20	GS BP	left side BP @ 8:00
107.7	20:20	gbs	ramming speed
106.3	21:30	GS gbs	
103.1	23:00	gbs	
90	24:53	gbs	
84.9	25:38	gbs	
85.7	25:50	GS sh BP	@ 12:00 noon → maybe (uncertain)
84.6	26:40	gbs	
88.0	27:50	gbs	shale
85.1	29:10	gbs	
	ASCENDING		
60.1	33:40	WL	roiling
34.2	35:00	BP	
	36:27		out of well

same

same

deeper GS below centralizer

BP = prominent bedding plane V = prominent vertical joint gb = gas bubbles from greater depth GS = gas source opening

Sh = shale Ss = sandstone St = siltstone WL = water level in well

Figure 3-56. Page 2 of observation log from borehole video taken in Kukoleck well (7969 Scotland Dr), December 1, 2009.

The borehole observation logs (Appendix C) provided geologic data used to construct the top of Berea Sandstone structure contour map (Figure 3-12, Attachment 4) and used to construct the geologic cross sections A-A′ and B-B′ (Figures 3-10 and 3-11, Attachments 2 and 3). The borehole observation logs also provided the detailed information about bedding planes, joints, gas bubbles, gas source zones, and static water levels shown in Attachments 5 and 6. These poster-size maps can be downloaded from the DMRM website at www.ohiodnr.com/mineral. Figures 3-57 and 3-58 are highly reduced versions of Attachments 5 and 6, respectively.

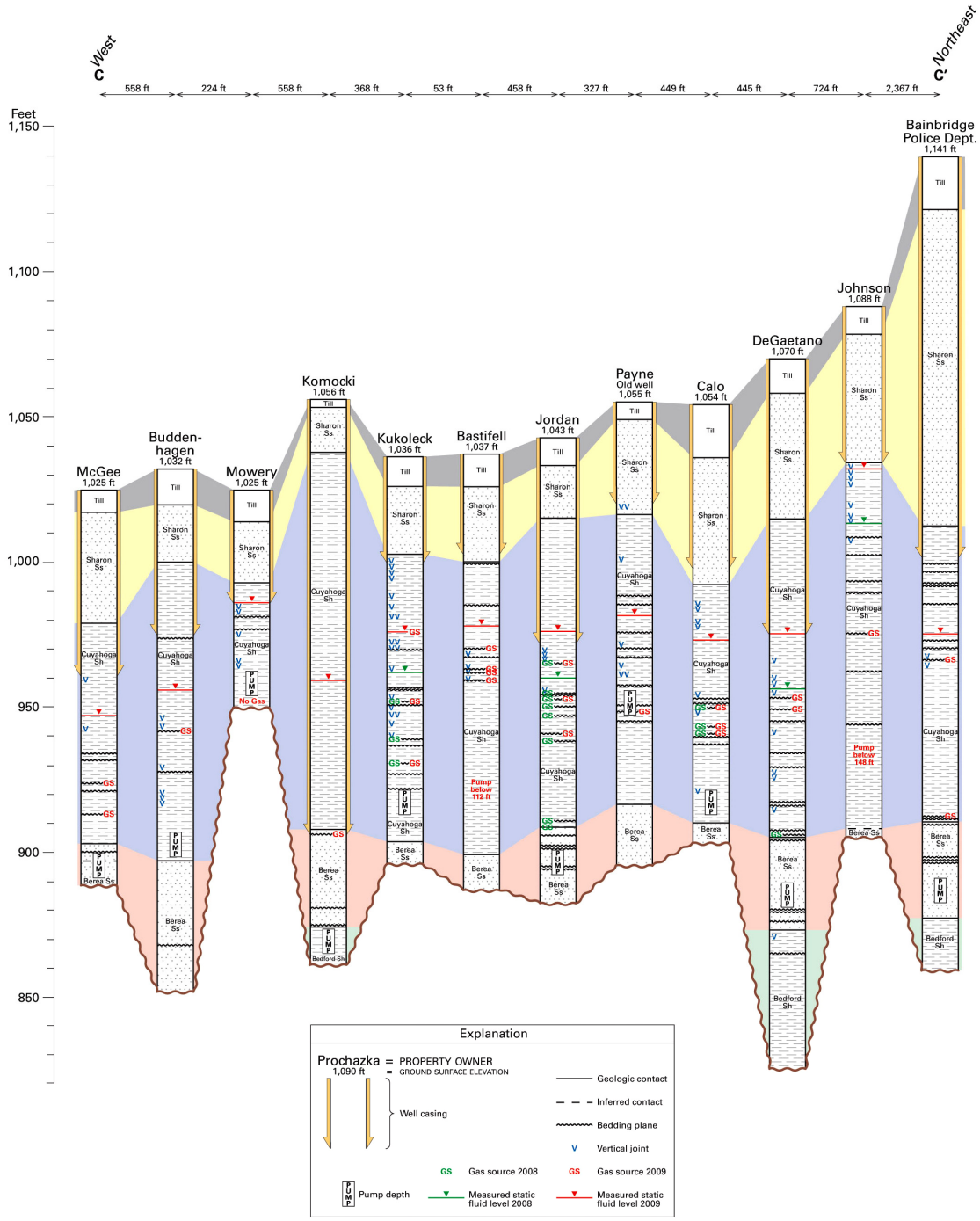

Figure 3-57. Highly reduced version of Attachment 5 – Interpreted Downhole Video Logs Along Cross Section C-C′.

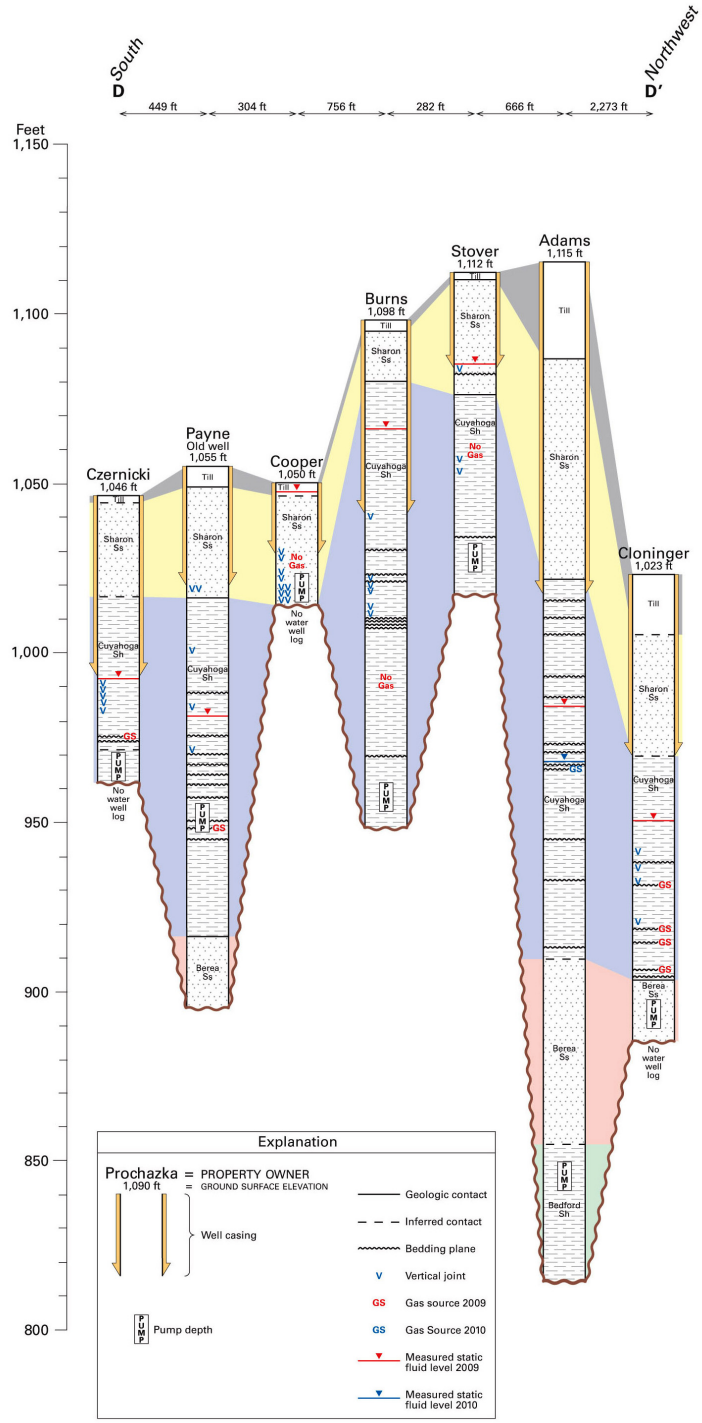

Figure 3-58. Highly reduced version of Attachment 6 – Interpreted Downhole Video Logs Along Cross Section D-D'.

Table 3-3, which covers the next two pages, summarizes the number and depths gas source zones recorded in the borehole observation logs in Appendix C. It also contains calculated values of hydrostatic pressure on the gas at each gas source opening. This calculation is made by multiplying the hydrostatic gradient of freshwater (0.433 psi/ft) times the difference in depth between the static water level and the depth of the gas source zone.

Table 3-3. Summary of Gas Source Data from Borehole Video Observation Logs

Property Owner - Address Date of borehole video	**Ground elevation** (ft amsl)	**Static water level depth** (ft)	**Depth to gas source opening** (ft)	**Elevation of gas source opening** (ft)	**Hydrostatic pressure on gas** (psi)	**Geologic unit of gas source**
Adams – 17820 English	1108					
May 14, 2009		131	Deeper GS	831 or less	63.2 or more	Bedford
April 1, 2010		149	152	956	1.3	Cuyahoga
Bastifell – 7981 Scotland	1837					
October 15, 2009		59	67	970	3.7	Cuyahoga
			69	968	4.5	Cuyahoga
			74	963	6.7	Cuyahoga
			78	959	8.4	Cuyahoga
Buddenhagen – 7897 Scotland	1032					
May 14, 2009		76	90	942	5.9	Cuyahoga
			Deeper GS	909 or less	20.4	Cuy / Berea
December 1, 2009		80	90	942	4.3	Cuyahoga
Burns – 17888 English	1095					
September 3, 2009		32	No gas seen	- - - -	- - - -	- - - -
Calo – 17969 Kingswood	1054					
January 13, 2008		81	104	950	10.0	Cuyahoga
			113	941	13.9	Cuyahoga
October 15, 2009		70	112	942	18.2	Cuyahoga
			113	941	18.6	Cuyahoga
			114	940	19.1	Cuyahoga
Cloninger – 7780 Bainbridge	1023					
December 1, 2009		73	92	931	8.2	Cuyahoga
			105	918	13.9	Cuyahoga
			109	914	15.6	Cuyahoga
			116	907	18.6	Cuyahoga
			120	903	20.4	Cuy / Berea
Cooper – 17974 English	1055					
September 2, 2009		1	No gas seen	- - - -	- - - -	- - - -
Czernicki – 17995 English	1055					
December 1, 2010		54	72	974	7.8	Cuyahoga
de Gaetano – 17971 Kingswood	1070					
March 17, 2008		114	164	906	21.7	Berea
September 2, 2009		95	116	954	9.0	Cuyahoga
			121	949	11.2	Cuyahoga
			131	939	15.5	Cuyahoga
Johnson – 17926 Kingswood	1088					
March 17, 2008		75	no gas seen	- - - -	- - - -	- - - -
September 2, 2009		55	113	975	25.1	Cuyahoga
			Deeper GS	953 or less	34.6 or more	Cuy / Berea
Jordan – 17990 English	1043					
January 11, 2008		83	77	966	*See note #1*	Cuyahoga
			88	955	2.2	Cuyahoga
			94	949	4.8	Cuyahoga
			98	945	6.5	Cuyahoga
			134	909	22.1	Berea
March 17, 2008		82	90	953	3.5	Cuyahoga
			96	947	6.1	Cuyahoga
			107	936	10.8	Cuyahoga
September 2, 2009		67	76	967	3.9	Cuyahoga
			89	954	9.5	Cuyahoga
			102	941	15.2	Cuyahoga

GS – gas source

Table 3-3 continued on next page

Table 3-3. Summary of Gas Source Data (continued)

Property Owner - Address Date of borehole video	**Ground elevation** (ft amsl)	**Static water level depth** (ft)	**Depth to gas source opening** (ft)	**Elevation of gas source opening** (ft)	**Hydrostatic pressure on gas** (psi)	**Geologic unit of gas source**
Komocki – 7950 Scotland	1056					
March 17, 2008		96	> 94	< 962	> 1	unknown
September 3, 2009		97	149	907	22.7	See note #2
Kukoleck – 7969 Scotland	1036					
March 17, 2008		74	84	952	4.3	Cuyahoga
			97	939	10.0	Cuyahoga
			106	930	13.9	Cuyahoga
			Deeper GS	923 or less	16.9 or more	Cuy / Berea
December 1, 2009		60	85	951	36.8	Cuyahoga
			106	930	45.9	Cuyahoga
			Deeper GS	923 or less	22.9 or more	Cuy / Berea
Maguire – 17925 English	1090					
April 15, 2010		36	45	1045	3.9	Cuyahoga
McGee – 7859 Scotland	1025					
October 15, 2009		78	93	932	40.3	Cuyahoga
			101	924	9.8	Cuyahoga
			112	913	48.5	Cuyahoga
Mechler – 7898 Scotland	1040					
April 1, 2010		3	No gas seen	- - - -	- - - -	- - - -
Mowery – 7915 Scotland	1025					
September 3, 2009		39	39	986	See note #3	Cuyahoga
Payne – 17975 English	1055					
December 1, 2009		74	107	948	14.3	Cuyahoga
December 1, 2009			No gas seen	- - - -	- - - -	- - - -
Pierce – 8139 Bainbridge	1100					
April 15, 2010		124	184	916	26.0	Berea
			193	907	29.9	Berea
Police – 8139 Bainbridge	1143					
October 15, 2009		164	172	971	3.5	Cuyahoga
		226	226	917	26.8	Cuy / Berea
Stover – 17860 English	1113					
September 2, 2009		27	No gas seen	- - - -	- - - -	- - - -
Szabo – 17904 English	1082					
April 1, 2010		21	No gas seen	- - - -	- - - -	- - - -

Deeper GS – gas bubbles seen rising below depth camera could reach indicating another gas source (GS) at greater depth
Note #1 – water seen pulsing into borehole above water level in well, caused by natural gas entering well, wellhead LEL > 0
Note #2 – gas enters well at bottom of casing at large bedding plane opening between Cuyahoga Shale and Berea Sandstone; gas flows down into bedding plane from overlying Cuyahoga Shale (i.e., U-tube effect)
Note #3 – bubbles seen at contact of casing and water level in well are vadose air, not natural gas, wellhead LEL = 0

The borehole observation logs also provided temporal and spatial data useful in determining the vertical and lateral migration of fugitive gas in the investigation area. Analysis of Table 3-3 shows that the number and depths of gas source zones in wells changes over time. For example, in the borehole video taken in the de Gaetano well (17971 Kingswood Dr) on March 17, 2008, three months after the explosion at the Payne residence (17975 English Dr), there is one gas source zone at 164 feet deep in the Berea Sandstone. In the borehole video taken on September 2, 2009, more than 20 months after the explosion, there are three gas source zones in the de Gaetano well, the deepest one at 131 feet and all three gas source zones are in the Cuyahoga Shale. This shows that the zone of fugitive gas near the de Gaetano well is rising through time. In the 18 months between the two borehole videotapes, the bottom of the gas zone, which used to be in the Berea Sandstone, rose 33 feet up into the Cuyahoga Shale.

The data in Table 3-3 can be used to analyze the movement of the fugitive gas zone in even more detail by looking at changes in the deepest detected gas source zone over time. Figure 3-59 shows changes in the depth of the deepest gas source zone for five wells where borehole videos were taken in both 2008 and in 2009. (The 125+ foot change in the depth to the deepest gas source zone in the Adams well (17820 English Dr) is not shown on Figure 3-59 because the second borehole video was taken in April 2010 while this report was being written).

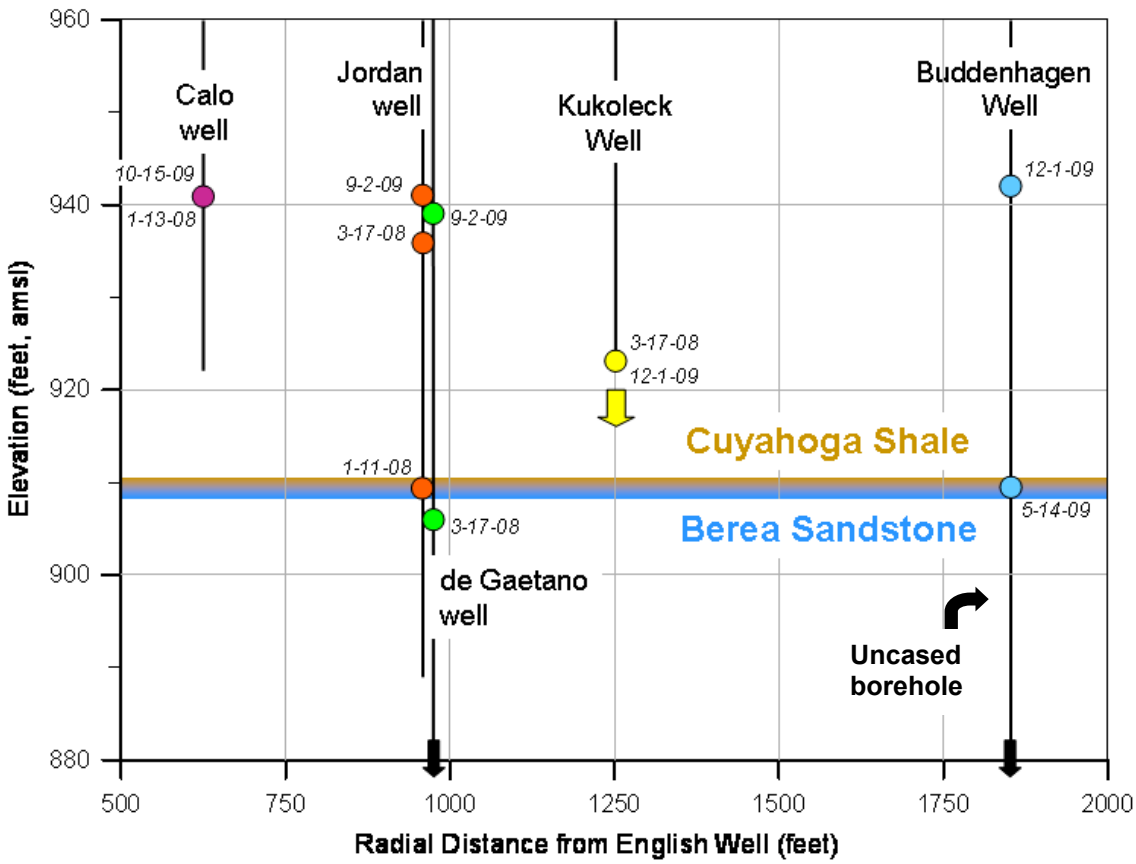

Figure 3-59. Comparison of depths to deepest gas source zone from borehole videos taken in 2008 versus ones taken in 2009 for five water wells on English and Scotland drives.

The data in Table 3-3 and Figure 3-59 show that over a two-year period the fugitive gas slowly migrated laterally and vertically within the geologic units comprising the local groundwater flow system. Figure 3-59 shows that the bottom of the gas zone at several different locations within the investigation area dissipated upward as gas migrated from the Berea Sandstone up into the Cuyahoga Shale. In all likelihood, as more time passes, the fugitive gas will migrate upward into the Sharon Sandstone, and eventually escape into the soil zone and atmosphere.

The upward movement of the bottom of the gas zone demonstrates that overpressured gas escaping from annular space in the surface-production casing of the English #1 gas well is not being replaced or augmented by gas from the Ohio Shale or from deeper commercial gas zones via fractures created during the 31-day period of annulus overpressurization.

Gas Migration within Local Groundwater System

To reach water wells in the investigation area, fugitive gas from the English #1 well migrated more than 1,000 feet vertically and 600 to 3,000 feet laterally through two different geologic materials: shale and sandstone. Although groundwater and gas can migrate through shale and sandstone, gas, being buoyant, does not adhere to the same laws that govern groundwater flow. Gas migration, however, can be strongly influenced by groundwater flow. Without understanding the mechanisms by which the fugitive gas migrated through the various layers of shale and sandstone and then into some, but not all, of the residential wells in the area, statements as to the causes of the subsurface gas invasions and its impact are speculative.

None of the additional data requested by the expert panel deal directly with groundwater flow or gas movement, but almost all of the additional data come to bear in determining how fugitive gas reached specific water wells at specific times. Because site-specific geologic investigations are best approached from the outside in, the materials in this section are presented first from the regional perspective and last from the perspective situation of individual property owners with wells.

Types of Porous Materials

Aquifers are bodies of rock and/or sediment that contain sufficient porosity and permeability to store and transmit groundwater to wells or springs. Groundwater flow in aquifers generally is laterally from high elevation recharge areas to lower elevation discharge areas. The two main aquifers in Geauga County are the Sharon Sandstone and the Berea Sandstone (Figure 3-60).

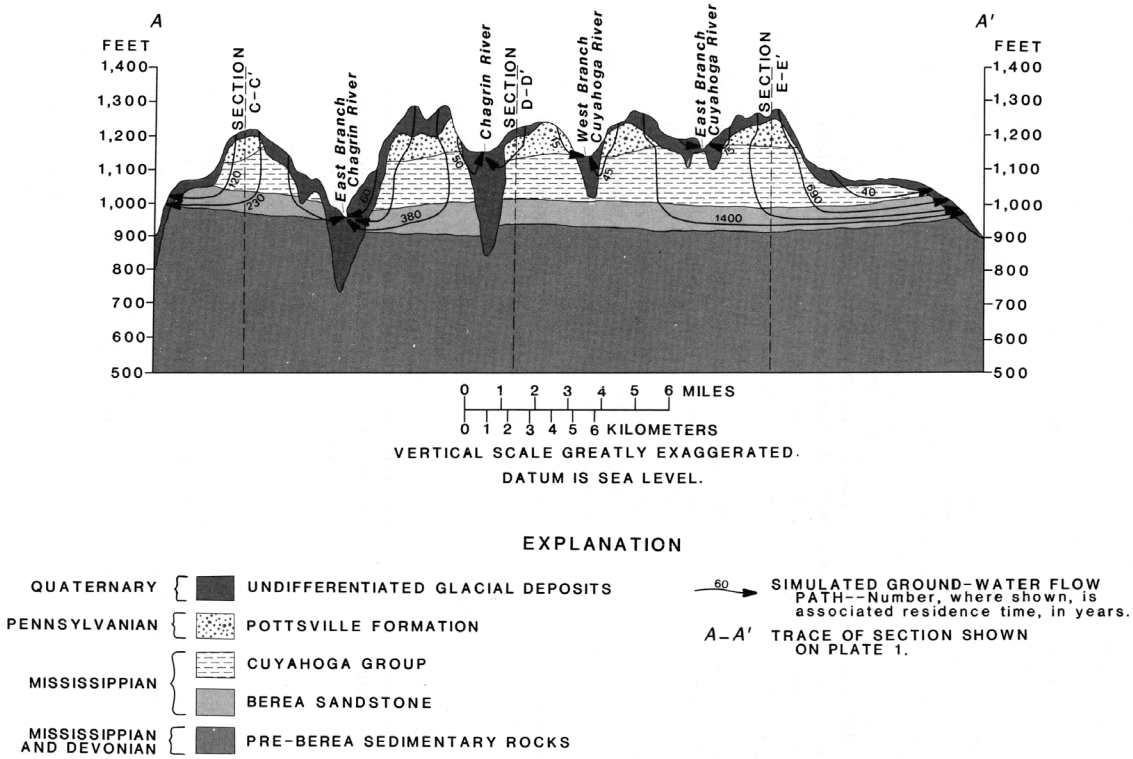

Figure 3-60. Groundwater flow along a west-east cross section parallel to route 422 in Geauga County (modified from Eberts and others, 1990).

Confining layers lack sufficient porosity and permeability to store and transmit groundwater to supply wells and springs. Confining layers impede groundwater flow. On a regional scale, groundwater flow through confining layers is vertical, either downward beneath major recharge areas or upward beneath major discharge areas. Figure 3-60 shows classic patterns of regional groundwater flow in aquifers (Sharon Sandstone and Berea Sandstone) and confining layers (Cuyahoga, Bedford, and Ohio shales) in Geauga County (Eberts and others, 1990).

The migration of gas in a groundwater flow system is controlled by the types of porosity in the aquifers and confining layers. Primary porosity is created as rocks are formed. In sedimentary rocks, it is also called intergranular porosity because it occurs between the grains of sediment. Figure 3-5 shows the large, interconnected primary pores in a local sample of Berea Sandstone where the porosity is 15.7 percent (Table 3-1). Shales, like the Cuyahoga, Bedford, and Ohio shales, possess primary porosity (Figures 3-4 and 3-8) but the pores are microscopic and so poorly interconnected that shales cannot store or transmit groundwater through primary pores.

Fracture porosity, also called secondary porosity, develops in sedimentary rocks after the sediments are compacted into rocks and joints, faults, and dissolution features develop. In permeable rocks like sandstones, fracture porosity augments the primary porosity. In poorly permeable rocks like shales and siltstones, fractures and bedding planes are the only features enabling water, oil, or gas to migrate. Figure 3-61 depicts a block of shale (left) possessing only fracture porosity and a block of sandstone (right) possessing "double porosity," i.e. both primary and secondary porosity (Kruseman and de Ridder, 1990).

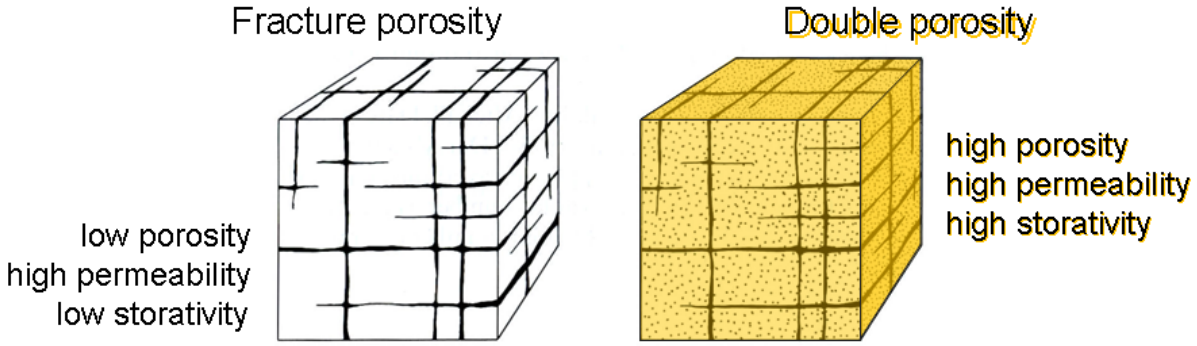

Figure 3-61. Representations of fractured rocks: left – fracture porosity only, right – double porosity (intergranular and fracture) (modified from Kruseman and de Ridder, 2001).

Depending on the width, length, and interconnectedness of fractures, rocks solely possessing fracture porosity can have high permeability even though the volume of pore space is small and the volume of water stored in the fractures is small (Figure 3-61). Fractured rocks lacking primary porosity like the Cuyahoga, Ohio, and Bedford shales in Geauga County, can transmit small quantities of water, oil, or gas but cannot store large quantities. Double porosity rocks possess high values of porosity, permeability, and storativity (Figure 3-61). As a result, rocks like the Sharon and Berea sandstones can transmit water, oil, or gas quickly and can store large quantities of these fluids, especially where the sandstone layers are thick.

Groundwater Flow in Geauga County

The U.S. Geological reports (Eberts and others, 1990; Jagucki and Darner, 2001) characterize the groundwater flow system in Geauga County using geologic maps and groundwater-level

measurements. Figure 3-62 (Jagucki and Darner, 2001) shows that the plan view pattern of groundwater flow in the Sharon Sandstone (labeled Pottsville Formation by the USGS) is radially away from topographically high recharge areas on the major hills and ridges toward topographically low discharge areas along major rivers and streams.

For example, refer to the water-table contours near the red dot in Bainbridge Township on Figure 3-62. At this location, groundwater in the Sharon Sandstone aquifer moves perpendicular to contour lines from the higher water-table elevations (1100 ft) near the red dot to lower water-table elevations (1000 ft) to the north, west, and south along river valleys. This same radial flow pattern can be seen throughout the county where groundwater in the Sharon Sandstone and the overlying glacial deposits flows outward away from upland areas and discharges to lower lying rivers and streams.

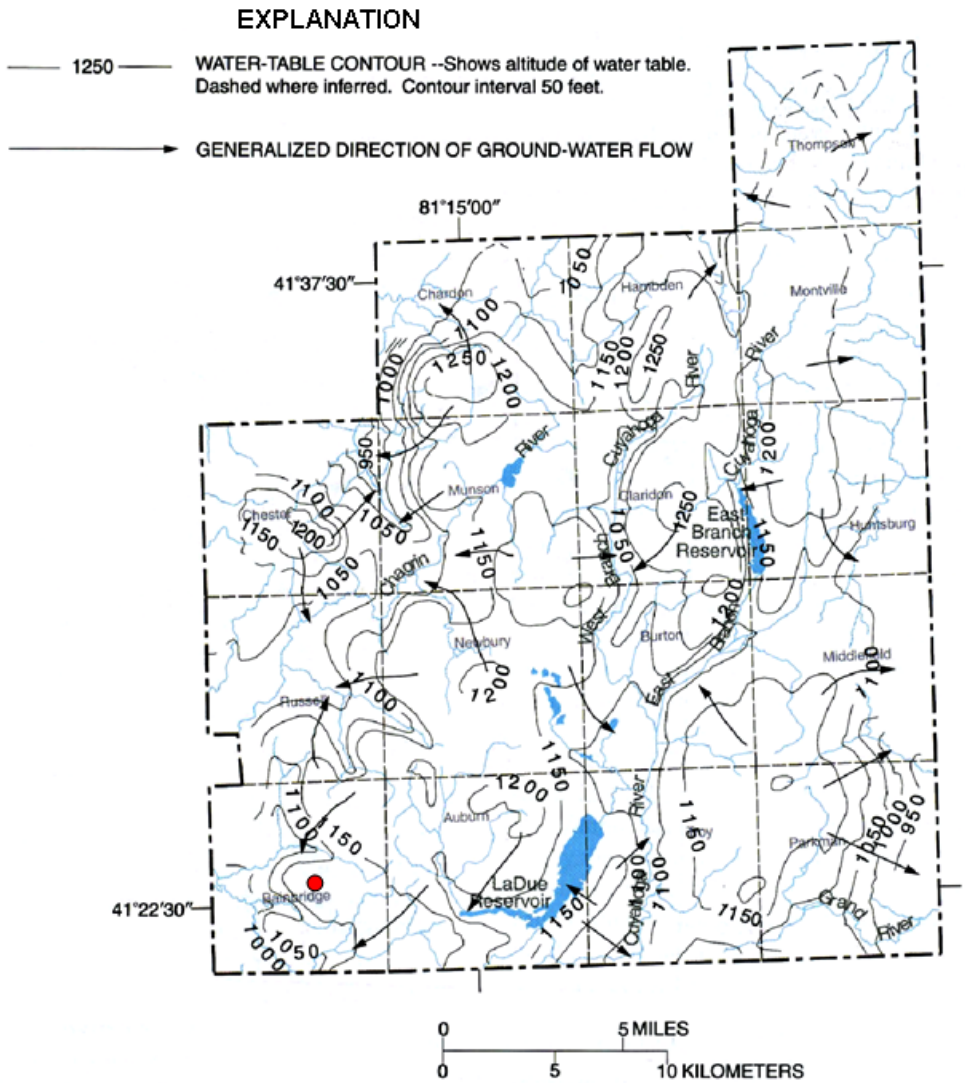

Figure 3-62. Water-table surface measured in wells in the Sharon Sandstone aquifer and glacial deposits in Geauga County, Ohio (modified from Jagucki and Darner, 2001).

Figure 3-63 shows contours of water levels measured in the Berea Sandstone aquifer in Geauga County (Jagucki and Darner, 2001). The arrows indicating groundwater flow directions in the Berea Sandstone aquifer also show a radial pattern of flow away from the elongate

groundwater mound extending from Montville Township to the southwest into Newbury Township. At the red dot on Figure 3-63 in Bainbridge Township, groundwater in the Berea Sandstone flows to the southwest toward the valley of the Aurora Branch of the Chagrin River.

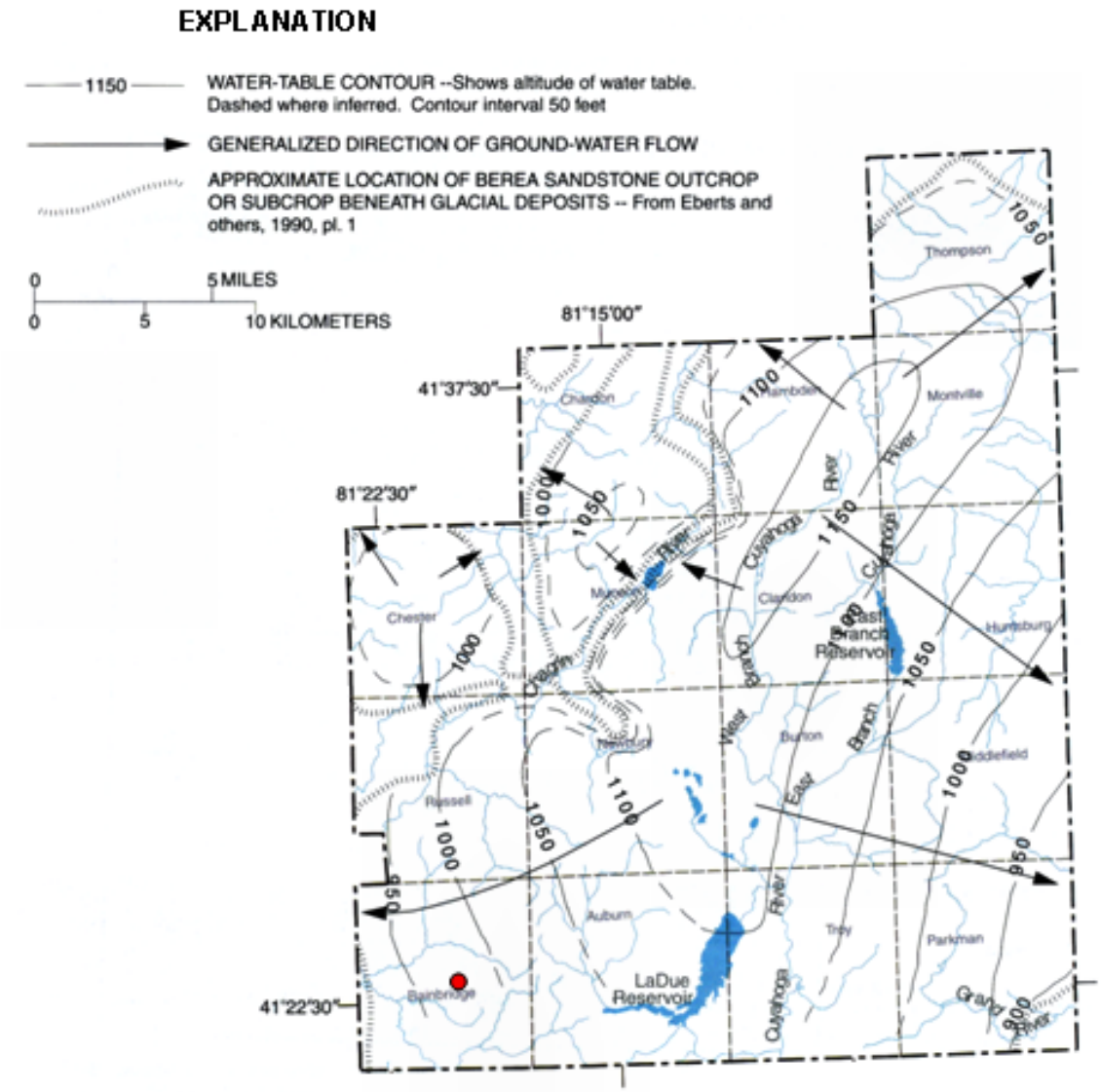

Figure 3-63. Potentiometric surface measured in wells in the Berea Sandstone in Geauga County, Ohio (modified from Jagucki and Darner, 2001).

Figure 3-62 shows that at the red dot, the water level in the Sharon Sandstone is about 1120 feet above sea level, whereas the water level at the red dot in the Berea Sandstone (Figure 3-63) is about 1080 feet above sea level. This indicates that groundwater flow in the Cuyahoga Shale, which lies between the Sharon Sandstone and the Berea Sandstone, is vertically downward from the shallow aquifer (Sharon Sandstone) into the deeper aquifer (Berea Sandstone). The Cuyahoga Shale is a confining layer (Figure 3-60). Because the Cuyahoga Shale lacks intergranular porosity, groundwater moves through it along the vertical joints (Figures 3-47 to 3-52), and in Attachments 5 and 6). Groundwater flow in the deeper Bedford and Ohio shales is largely vertical along similar sets of joints (Table 3-2, Figure 3-6 and 3-7).

1980s Studies of Annulus Overpressurization by S.S. Harrison

In the 1980s, Dr. Samuel Harrison, Department of Geology at Allegheny College in Meadville, Pennsylvania, published two papers in *Ground Water*, a professional journal serving the international community of groundwater scientists and engineers. The papers present his research on the impacts of gas released from overpressured annuli of gas wells in northwestern Pennsylvania (Harrison, 1983, 1985). The geologic setting and impacts in his investigations are strikingly similar to those in Bainbridge Township. Figure 3-64 shows the upward movement of gas in the annulus of an overpressured well and its lateral spreading within an overlying permeable layer, where the gas then develops of an upward pressure gradient.

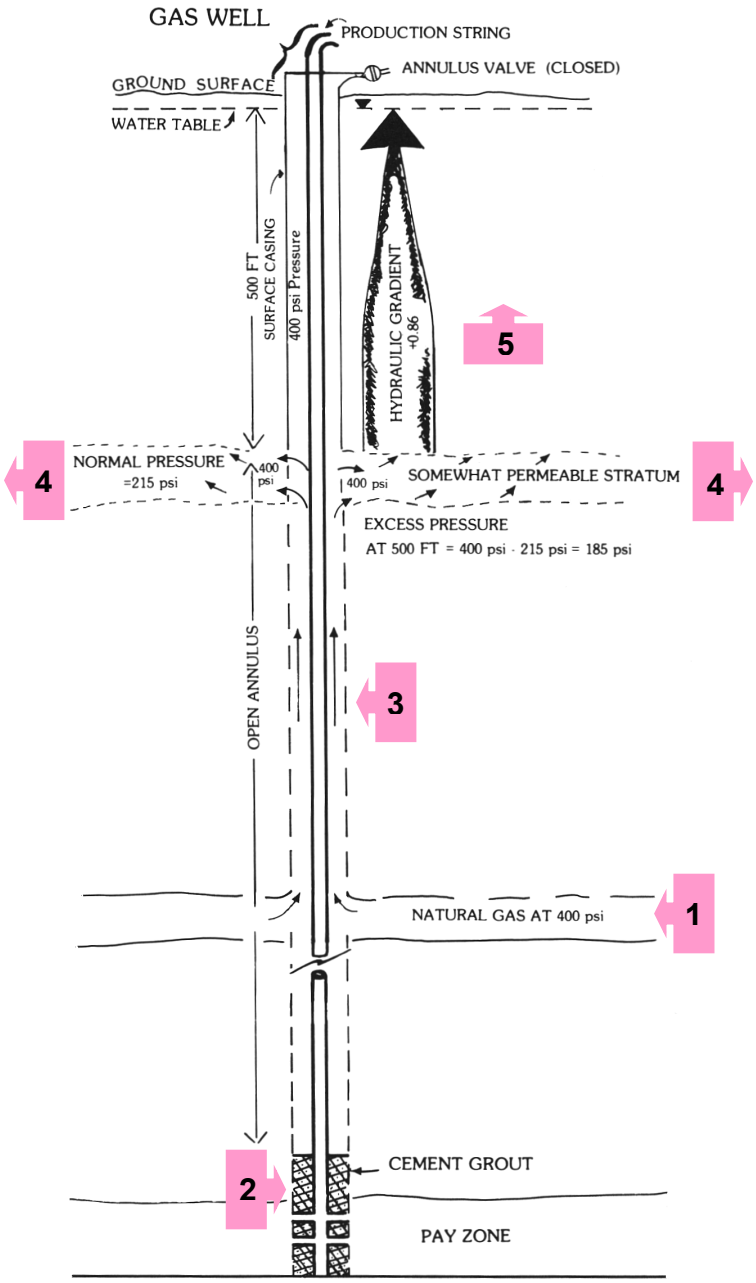

Figure 3-64. An overpressurized annulus creates large pressure gradients enabling groundwater and free gas to move radially outward into more permeable strata (modified from Harrison, 1985).

Harrison's research was concerned with contamination of residential water wells completed in shallow aquifers by the escape of brine and natural gas from the annuli of overpressured gas wells. Figure 3-64 shows how natural gas from a deep gas reservoir [1] or an inadequately cemented pay zone [2], moves up the annular space adjacent to poorly permeable rocks [3], escapes into a shallow, more permeable unit [4] and spreads gas radially around the gas well [4]. Once the gas spreads radially outward in the permeable layer, it migrates upward to the land surface. Pressure gradients, shown in Figure 3-64, cause the gas to migrate to these locations. A key factor causing the contamination of residential wells by natural gas was the wide, radial re-distribution of the gas in the overlying permeable layer. The following statements, listed by topic, were abstracted from Harrison (1983, 1985). The statements are based on observations and interpretations made during his research.

Annulus Overpressuring:

> Novak (1984) reviewed 10 cases of aquifer contamination by gas and oil well operations in northwestern Pennsylvania and found that overpressurization of the well annulus was cited as the cause of contamination in 3 out of 5 incidents [by Pennsylvania DNR] where contaminants had been introduced into aquifers from a subsurface source. In one case, natural gas from an overpressured annulus travelled to household water wells located more than 4000 feet from the gas well. (Harrison, 1985, p. 317)

> In some extreme cases of overpressuring of oil- and gas-well annuli, where the pressure of fluids in the annulus below the surface casing becomes too great, propagation of existing fractures in some strata might occur… Guidelines for Class II injection wells [at that time, not now] provided by the U.S. Environmental Protection Agency (USEPA) indicate that if a fracture gradient of 0.73 psi/ft of depth is exceeded, propagation of existing fractures could occur in some instances (USEPA, 1984)… Referring to a well with a surface casing that extends 500 feet below the water table [Figure 3-64], the hypothetical maximum pressure that should be exerted on that formation to avoid propagation of fractures would be 0.75 psi/ft times 500 feet, or 375 psi. (Harrison, 1985, p. 323)

Gas Contamination Pathways:

> Possible routes of contaminants from the annulus of an oil or gas well to a shallow aquifer are: (1) lateral migration through highly permeable strata and then upward movement through less permeable strata, (2) lateral movement through permeable strata to fractures that can provide a pathway upward, and (3) movement directly into the shallow aquifer where the surface casing of the gas well is of insufficient depth or through a leak in a surface casing. (Harrison, 1983, p. 690).

Sediment and Turbidity in Residential Wells:

> Shortly after drilling and hydro-fracturing a gas well, household-water wells located at the base of the valley wall became turbid. Natural gas was being drawn into the alluvial wells and the 'boiling' action that resulted, as gas bubbles floated up through the casing, dislodged sediment at the bottom of the well and from the casing, resulting in the turbidity. (Harrison, 1983, p. 697)

> Several household water wells became contaminated with natural gas several months after a nearby gas well was drilled and hydro-fractured. The bubbling of the natural gas in the water wells resulted in turbidity and the buildup of gas was sufficient that some homeowners reported hearing explosions in their pump houses. In one instance a pump house door was blown off and in another instance a homeowner demonstrated the presence of gas in her well by igniting the water as it discharged from her garden hose. (Harrison, 1983, p. 698)

The statements made by Harrison (1983, 1985) and his insights into the mechanisms causing contamination of shallow residential wells by overpressuring the annuli of gas wells are applicable to subsurface gas invasions in Bainbridge Township.

Pressure Buildup and Propagation from the English #1 Gas Well

Overpressurization of the annulus in the English #1 gas well occurred for 31 days before the explosion at the Payne home (17975 English Dr), from late on November 16 to early on December 15, 2007 (Table 1-1). It is during this period that the subsurface pressure gradients described by Harrison (1983, 1985) were established in the investigation area, where the Ohio and Bedford shales act as the poorly permeable layer above the pay zone [3] and the Berea Sandstone acts as the shallow, overlying more permeable stratum [4], see Figure 3-64.

There are more similarities between what was observed in the investigation area in Bainbridge and what was observed in northwestern Pennsylvania (Harrison, 1983, 1985). On December 11, 2007, the water discharging from the Payne's spigots turned cloudy (turbid); probably in response to the advancing pressure front loosening sediment at the bottom of (new) well and along the borehole walls, as also observed by Harrison (1983, 1985). On December 12, 2007, the well at the police station on Bainbridge Road was reported to have more gas in it than normal (Table 3-1, Appendix H). On December 14, 2007, several residents on English and Scotland drives complained of natural gas in their well water (Table 3-1). And, in the early morning on December 15, 2007, at nearly the same time as the explosion at the Payne home, water in the Jordan well (17990 English Dr) rose 15 to 18 feet above the land surface for several hours in a display of pressure release much like that of an erupting geyser in Yellowstone National Park (Figure 3-65). The additional fluid pressure needed to drive groundwater in the Berea Sandstone this high is about 7.8 psi.

Figure 3-65. Jordan well (17990 English Dr) showing level above land surface to which groundwater reached on December 15, 2007.

These anecdotes manifest the build-up of fluid pressure in the Berea Sandstone from the escape of pressurized gas in the annular space of the English #1 well, as described by Harrison (1985) more than 20 years earlier (Figure 3-64). The similarities between what occurred in Bainbridge Township in November and December 2007, and what occurred in northwestern Pennsylvania in the 1980s are even more striking because the Payne, Jordan, and police station wells are all completed in the same overlying permeable unit, Berea Sandstone (Appendix B), which his analogous to the descriptions and diagrams in Harrison (1983, 1985).

Due to differences in the porosity and permeability between the Berea Sandstone (double porosity) and the underlying Ohio and Bedford shales (fracture porosity), the build-up and propagation of pressure through these two types of rock are different. Figure 3-66 conceptually shows the dominant sets of fractures in the Berea Sandstone around the English #1 Gas Well. The two prominent joint sets shown on Figure 3-66 are based on the dominant joint bearings measured in the Geauga County area (N 55° E and N 55° W), described earlier (Figure 3-25). If the joint spacing on Figure 3-66 conceptually represents that in the Berea Sandstone, then the joint spacing in the more brittle Ohio Shale will be denser (i.e. adjacent joints will be closer).

Figure 3-66. Representation of dominant sets of (natural) joint bearings in the Berea Sandstone based measurements in northeastern Ohio.

Computing temporal and spatial changes in fluid pressures from a producing oil or gas well is a common topic in petroleum engineering textbooks. Equation (1) describes the change in pressure (Δp) at any time (t), at any radial distance (r) from a well producing oil or gas at a constant rate (Q) (Matthews and Russell, 1967; Warner and Lehr, 1977). Equation (1) is used to compute pressure gradients and the propagation of pressures through time.

$$\Delta p = \frac{162.6 Q \mu}{kb}\left[\log \frac{kt}{\phi \mu c r^2} - 3.23\right] \qquad (1)$$

where Δp = change is fluid pressure (psi),
Q = production rate (barrels per day),
μ = viscosity (centipoise),
k = reservoir permeability (millidarcies),
b = reservoir thickness (feet),
t = time (hours),
Φ = reservoir porosity (decimal),
c = reservoir compressibility (1/psi), and
r = radial distance to point of interest (feet)

Although equation (1) looks menacing, it is high school algebra with a few long forgotten Greek letters representing variables. The equation assumes the reservoir is isotropic, homogeneous, flat lying, and infinite; gas is released immediately from storage in pores; the reservoir is overlain and underlain by non-permeable rocks; and the well produces at a constant rate, is open across the entire reservoir thickness, and there is no gas stored in the production casing. By examining the terms in equation (1), one sees that Δp is directly proportional to Q. This makes sense; the more gas that builds up inside the annulus, the larger the pressure change. One also sees that Δp is inversely proportional to k and Φ, such that smaller permeability and the porosity values yield larger values of fluid pressure at a specified distance.

Figure 3-67 conceptually shows pressure changes in poorly permeable rock, like the Ohio Shale, around the overpressurized surface-production casing annulus in the English #1 well. The yellow lines represent contours of the percentage change in fluid pressure relative to the total fluid pressure in the overpressurized annulus (100 percent). The resulting pressure gradient is steep, meaning that a large change in pressure (40 to 20 percent) occurs in a short distance.

Figure 3-67. Conceptual changes in the pressure distribution in the Ohio Shale several weeks after the annulus in the English #1 well was shut in.

Because the Ohio Shale has low porosity, low storativity, and low permeability, which is consistent with rocks having only fracture porosity (Figure 3-61), changes in fluid pressures in the annulus of the English #1 well will not propagate very far from the overpressurized wellbore in this amount of time. This assessment assumes that the network of closely-spaced natural fractures in the Ohio Shale acts like an equivalent porous medium, which is a reasonable assumption at the scale of the diagram.

In contrast, Figure 3-68 conceptually shows fluid pressure changes in permeable rock, like the Berea Sandstone, around the overpressurized annulus in the English #1 well. In this case, the pressure gradient is flat, meaning that a large change in pressure (40 to 20 percent) occurs over a large distance. Because the Berea Sandstone is a double porosity medium, it stores more fluid and is much more porous and permeable than the Ohio Shale. As a result, changes in fluid pressure in the annulus of the English #1 well will propagate a much greater distance from the overpressurized wellbore, compared to the Ohio Shale (Figure 3-66), in the same amount of time.

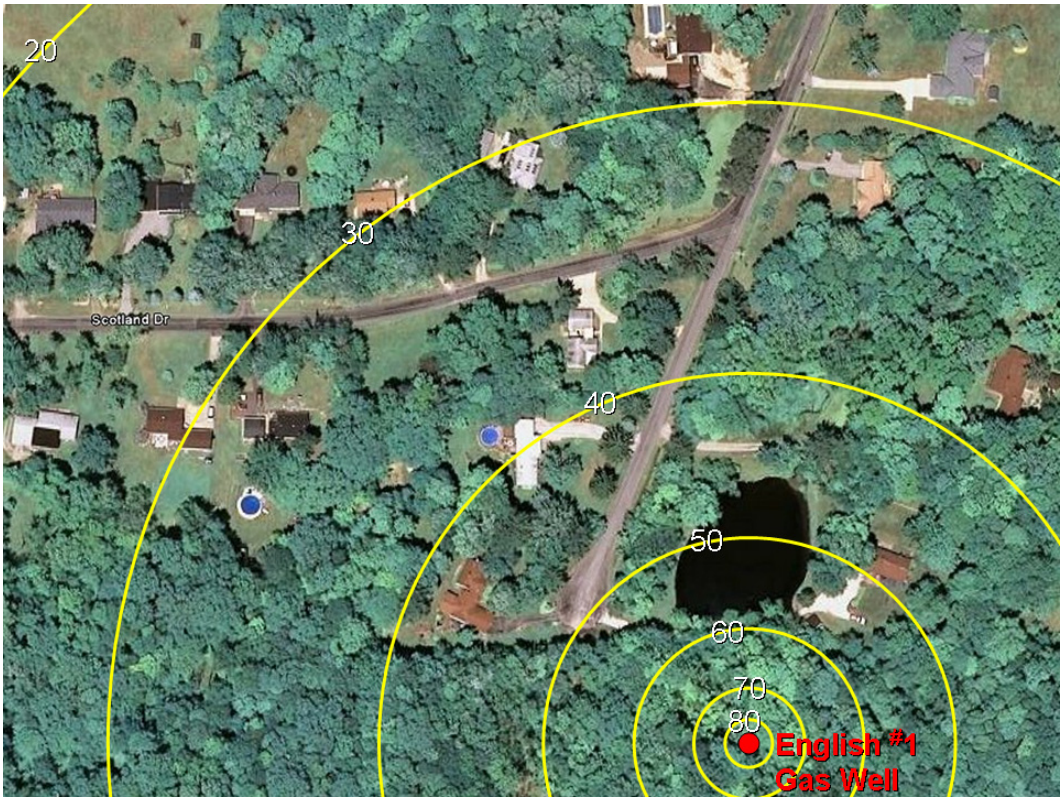

Figure 3-68. Conceptual changes in the pressure distribution in the Berea Sandstone several weeks after the annulus in the English #1 well was shut in.

Using the site-specific data requested of DMRM, equation (1) was used to estimate temporal and spatial changes in fluid pressures in the Berea Sandstone and in the Ohio Shale. The estimates of pressure change in the Berea Sandstone can be benchmarked using anecdotal evidence reported by residents, such as the presence of turbidity or gas in well water and the occurrence of flowing artesian (geyser-like) condition in the Jordan well. The purpose of these calculations is not to determine "spot on" values of pertinent parameters; rather, it is to (1) demonstrate that fluid pressure changes, which in large part control the migration of natural gas, follow the principles and laws of physics, and (2) to show that observations made by

Harrison (1983, 1985) in northwestern Pennsylvania and by residents in Bainbridge Township demonstrate the applicability of these principles and laws. Thus, these calculations are for elucidating the big picture, not for examining fine details.

Figure 3-69 is from an EXCEL spreadsheet used to estimate changes in fluid pressure in the Berea Sandstone at several distances from the English #1 well. The values of parameters on the right side of equation (1) either were measured by Weatherford Labs (k and Φ) or obtained from tabulated values in the professional literature (μ, b, c). The two the remaining variables (t and r) were assigned values relevant to the problem, such as setting t equal to 31 days and setting r equal to distances similar to the distances that residential water wells completed in the Berea Sandstone are from the English #1 gas well.

Knowing that the distance from the Jordan well to the English #1 well is 958 feet and that the fluid pressure in the Jordan well was about 7.8 psi above normal on December 15, 2007, one can estimate fluid pressure changes in the Berea Sandstone after 31 days of overpressurization. Figure 3-69 shows these calculations, which are conservative and actually overestimate the amount of pressure change because equation (1) assumes a constant outflow of gas from the annulus of the English #1 well.

Parameters & Variables		Values Used for Jordan Well				
Δp =	change in reservoir pressure (psi)	Δp =	7.8	psi		
Q =	injection rate (bbls/day)	Q =	11.4	gpm =	390.9	bbls/d
k =	intrinsic permeability (millidarcies)	k =	351	md		
μ =	viscosity (centipoise)	μ =	1.0	cp		
b =	reservoir thickness (feet)	b =	50	ft		
Φ =	reservoir porosity (decimal)	Φ =	0.157			
t =	time (hours)	t =	744	hrs =	31	days
r =	radial distance to point of interest (feet)	r =	variable	feet		
c =	reservoir compressibility (1/psi)	c =	7.50E-06	1/psi		

Δp in Jordan well	
Observed	Calculated
7.8	7.8

r	Δp
10	22.1
150	13.6
500	9.8
958	7.8
1500	6.4
2000	5.5
2500	4.8
3000	4.2
4000	3.3

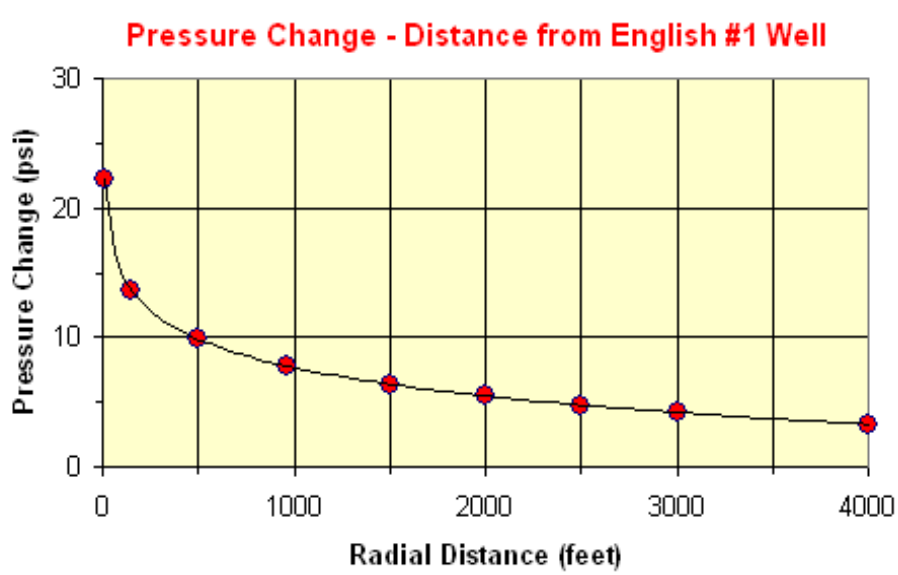

Figure 3-69. Estimated pressure increases in the Berea Sandstone at various radial distances from the English #1 well 31 days after the annulus was shut in.

The correspondence between observed and estimated values of pressure change at the Jordan well (blue field, left side) on December 15th (day 31) gives credence to the estimates of fluid pressure change at other distances. For example, the public water-supply well at the police station is 3890 feet from the English #1 well. The estimated pressure increase at that distance is about 3.4 psi (Figure 3-69).

These progressive changes in fluid pressure in the Berea Sandstone explain why water in several residential wells turned cloudy and turbid at different times, why water filters became dirty after the explosion at the Payne home, and why more gas was reported in police station well the day before the explosion. Harrison (1983, 1985) reported similar changes in the turbidity of well waters and the increased presence of gas as changes in fluid pressure from overpressured annuli of gas wells in northwestern Pennsylvania loosened sediment on borehole walls, caused sediment burps at the bottom of wells, and dislodged gas bubbles into wellbores that were perched in nearby bedding planes and joints.

Equation (1) also can be used to examine changes in fluid pressure over time at a specific location. Figure 3-70 shows the values of parameters and variables used to calculate temporal changes in fluid pressure in the Berea Sandstone at the Jordan well (17990 English Dr).

Parameters & Variabes		Values Used in for Jordan Well				
Δp =	change in reservoir pressure (psi)	Δp =	7.8	psi		
Q =	injection rate (bbls/day)	Q =	11.6	gpm =	397.7	= bbls/d
k =	intrinsic permeability (millidarcies)	k =	351	md		
μ =	viscosity (centipoise)	μ =	1.0	cp		
b =	reservoir thickness (feet)	b =	50	ft		
Φ =	reservoir porosity (decimal)	Φ =	0.157			
t =	time (hours)	t =	variable	hours		
r =	radial distance to point of interest (feet)	r =	958	feet		
c =	reservoir compressibility (1/psi)	c =	7.50E-06	1/psi		

Δp in Jordan well	
Observed	Calculated
7.8	6.8

t	Δp
12	1.3
48	3.5
96	4.7
168	5.6
264	6.3
360	6.8
456	7.2
576	7.5
696	7.8

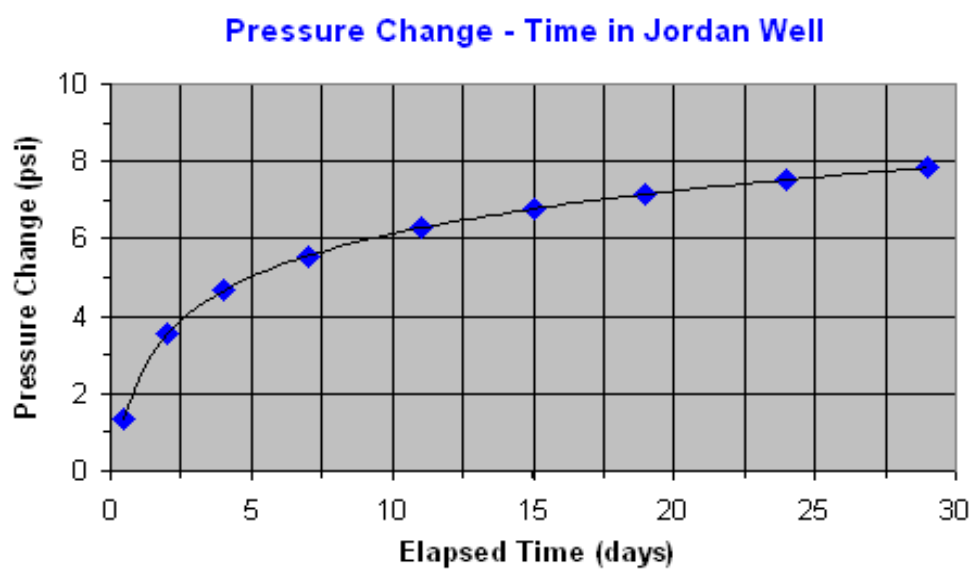

Figure 3-70. Estimated pressure increases in the Berea Sandstone at the Jordan well for various times after the English #1 well annulus was shut in.

Estimated fluid pressure versus time graphs similar to Figure 3-70 can be made at the location of any water well in the investigation area that is uncased (open) in the Berea Sandstone. Equation (1) cannot be used to make similar estimates for shallower water wells that obtain water from the Cuyahoga Shale. Figure 3-71 shows the results of these calculations for the radial distances from of the English #1 well from the Jordan, McGee, and police station wells, which are all uncased in the Berea Sandstone. Two important relationships relating how fluid pressures changes at different locations in the Berea Sandstone are seen in this graph.

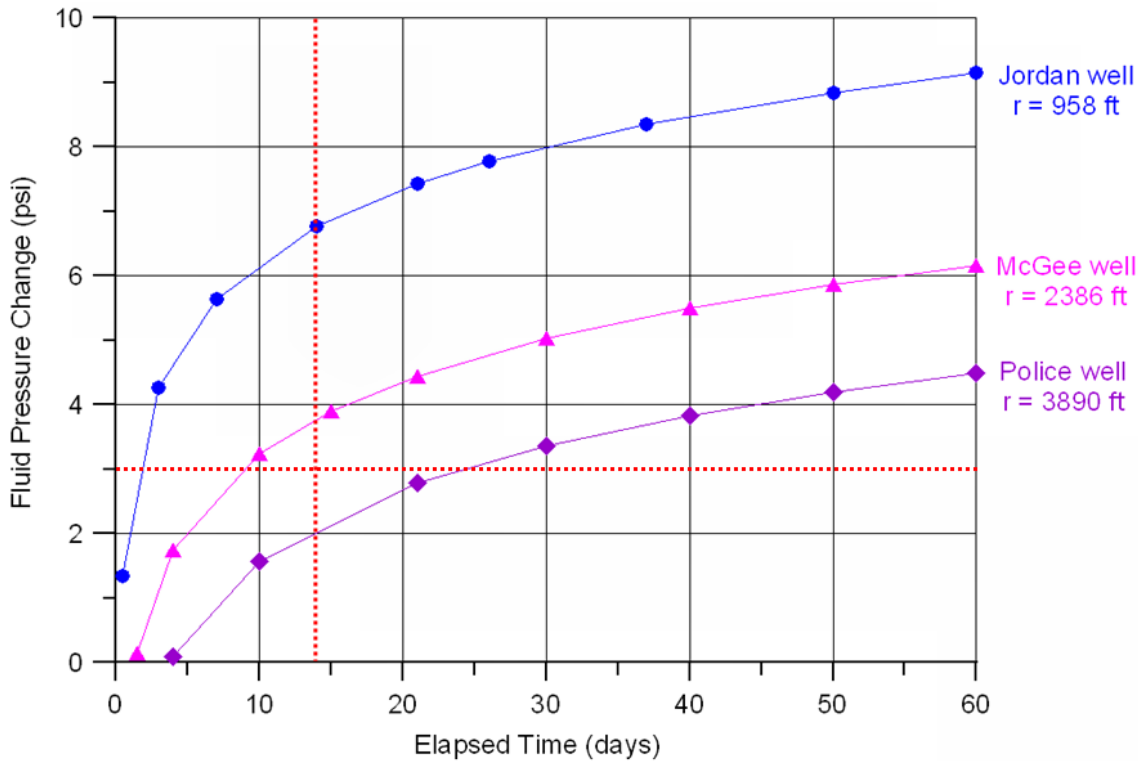

Figure 3-71. Estimated pressure increases versus time after the English #1 well was shut in, computed at the distances of three water wells completed in the Berea Sandstone.

The first general relationship can be stated as: the closer a water well completed in the Berea Sandstone is to the English #1 well, the larger will be its rate of pressure increase. Using the vertical red line on Figure 3-71 as a guide, the estimated pressure change in the police station, McGee, and Jordan wells 14 days after the English #1 well is shut-in are 2.0, 3.7, and 6.8 psi, respectively.

The second general relationship can be stated as: the farther a water well completed in the Berea Sandstone is from the English #1 well, the longer it will take for a specific change in fluid pressure to reach that well. Using the horizontal red line on Figure 3-71 as a guide, a 3.0 psi pressure change occurs after 2.5 days in the Jordan well, but takes about 9 days to occur in the McGee well and nearly 25 days to occur in the police station well.

Now, suppose it takes a pressure change of 5 psi to cause the accumulated sediment and rust particles at the bottom of a well to burp and cause the well to temporarily become turbid. The differences in the dates that well owners noted cloudiness in their well water or the presence of more natural gas than normal is explained by these relationships (Table 1-1). Fluid pressure changes in shallower wells in the investigation area that are completed in the Cuyahoga Shale

also conform to the principles and laws of physics. These wells also may experience periods of increased water turbidity or increased natural gas content, but estimating the timing and magnitude of pressure changes in these wells cannot be done realistically with equation (1).

In reality, the fluid pressure in the Berea Sandstone immediately above the surface-production casing shoe in the English #1 well was not constant as assumed in the calculated fluid pressure changes in Figures 3-69, 3-70, and 3-71. As listed in Table 1-1, between November 17 and December 12, 2007, the pressure build-up inside the English #1 well annulus was blown down (released to the atmosphere) several times. As a result, the assumed constant fluid pressure applied to the Berea Sandstone adjacent the surface casing in the English #1 well actually included several pressure pulses. So, in reality, there were several episodes of fluid pressure rise and decline that produced pressure waves in the Berea Sandstone. Each one of these pulses could cause the increased turbidity described by Harrison (1983, 1985) and observed by residents in the investigation area.

This is not the only place in the report where turbidity issues are addressed. Turbidity is also addressed in an upcoming section in this chapter dealing with the "black goo" found in several water wells inside and outside the investigation area.

The estimated changes in fluid pressure shown in Figures 3-69, 3-70, and 3-71 are based on the laws of physics that govern the propagation of pressure. Similar laws govern the flow of heat, fluids, and electricity. From a computational viewpoint, the calculated fluid pressures in these figures are not unique. Slightly different combinations in the values of k, Φ, and Q could yield similar results. From a scientific viewpoint, however, it is important that the values used in equation (1) reproduced the approximate pressure increase observed in the Jordan well on December 15, 2007. The ability of equation (1) to reproduce an observed state of the physical system using pertinent parameter values gives credibility to the technical approach. It is a hypothesis test demonstrating that the technical approach works for wells completed in the Berea Sandstone.

Groundwater Flow in the Investigation area

Because gas and water are both fluids, they often travel the same pathways through a porous medium even though they don't travel them in the same direction or the same rate. As such, insights gained about the movement of groundwater in the investigation area and can be useful to the investigation of gas migration.

Figure 3-72 depicts the groundwater flow system on a north-south cross section along English Drive. Locally, the Sharon and Berea sandstones are double porosity aquifers and the Cuyahoga and Bedford shales are confining layers with only fracture porosity. Figures 3-62 and 3-63 show that the directions of groundwater flow in both the Sharon Sandstone and the Berea Sandstone in the impacted are laterally to the southeast, which is to the right on Figure 3-72. As depicted on Figures 3-57 and 3-58 (Attachments 5 and 6), water levels in the Sharon Sandstone are higher than water levels in the underlying Berea Sandstone. This is portrayed on Figure 3-72 by the dashed yellow and red lines. The difference in water levels in these two aquifers results in vertically downward groundwater flow in the Cuyahoga Shale (Figure 3-72), which is also shown in plan view on Figures 3-62 and 3-63.

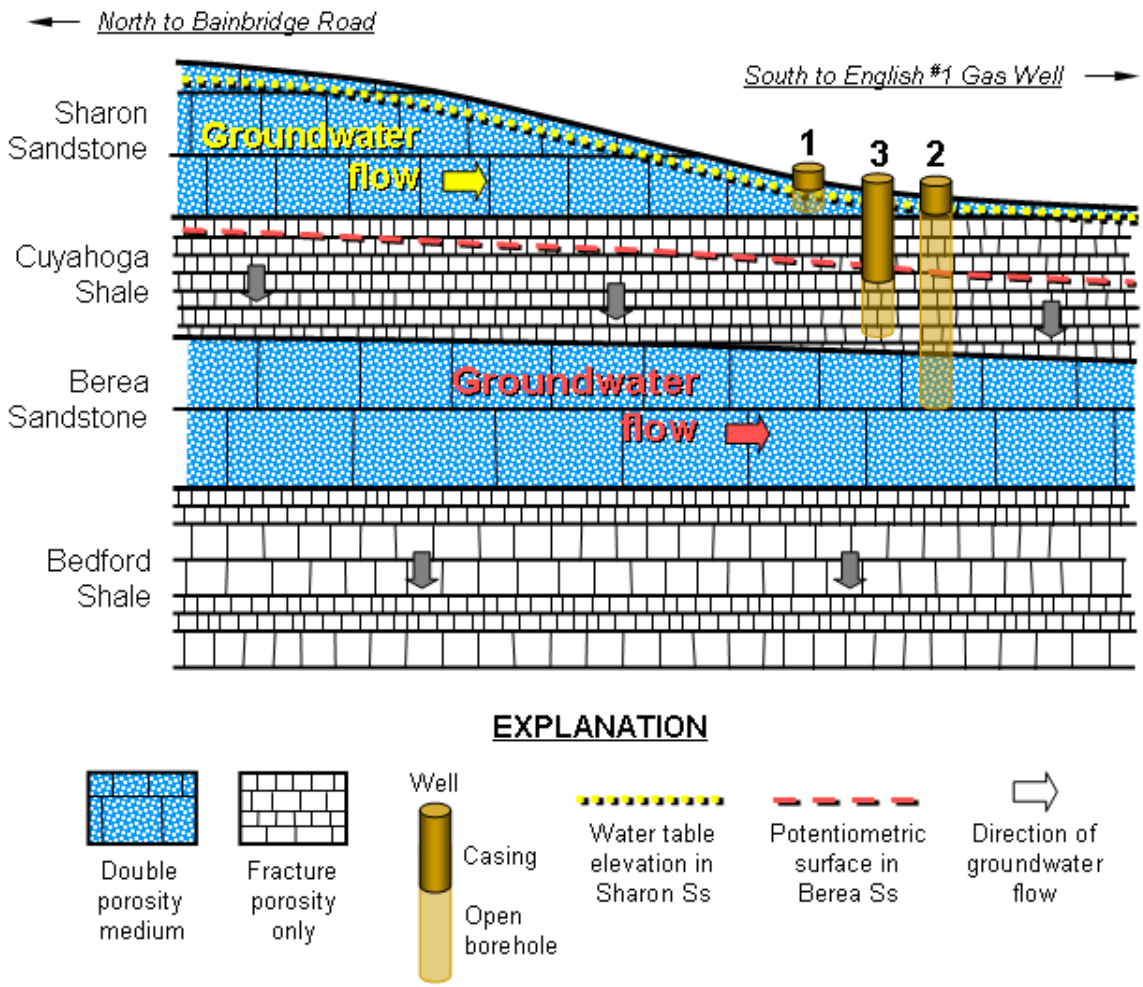

Figure 3-72. Groundwater flow system in the area of the subsurface gas invasions in Bainbridge Township.

Figure 3-72 portrays the depths of most of the residential water wells in the area, the common casing lengths, and the common lengths of uncased (open) borehole. For example, water wells completed in the Sharon Sandstone (labeled well 1) are shallow, have short casings, and little uncased borehole to store water or for water to enter the well, all of which produces an adequate well because of the high porosity and permeability of the Sharon Sandstone. These wells, however, are subject to poor yield during droughts when water levels in the aquifer decline 10 or more feet.

Wells completed in the Cuyahoga Shale (well 2) obtain water solely from joints and bedding planes that intersect the uncased portion of the borehole. Typically, wells completed in shales, which only have fracture porosity, need to rely on borehole storage (i.e. a deep borehole) to provide a stable supply of water because shale does not quickly replenish water pumped from the borehole. As a result, these wells often need to be deepened or to have the pump lowered to supply an adequate amount of water in dry years or when water demands are large.

Water wells completed in the Berea Sandstone (well 3) commonly are also uncased through the lower portion of the Cuyahoga Shale. These are usually the most productive and most reliable wells in the area because of they have a large amount of casing storage, are uncased in the

highly porous and permeable Berea Sandstone, and because the Berea Sandstone is a confined aquifer in the local area and is not as susceptible to droughts as the overlying Sharon Sandstone.

Figure 3-73 shows several sets of vertical joints in the Sharon Sandstone at an outcrop south of Bainbridge Road near its intersection with Millbrook Drive. Figure 3-74 shows the water table in the Sharon Sandstone in one of the numerous pits in the area dug for mining aggregate.

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Figure 3-73. Sharon Sandstone outcrop just south of Bainbridge Road at Millbrook Drive showing several sets of vertical joints.

Figure 3-74. Water table seen in a former aggregate pit dug in the Sharon Sandstone just west of 17938 English Drive and north of 7619 Scotland Drive.

As in most unconfined aquifers, the water table in the Sharon Sandstone rises and falls seasonally with changes in precipitation, evaporation, transpiration, and well pumpage. Increases in the height of the water table most commonly occur in the spring following snow melt, when infiltration of rainfall is great, and evaporation and transpiration are low. This often can be observed in shallow wells, especially those with inadequate casing sticking up above the land surface, when groundwater flows over the top of the casing, as seen this past spring (2010) in the Cooper well at 17974 English Drive (Figure 3-75). This exemplifies the typical seasonal increase in fluid pressure in wells (well 1 in Figure 3-72) completed in unconfined aquifers like the Sharon Sandstone. It is important for this investigation to recognize that this pressure increase is not caused by the same process that increased fluid pressures in the Berea Sandstone in late 2007 and caused groundwater to spurt 15 to 18 feet above the top of the Jordan well.

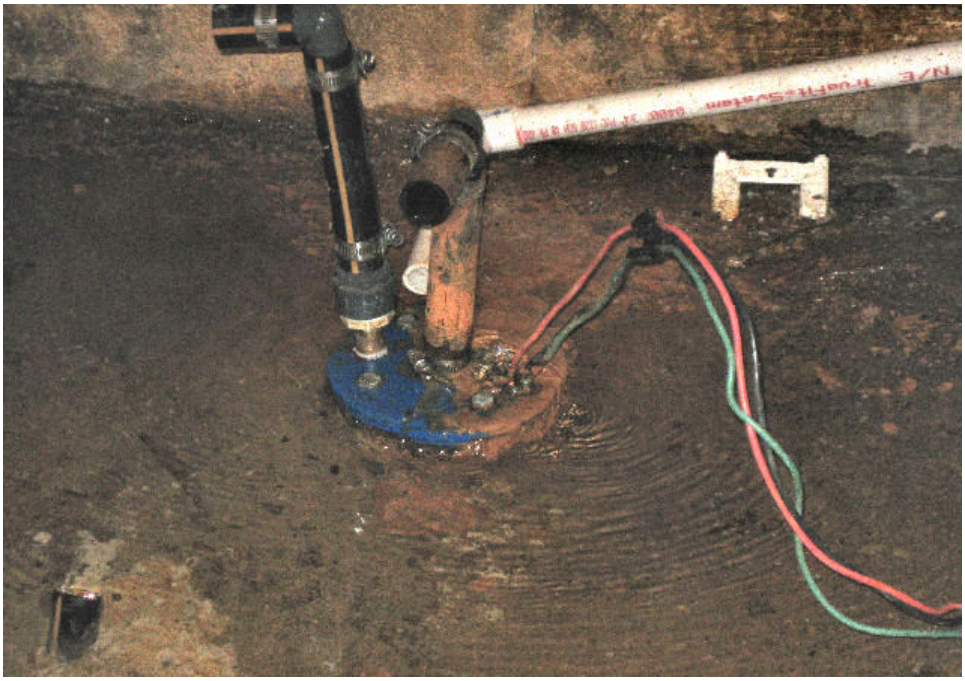

Figure 3-75. Groundwater in the Sharon Sandstone flowing above the land surface (garage floor) in Cooper well (17974 English Dr), March 2010.

Figure 71 also shows that groundwater flow in the Sharon and Berea sandstones is lateral to lower water-level elevations at the bottom of English Drive. This general direction of groundwater flow can change when one or more residential wells completed in the either sandstone creates a local cone of depression in the water table surface in Sharon Sandstone or in the potentiometric surface in the Berea Sandstone.

Groundwater flow in the Cuyahoga Shale and in the Bedford and Ohio shales is vertically downward from the higher water levels in the Sharon Sandstone to the lower water levels in the Berea Sandstone and to the even lower water levels near the major streams and rivers in the area. The vertical flow of groundwater is these confining shale layers is solely along vertical joints and bedding planes (Figures 3-47 to 3-52) in a stair-step fashion because little intergranular porosity exists in shales. Gas migration in these confining layers is also vertical and limited to the same pathways along joints and bedding planes as groundwater, except gas moves in a step-wise upward direction because of its buoyancy in water.

Gas Migration in Media with only Fracture Porosity

The step-wise upward migration of natural gas along joints and bedding planes in shales can be visualized in Figures 3-47 to 3-52 with the concepts presented in the following four diagrams. Figure 3-76 incorporates the concept of flow in channels within fracture planes demonstrated by Rasmusson and Neretnieks (1996). In their research on flow of radionuclides along fractures, they recognized that fractures (joints) contain interconnected open spaces (channels), dead end open spaces, and places where no porosity exists because opposing sides of a joint contact each other. Free gas can migrate upward only along the portion of a joint containing channels. If a channel intersects a bedding plane, gas can migrate laterally along the bedding plane until it reaches another joint with a channel that intersects the bedding plane (Figure 3-76). Because of its buoyancy in water and the lack of intergranular pore space in shale, gas in the Ohio, Bedford, and Cuyahoga shales only migrates upward in channels along joints.

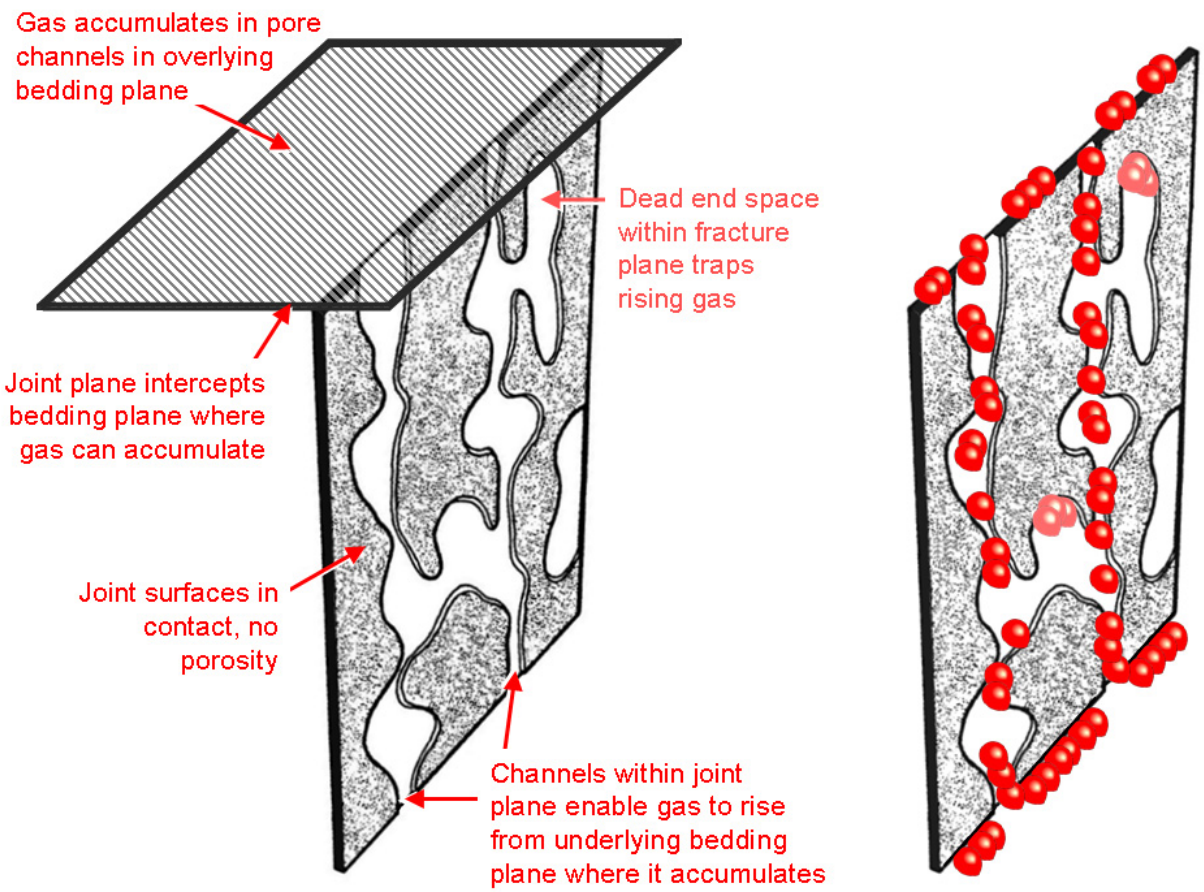

Figure 3-76. Potential paths of gas migration and groundwater flow along a vertical joint in shale (modified from Rasmusson and Neretieks, 1996).

The same terminology is used to characterize the space along bedding planes in shale, where gas and water can only move within interconnected channels (Figure 3-77). Because the bedding planes are overlain by shale lacking intergranular porosity, gas can accumulate along bedding planes until a change in fluid pressure causes the gas to move laterally and then escape upward into a channel in an intersecting vertical joint. This step-wise migration of gas in fractured media is slow but persistent.

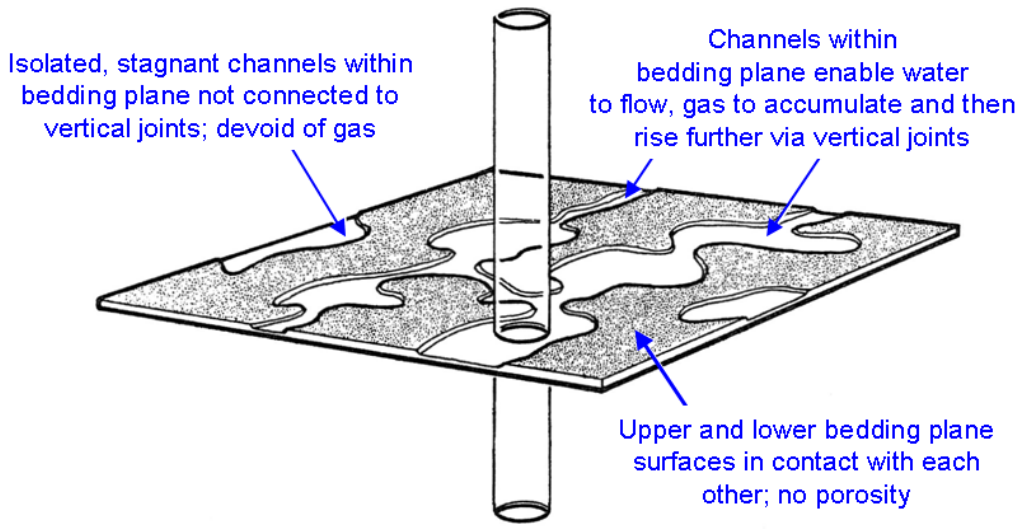

Figure 3-77. Potential migration paths for gas and groundwater along a bedding plane (modified from Rasmusson and Neretieks, 1996).

As seen on Figure 3-78, these concepts explain how multiple gas source zones occur and how the entire thickness of accumulated gas slowly migrates upward to eventually escape into wells, joints, outcrops, and soil. This results in the total mass of gas slowly diminishing over time.

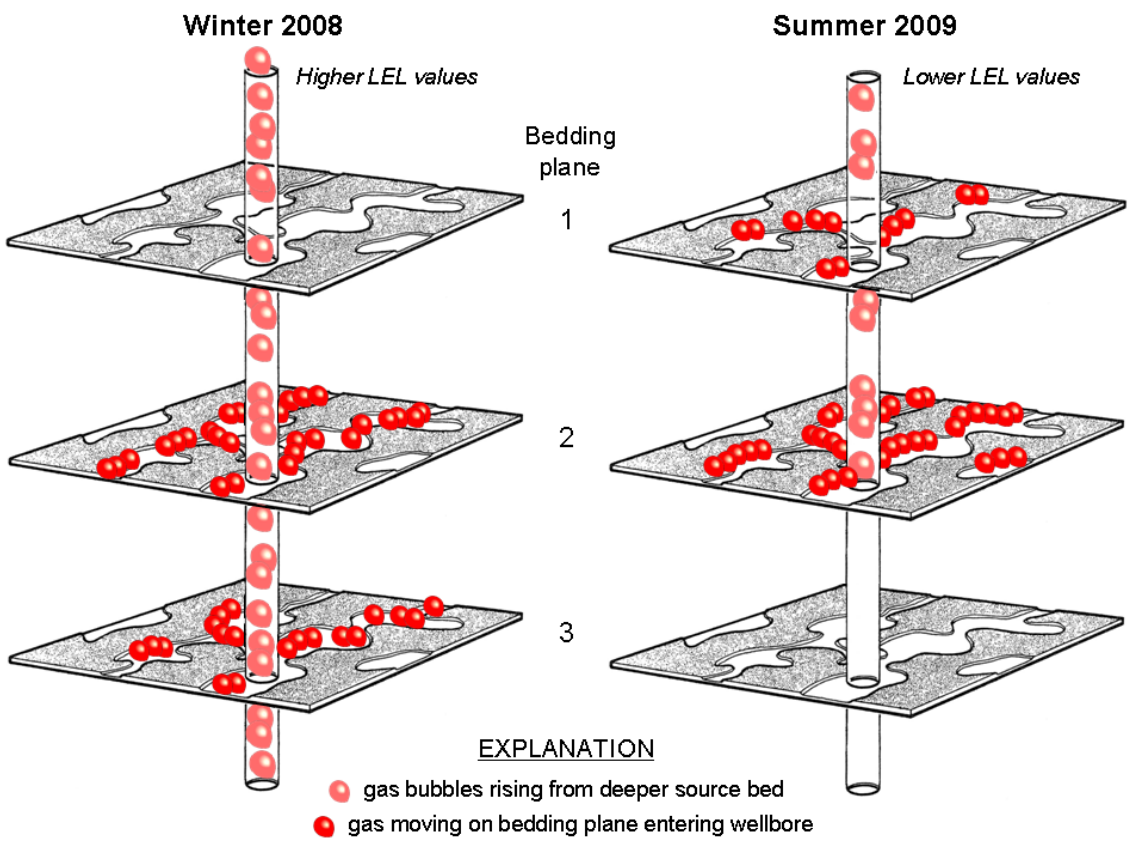

Figure 3-78. Gas migrating along bedding plane channels that intersect a well (joints connecting bedding planes not shown) (modified from Rasmusson and Neretieks, 1996).

The concepts shown on Figures 3-76, 3-77, and 3-78 were observed in several borehole videos taken in the winter of 2008. In these videos gas bubbles entered wellbores from channels in one or more bedding planes (e.g. bedding planes 2 and 3 on Figure 3-78, left side) and from deeper bedding planes. This indicated that the bottom of the fugitive gas zone was below the depth of bedding plane 3 (Figure 3-78) at this time. The right side of Figure 3-78 portrays changes in the vertical distribution gas observed in the borehole videos taken in 2009, 15 to 18 months later. If no gas rises from below to replenish the gas escaping from the top of the fugitive gas zone, the deepest gas source moves upward from bedding plane 3 to bedding plane 2 (Figure 3-78). This is exactly what was observed in the summer of 2009 in the videos taken in the Jordan and de Gaetano wells. It also was observed over a shorter time span in the borehole videos taken in the Buddenhagen in May and December 2009, and in the borehole videos taken in the Adams well in May 2009 and April 2010.

Table 3-4, a subset of the data in Table 3-3, specifically lists only those water wells in which two or more borehole videos were taken, so comparisons can be made between the observed depths of the deepest gas source zones at different times.

Table 3-4. Changes in the Depth of the Bottom Gas Source Zone Between 2008 and 2010

Owner	Address	Date, Borehole Video	Depth to Deepest Gas Source (ft)	Geologic Unit	Change in Bottom of Gas Zone (ft)
Adams	17820 English Dr	14-May-09	> 277	≥ Berea Ss	
		1-Apr-10	153	Cuyahoga Sh	**> 124 up**
Buddenhagen*	7897 Scotland Dr	14-May-09	> 90	Cuyahoga Sh	
		1-Dec-09	90	Cuyahoga Sh	**> 0 up***
Calo	17969 Kingswood Dr	1-Jan-08	113	Cuyahoga Sh	
		15-Oct-09	114	Cuyahoga Sh	**negligible**
de Gaetano	17971 Kingswood Dr	17-Mar-08	164	Berea Ss	
		2-Sep-09	131	Cuyahoga Sh	**33 up**
Jordan	17990 English Dr	11-Jan-08	134	Berea Ss	
		2-Sep-09	102	Cuyahoga Sh	**29 up**

* Camera depth limited by centralizer. Gas bubbles emanating from below centralizer seen in May video but not in December video.

The right-most column in Table 3-4 shows that the bottom of the fugitive gas zone near three of these wells rose 30 feet or more over periods of 7 to 20 months. Videos taken in a fourth well (Buddenhagen) showed that the bottom of the gas zone rose but because the camera could not reach below a centralizer, the amount of rise could not by recorded. The adjacent column shows that the bottom of the fugitive gas zone in the three deepest wells migrated upward out of the Berea Sandstone into the Cuyahoga Shale. <u>This is what is expected when a single pulse of fugitive gas enters the subsurface from the overpressurized annulus of the English #1 well and migrates upward into the overlying geologic units without being replenished by additional gas from the from a deeper gas source in a commercial gas production zone.</u>

Gas Migration in Porous Media

The previous section described the application of published concepts of water and gas movement along joints and bedding planes in media having only fracture porosity. This section presents published concepts of water and gas movement in media with intergranular porosity. Like all fluids, water and gas move under the influence of pressure gradients. (Water movement

is a function of hydraulic gradients, which include both pressure head and elevation head). Gas movement, unlike water, is not controlled exclusively by pressure gradients. Gas movement is also controlled by its buoyancy within water. As a result, gas movement in intergranular media where groundwater flow is not vertical, as in shale confining layers, is controlled by two factors: (1) its buoyancy, and (2) the magnitude and direction of groundwater flow. As a result, gas migration in the Berea and Sharon sandstones in not like gas migration in the Ohio, Bedford, and Cuyahoga shales.

Figure 3-79 uses force vectors to represent the two processes controlling the movement of gas and the single process controlling the movement of water. The case on the left represents hydrostatic conditions, where there is no water movement and gas migrates solely under its buoyancy (Panel 1). Here, the downward force of gravity on a small sphere of wate is equal to the density of water (ρ_w) times the gravity constant (g). Under hydrostatic conditions, this force is exactly offset by the upward buoyant force of water itself, which is the product of $-\rho_w$ times g. Hence, the net effect of the upward force ($-\rho_w g$) and the downward force ($\rho_w g$) is equal to 0, meaning that the water is stationary and not moving.

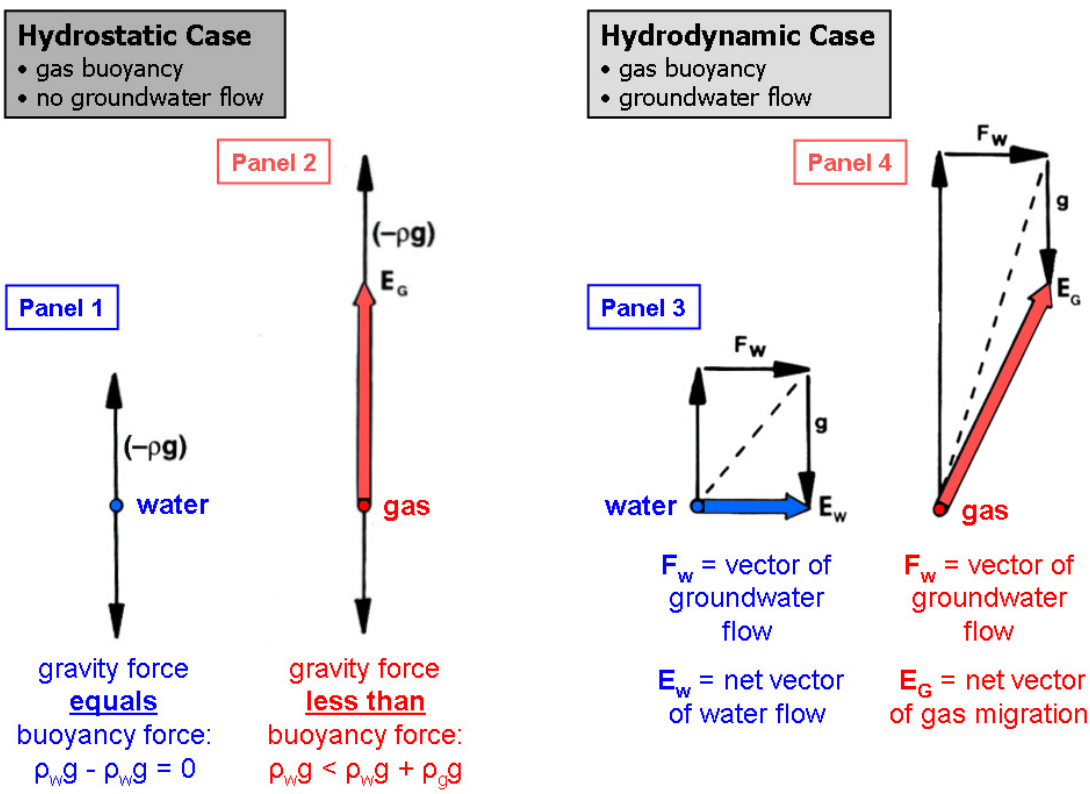

Figure 3-79. Subsurface gas migration in a medium with primary porosity under hydrostatic and hydrodynamic groundwater conditions (modified from Dahlberg, 1995).

The force analysis describing the movement of gas in the hydrostatic case (Panel 2) must also account for the buoyancy of gas in water. In this case, the downward force of gravity ($\rho_w g$) is less than the upward buoyant force of gas in water ($\rho_w g + \rho_g g$). As a result, the net force vector of gas movement (E_G), shown by the red arrow in Panel 2, is upward. So, when there is no groundwater movement, gas rises vertically through a column of water. Gas bubbles rising through a static column of well water (no pumping) was observed in many of the borehole videos (Figures 3-36 to 3-42). It is also seen when scuba divers exhale in calm water.

Analysis of the hydrodynamic case, where groundwater flow occurs, is portrayed in Panels 3 and 4. If groundwater moves horizontally from left to right, the force vector of groundwater flow (F_w) is due right (Panel 3). Because the gravity force vector of water is equal and opposite to the buoyancy force vector of water, the net force vector of groundwater flow (E_w) is equal in magnitude and direction to F_w (Panel 3). Panel 4 shows that the effect of groundwater flow (F_w) on the net force vector of gas movement (E_G) is to slant E_G such that it has a vertical component due to buoyancy and a horizontal component due to groundwater flow. If the force vector of groundwater flow is larger than shown in Panels 3 and 4, gas will migrate more horizontally. If the force vector of groundwater flow is less than shown in Panels 3 and 4, gas will migrate more vertically. This concept is seen when watching the flight of a golf ball in a quartering wind. If a golfer aims directly at the target, ignoring the wind coming from the left, the golf ball lands to the right of the target, no doubt in a deep bunker, because the magnitude and direction of the wind caused the ball to move right of the direct line to the target.

This is what occurs to gas migrating in the Berea and Sharon sandstones in the investigation area. Fugitive gas rising into the Berea Sandstone from the Ohio and Bedford shales migrates upward along an inclined path that also accounts for the magnitude and direction of groundwater flow. When residential wells are in use, the upward migration of gas in the Berea Sandstone can be altered significantly by pumping cones of depression that change the magnitude and direction of groundwater flow.

The vector analysis in Figure 3-79 assumes an infinite porous medium. Real gas reservoirs are bounded on top by poorly porous, poorly permeable caprocks that prevent the upward escape of gas into overlying strata. Typically, caprocks are shales, salt layers, and anhydrite beds. Figure 3-80 shows contours of the bottom of the Cuyahoga Shale, which acts as a leaky caprock overlying the Berea Sandstone, and the path that fugitive gas from the English #1 well would take along the steepest gradient to the high point in the Berea Sandstone (yellow **x**).

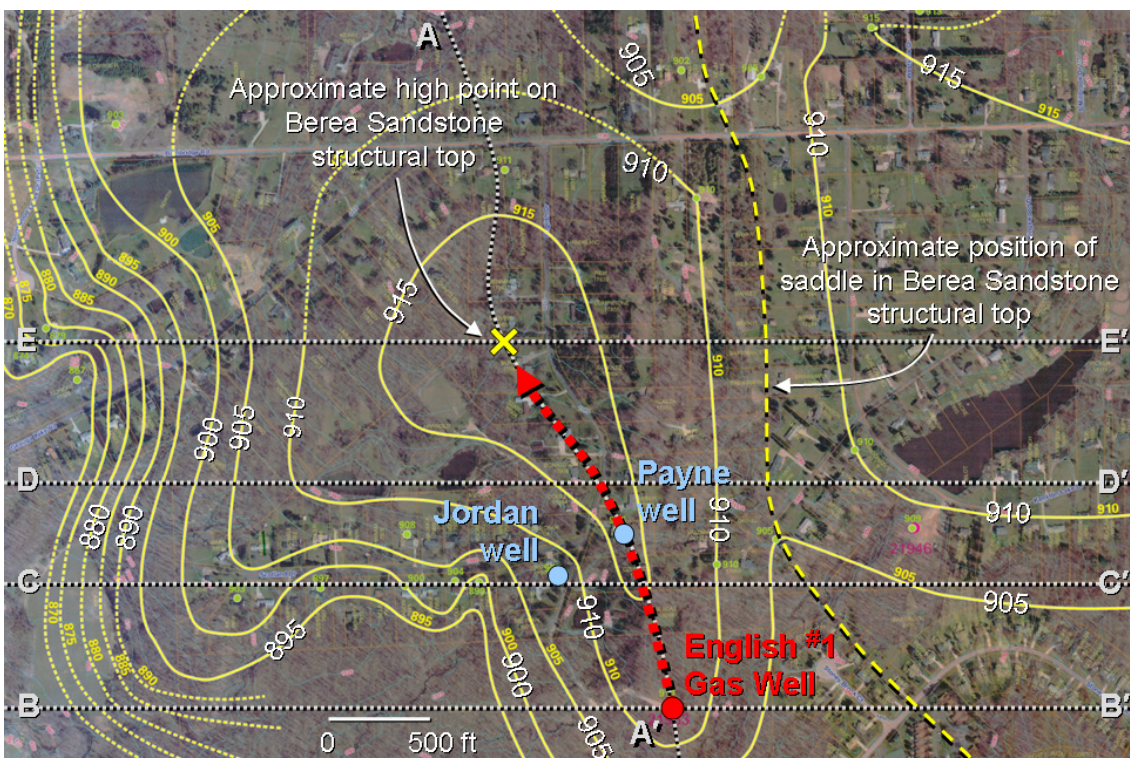

Figure 3-80. Structure contours of the bottom of the Cuyahoga Shale.

Because of its buoyancy, gas will migrate upward along the steepest gradient on the bottom of a caprock surface. It is not coincidence that the Payne well and the Jordan well, where the gas explosion and the geyser-like eruption of groundwater occurred on December 15, 2007, both lie along the steepest gas migration path between the English #1 well and the high point on the top of the Berea Sandstone surface.

Natural gas will continue to migrate upwards along the steepest gradient until it either becomes trapped (Figure 3-13) or it finds a vertical joint in the caprock and migrates upward in channels along it. In the later case, the caprock is leaky and is more likely to retard the upward gas migration than to prevent it. The presence of gas in the Cuyahoga Shale, as seen in numerous borehole videos, demonstrates it is a leaky caprock. As the gas migrates along the steepest gradient in the top of the Berea Sandstone surface, it escapes into the Cuyahoga Shale caprock along the numerous vertical joints in the shale beds, as seen in the borehole videotapes (Figures 3-46 to 3-52).

Temporal and Spatial Patterns of Gas Migration in Investigation area

This section combines the preceding concepts, principles, and data into a detailed conceptualization of fugitive gas movement from the overpressured annulus of the English #1 well into residential water wells in the investigation area. Three series of diagrams are used to display temporal and spatial patterns of gas migration in plan view and in cross section view.

Any conceptualization of subsurface gas migration must correspond to the observed timeline of events occurring from November 2007 to the present (Table 1-1). As described in the previous section, the physical processes controlling gas migration change from place to place and over this time period. As a result, the detailed conceptualization of gas movement was divided into three stages in which one or more of the physical processes controlling gas migration is unique to each stage. This enables analysis of temporal and spatial patterns of gas migration to be based on physical processes and it enables observations of gas source zones in borehole videos and measurement of wellhead LELs to be used to test whether conceptualization of the physical processes operating during each stage is valid. Listed below are the three stages.

- **Stage 1 – Pressure Buildup**
  This stage includes the events during construction of the English #1 well up to mid-December 2007, when the explosion at the Payne house (17975 English Dr) and the artesian flow out of the Jordan well (17990 English Dr) occurred. It is characterized by the escape of natural gas and the build-up of subsurface fluid pressures due to overpressurization of the English #1 well. Stage 1 ends with the cement-squeeze jobs that sealed off sources of deep gas in the annular space in the surface-production casing of the English #1 well and any further escape of gas.

- **Stage 2 – Intentional Pressure Dissipation**
  In Stage 2, the elevated fluid pressures built up during Stage 1 dissipate due to intentional overpumping of selected residential wells and release to the atmosphere through wells. During Stage 2, water well use at several properties is replaced by use of commercial water tanks. Stage 2 extends from mid-December 2007 to July 2008.

- **Stage 3 – Passive Pressure Dissipation**
  Stage 3 is characterized by passive (natural) dissipation of subsurface fluid pressures as intentional overpumping of selected residential wells ceases and normal residential use of wells recommences in homes not supplied by water tanks. Stage 3 extends from the summer of 2008 to the present.

The following sequence of eight figures show the conceptual migration of fugitive gas during each of the three stages. Each figure is preceded by a facing page documenting the observations and data used to delineate the extent of gas migration and an explanation of the physical processes causing the gas to migrate in the different geologic units.

Each conceptualization represents the lateral and vertical extent of fugitive gas migration at a specific time within one of the three stages of gas migration described above. The lateral and vertical extent of fugitive gas portrayed in these figures in constrained by the events listed in Table 1-1, by observations made in the borehole videos (Table 3-3), and by the measurement of wellhead LEL values in water wells. Thus, the temporal and spatial distributions of fugitive gas depicted in these figures are constrained by data collected in the investigation area. The distributions of fugitive gas also incorporate results of the analyses made by the expert panel that deal with the physical migration of the fugitive gas. As a result, in these figures natural gas is shown to be:

- rising upward and out of the Ohio and Bedford shales into the Berea Sandstone solely within a cylinder of space immediately around the English #1 well, as indicated by the pressure analysis presented earlier in Chapter 3;

- migrating vertically along joints and horizontally along bedding planes within the Ohio and Bedford shales underlying the Berea Sandstone,

- initially migrating vertically in the Berea Sandstone due to its buoyancy and upon reaching the top of the Berea Sandstone, which is the bottom of the leaky Cuyahoga Shale caprock, being redistributed laterally by migrating to the high point in the top of Berea Sandstone surface along the steepest gradient,

- unless diverted by pumping of residential water wells along Scotland Drive or by spilling to the east under the saddle in the top of Berea Sandstone surface, and then

- slowly rising upward out of the Berea Sandstone into vertical joints in the Cuyahoga Shale to eventually be captured by water wells and recorded by wellhead LEL measurements or further dispersed upward into soil zones and the atmosphere.

Each of the diagrams depicting the temporal and spatial distribution of the natural gas emanating from the overpressurized annulus in the surface-production casing in the English #1 well is consistent with and constrained by site-specific field and lab data and with well-established concepts of water and gas flow in porous and fractured media.

The water wells numbered 1 to 6 in the "A" panel in the diagrams (i.e. Figures 3-81A, 3-82A, etc.) represent wells with similar well construction along the cross section. Although not described until the next section in Chapter 3, the "red balloons" sitting atop the numbered wells represent the spatial and temporal detection of natural gas from LEL measurements in similarly located and constructed water well.

Facing page to Figure 3-81

Stage 1
Mid-November 2007

- Fugitive gas is just beginning to rise into the Berea Sandstone from vertical migration in the Ohio and Bedford shales below the cemented surface casing shoe, immediately adjacent to the English #1 well (Figure 3-81A, B).

- The direction of groundwater flow is unaffected by the slight increase in fluid pressures in the Berea Sandstone near the English #1 well (Figure 3-81B).

- There is no observed fugitive gas or turbidity in residential water wells (Table 1-1).

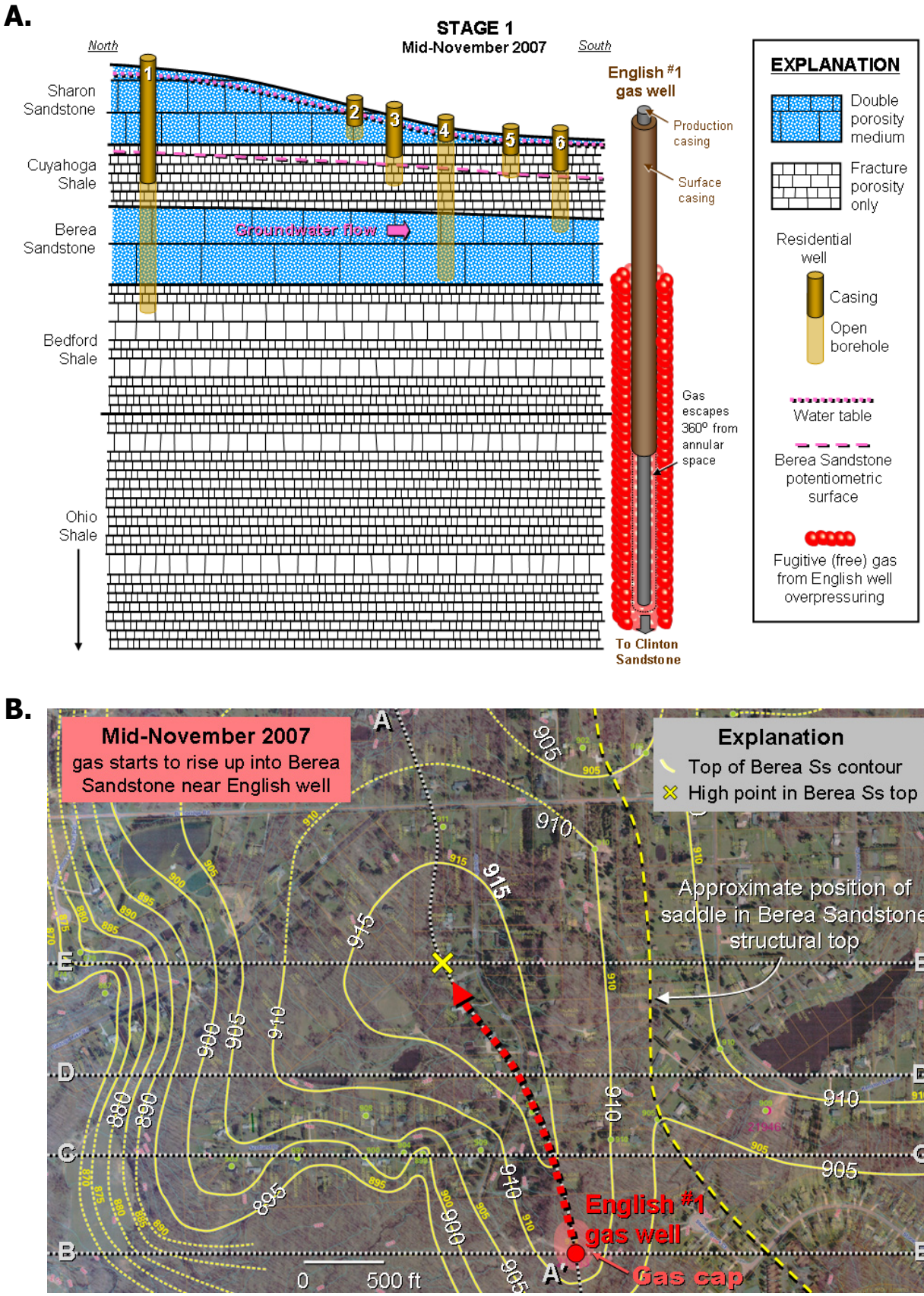

Figure 3-81. Stage 1, Mid-November 2007: A – Vertical extent of fugitive gas migration from English #1 well, B – Areal distribution of fugitive gas in Berea Sandstone.

Facing page to Figure 3-82

Stage 1
Late November 2007

- Fugitive gas continues to rise up into the Berea Sandstone from vertical migration in the Ohio and Bedford shales below the cemented surface casing shoe, immediately adjacent to the English #1 well (Figures 3-82A, B).

- Noise is heard from the release of pressure in the English #1 well annulus, which produces pressure pulses in the subsurface.

- Gas in the Berea Sandstone rises to the top of the sandstone and begins to migrate along the steepest slope up toward the high point in the sandstone.

- The gas in the Berea Sandstone also begins to spread laterally (west-east). At the English #1 well the gas cap is approximately 2 feet thick.

- Groundwater flow directions are still unaffected by the small, local increase in fluid pressures in the Berea Sandstone near the English #1 well (Figure 3-82A).

- Reports of turbidity and increased natural gas in the new Payne well and in the police station well happen shortly after this time, indicating movement of pressure pulses through the Berea Sandstone (Table 1-1).

Cz = Czernicki well (17995 English Dr)
Jo = Jordan well (17990 English Dr)
Pa = Payne wells (17975 English Dr)

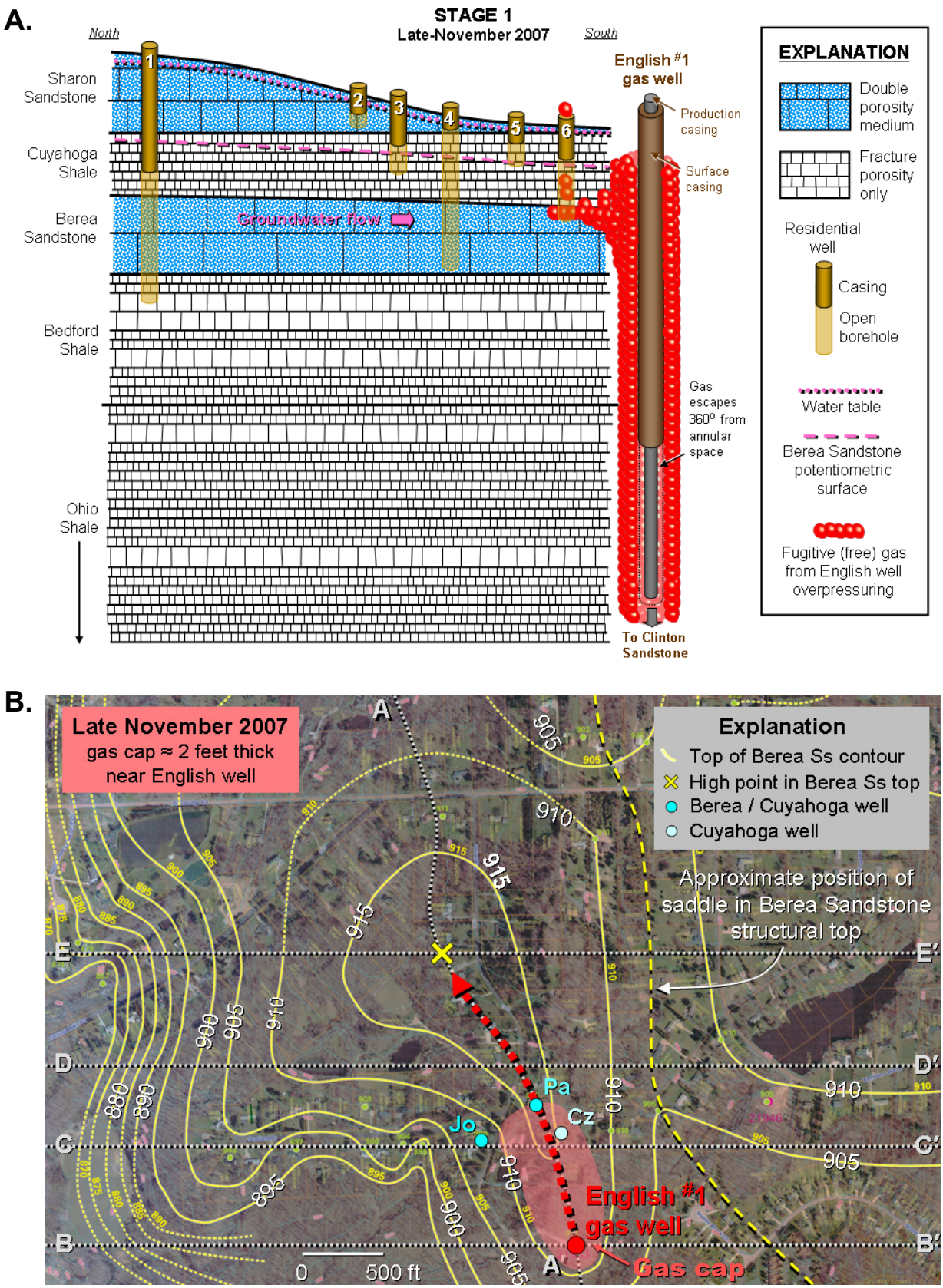

Figure 3-82. Stage 1, Late November 2007: A – Vertical extent of fugitive gas migration from English #1 well, B – Areal distribution of fugitive gas in Berea Sandstone.

Facing page to Figure 3-83

Stage 1
Early December 2007

- Fugitive gas continues to rise up into the Berea Sandstone from vertical migration in the Ohio and Bedford shales below the cemented surface casing shoe, immediately adjacent to the English #1 well (Figure 3-83A, B).

- Gas in the Berea Sandstone continues to rise to the top of the Berea Sandstone and spread laterally as the gas cap thickens and migrates along the steepest slope up toward the high point in the top of the sandstone (Figure 3-83A, B).

- The fugitive gas now exists in the Berea Sandstone beneath the Cooper, Payne, Jordan, and Czernicki wells. Gas is likely beginning to migrate vertically along joints in the Cuyahoga Shale above these properties (Figure 3-83A, B).

- The gas in the Berea Sandstone beneath of the Payne property (17975 English Dr) is likely entering the uncased portion of the old (abandoned) well and rising upward in the casing into the covered well pit (Figure 3-29). As time progresses, this gas will become pressurized in the well pit under the cement cover and the small tunnel connecting the well pit to the basement of the Payne house (Figure 3-29). The gas in the casing of the old well will also increase in pressure and because the casing terminates part way into the Sharon Sandstone (Figure 3-54), the pressurized gas will be able to migrate laterally away from the old (abandoned) Payne well (Figure 3-83A). Had measurements been made at this time, there were likely measureable LEL values in the Czernicki, Jordan, and old Payne wells at this time (Figure 3-83A).

- At the English #1 well the gas cap is approximately 3 feet thick (Figure 3-83A).

- Groundwater flow in the Berea Sandstone is impacted by the increase in fluid pressures, causing the potentiometric surface to rise in the shape of a mound centered on the English #1 well (Figure 3-83A).

Ba = Bastifell well (7981 Scotland Dr)
Bu = Buddenhagen well (7897 Scotland Dr)
Ca = Calo well (17969 Kingswood Dr)
Co = Cooper well (17974 English Dr)
Cz = Czernicki well (17995 English Dr)
de = de Gaetano well (17971 Kingswood Dr)
Jh = Johnson well (17928 Kingswood Dr)
Ko = Komocki well (7950 Scotland Dr)
Ku = Kukoleck well (7969 Scotland Dr)
Ma = Mason well (7941 Scotland Dr)
Mc = McGee well (7859 Scotland Dr)
Oh = Ohara well (7846 Scotland Dr)
Pa = Payne wells (17975 English Dr)
Jo = Jordan well (17990 English Dr)
Pr = Prochazka well (17927 Kingswood Dr)

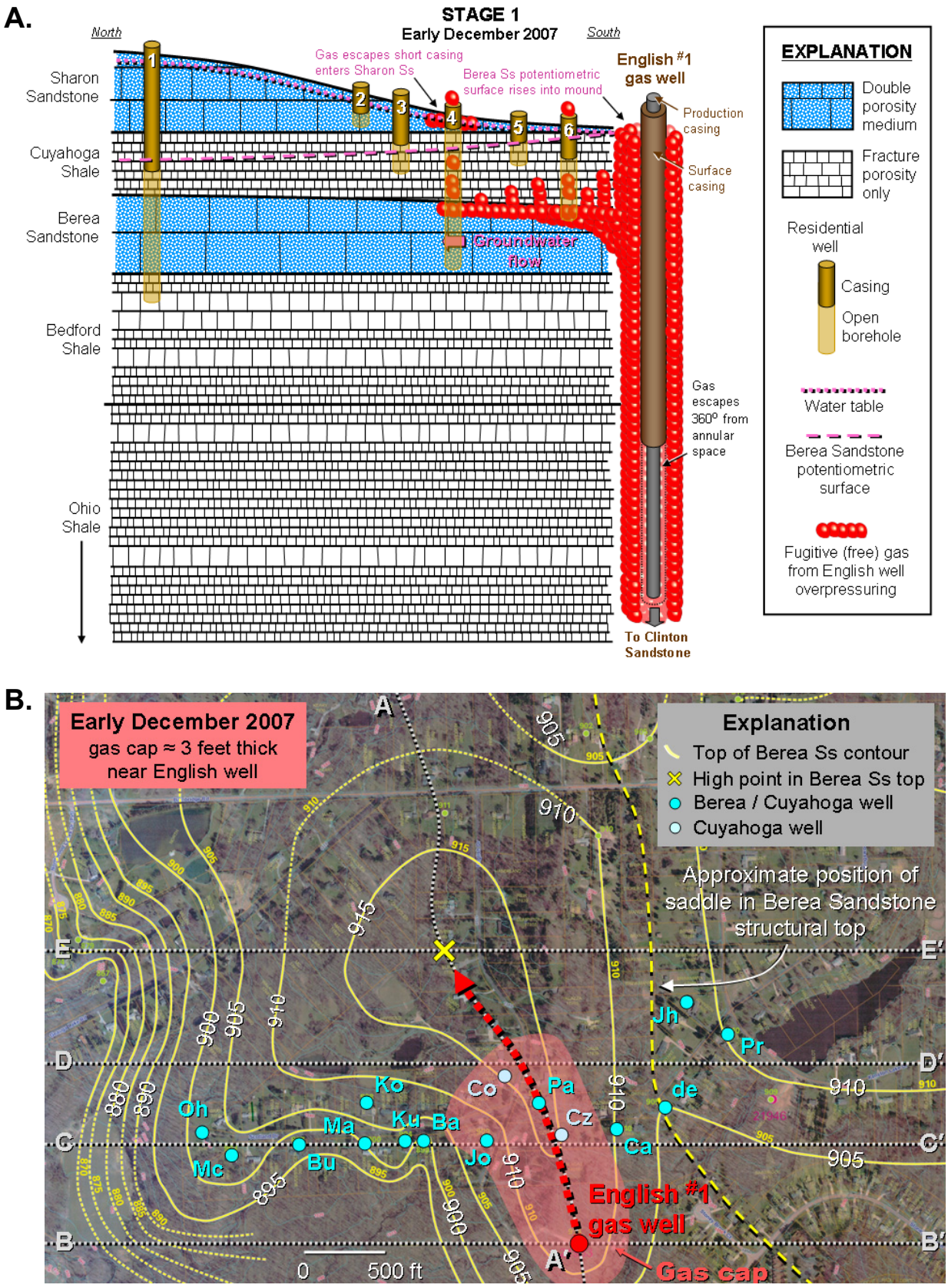

Figure 3-83. Stage 1, Early December 2007: A – Vertical extent of fugitive gas migration from English #1 well, B – Areal distribution of fugitive gas in Berea Sandstone.

Facing page to Figure 3-84

Stage 1
December 15, 2007

- Fugitive gas continues to rise up into the Berea Sandstone from vertical migration in the Ohio and Bedford shales below the cemented surface casing shoe, immediately adjacent to the English #1 well (Figure 3-84A, B). Gas in the Berea Sandstone continues to rise to the top of the Berea Sandstone and to spread laterally as the gas cap thickens and migrates along the steepest slope up toward the high point in the sandstone. The gas cap is pulled to the west by normal pumping in the numerous Berea Sandstone wells along Scotland Drive (Figure 3-84A, B).

- The fugitive gas now exists in the Berea Sandstone beneath the Cooper, Payne, Jordan, and Czernicki, Donaldson, McGee, Buddenhagen, Selby, Mason, Kukoleck, and Bastifell wells. Gas is likely beginning to migrate vertically along joints in the deeper parts of the Cuyahoga Shale below these properties (Figure 3-84A, B).

- The pressurized gas in the old Payne well continued to enter the basement through the small tunnel in the pressurized well pit. It is this gas that came into the house from the fugitive gas in the Berea Sandstone, via the old well, that caused the explosion on the morning of December 15, 2007. It is this gas from the Berea Sandstone that also likely spread in the Sharon Sandstone under the Gaub and Donaldson properties and produced the extremely high wellhead LEL values measured in their shallow wells (Appendix J).

- On December 16, 2007, the fire department measured wellhead LELs above zero in the Komocki, Kukoleck, Mason, Ohara, McGee, Bastifell, Buddenhagen, Czernicki, Payne, and Jordan wells. This indicates that fugitive gas is present in the Berea Sandstone beneath these properties. No gas is detected from LEL measurements taken at this time in the Adams, de Gaetano, Prochazka, and Johnson wells, indicating that fugitive gas is not yet present in the Berea Sandstone beneath these properties.

- At the English #1 Gas Well the gas cap is approximately 4 feet thick (Figure 84A).

- Groundwater flow in the Berea Sandstone is impacted by the substantial increase in fluid pressures creating the potentiometric mound centered on the English #1 well. The fluid pressure in the Berea Sandstone becomes so large at the Jordan well that it blows the existent column of water in the wellbore into the air. It continues to blow groundwater into the air for several hours until groundwater in the Berea Sandstone near the well is replaced by gas; then the well blows gas out of the wellhead for several more hours (Figure 3-84A).

Ba = Bastifell well (7981 Scotland Dr)
Ca = Calo well (17969 Kingswood Dr)
Cz = Czernicki well (17995 English Dr)
Jh = Johnson well (17928 Kingswood Dr)
Ku = Kukoleck well (7969 Scotland Dr)
Mc = McGee well (7859 Scotland Dr)
Pa = Payne wells (17975 English Dr)
Pr = Prochazka well (17927 Kingswood Dr)
Bu = Buddenhagen well (7897 Scotland Dr)
Co = Cooper well (17974 English Dr)
de = de Gaetano well (17971 Kingswood)
Ko = Komocki well (7950 Scotland Dr)
Ma = Mason well (7941 Scotland Dr)
Oh = Ohara well (7846 Scotland Dr)
Jo = Jordan well (17990 English Dr)

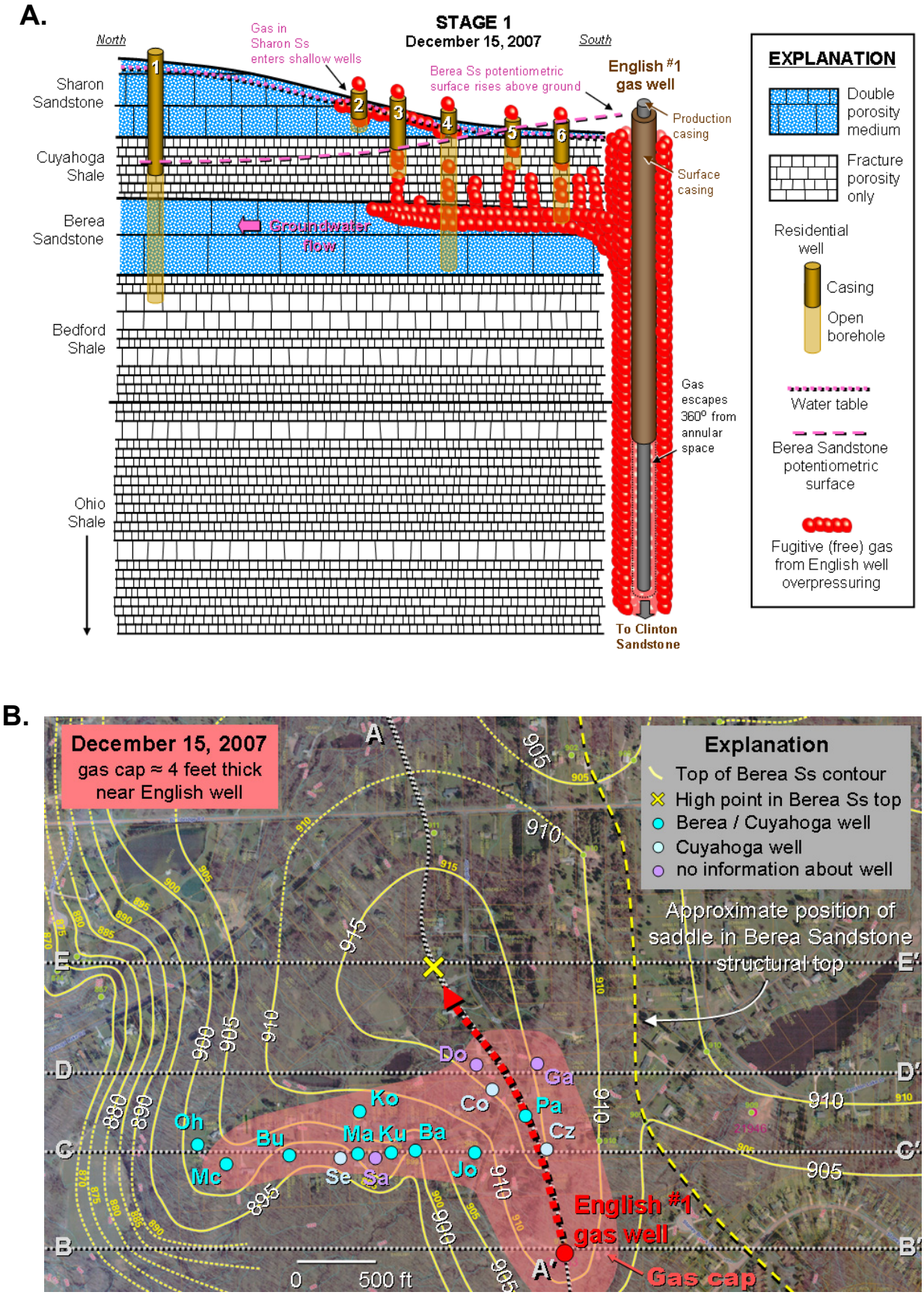

Figure 3-84. Stage 1, December 15, 2007: A – Vertical extent of fugitive gas migration from English #1 Gas Well, B – Areal distribution of fugitive gas in Berea Sandstone.

Facing page to Figure 3-85

Stage 2
Early January 2008

- Fugitive gas emanating from the English #1 well annulus is eliminated by completion of the cement squeeze jobs. Gas continues to rise up into the Berea Sandstone from vertical migration in the Ohio and Bedford shales below the cemented surface casing show, immediately adjacent to the English #1 well, where the gas cap is about 6 feet thick (Figure 3-85A, B).

- Gas in the Berea Sandstone continues to rise to the top of the sandstone and to spread laterally as the gas cap thickens and migrates along the steepest slope up toward the high point in the sandstone.

- Intentional overpumping of selected residential wells by OVE at the direction of DMRM (Figure 3-85B) slowly begins to dissipate gas beneath these properties as cones of depression form lowering the hydrostatic pressure in the wells, which enables gas to migrate into the wellbore (Figure 3-85A, B) and the bottom of the gas zone to rise near each pumped well.

- Fugitive gas now exists in the Berea Sandstone beneath the Cooper, Payne, Jordan, and Czernicki, Donaldson, McGee, Buddenhagen, Selby, Mason, Kukoleck, Bastifell, Calo, de Gaetano, Prochazka, Johnson, and Gaub wells. Gas is migrating vertically along joints in the Cuyahoga Shale beneath these properties (Figure 3-85A, B).

- The existence of gas in the Calo, de Gaetano, Johnson, and Prochazka wells indicates that the gas cap has grown sufficiently thick to spill under the low ridge (saddle) in the top of the Berea Sandstone surface (dashed yellow line on Figures 3-81B to 3-88B) and to enter the area of higher elevation of the top of the Berea Sandstone on the east side of the low ridge (Figure 3-85B, Attachment 4).

- Groundwater flow in the Berea Sandstone and in the Cuyahoga Shale is greatly impacted by the formation of numerous cones of depression created by the intentional overpumping of selected residential wells (Table 1-1). This pulls the gas cap in the Berea Sandstone to the west beneath Scotland Drive while also diminishing the thickness of the gas cap in this area.

Ba = Bastifell well (7981 Scotland Dr)
Ca = Calo well (17969 Kingswood Dr)
Cz = Czernicki well (17995 English Dr)
Ga = Gaub well (17939 English Dr)
Ko = Komocki well (7950 Scotland Dr)
Ma = Mason well (7941 Scotland Dr)
Oh = Ohara well (7846 Scotland Dr)
Jo = Jordan well (17990 English Dr)
Bu = Buddenhagen well (7897 Scotland Dr)
Co = Cooper well (17974 English Dr)
de = de Gaetano well (17971 Kingswood)
Jh = Johnson well (17928 Kingswood Dr)
Ku = Kukoleck well (7969 Scotland Dr)
Mc = McGee well (7859 Scotland Dr
Pa = Payne wells (17975 English Dr)
Pr = Prochazka well (17927 Kingswood Dr)

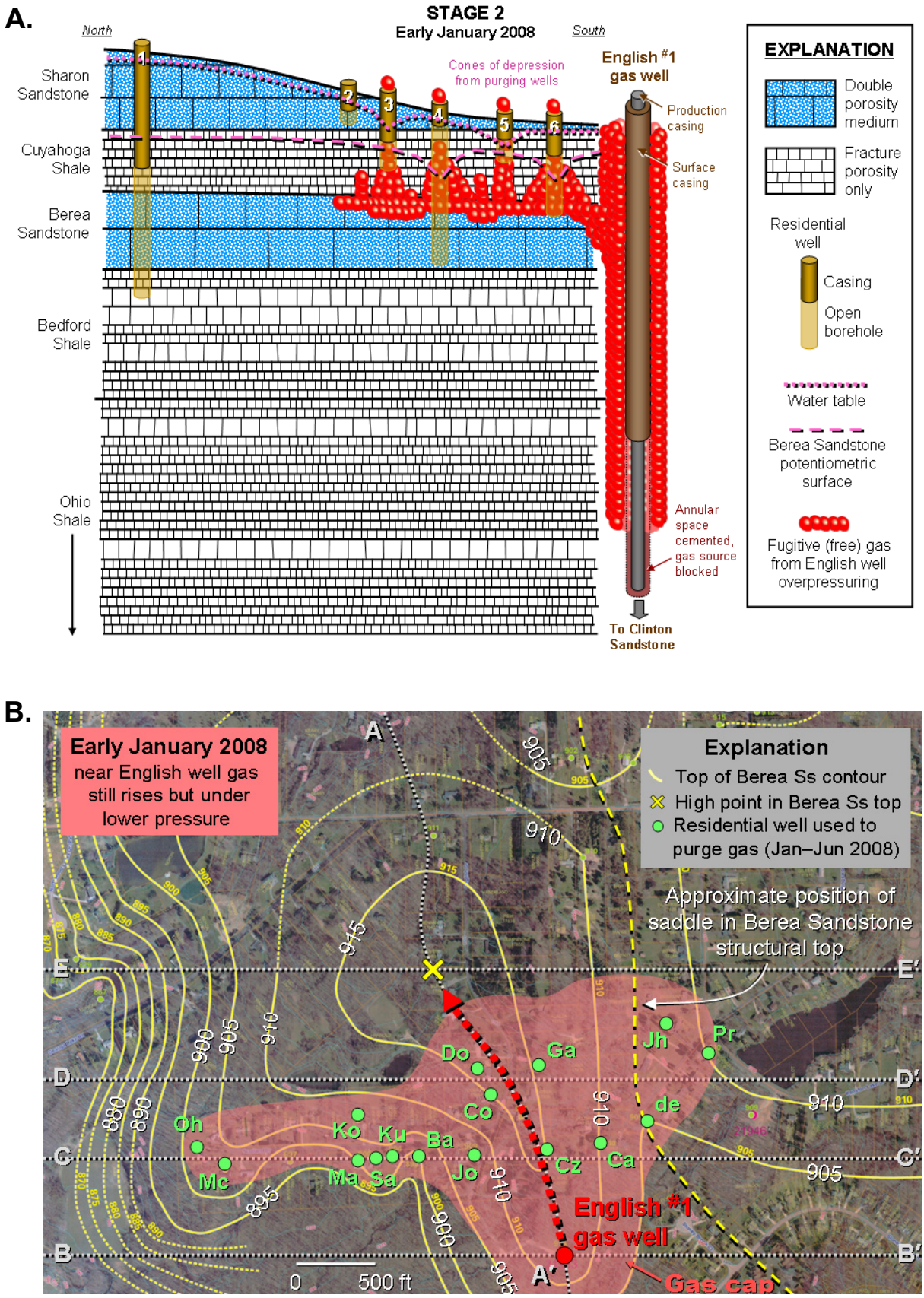

Figure 3-85. Stage 2, Early January 2008: A – Vertical extent of fugitive gas migration from English #1 Gas Well, B – Areal distribution of fugitive gas in Berea Sandstone.

Facing page to Figure 3-86

Stage 2
March 2008

- Fugitive gas emanating from the English #1 well annulus was stopped by completion of the cement-squeeze jobs more than three months ago. Residual gas continues to rise up into the Berea Sandstone from vertical migration in the Ohio and Bedford shales immediately adjacent to the English #1 well, where the gas cap is about 6 feet thick (Figure 3-86A, B).

- Gas in the Berea Sandstone continues to rise to the top of the sandstone and to spread laterally as the gas cap thickens and migrates along the steepest slope up toward the high point in the sandstone.

- Intentional overpumping of selected residential wells (Figure 3-86B) slowly begins to dissipate gas beneath these properties as cones of depression form lowering the hydrostatic pressure in the pumping wells, enabling gas to migrate into the wellbore (Figure 3-86A, B).

- Aggressive overpumping of the Jordan well locally removes all gas from the Berea Sandstone, as seen on the March 2008 borehole video. Beneath the Jordan property, the gas cap has migrated up into the Cuyahoga Shale.

- Fugitive gas now exists in the Berea Sandstone beneath the Cooper, Payne, Jordan, and Czernicki, Donaldson, McGee, Buddenhagen, Selby, Mason, Kukoleck, Bastifell, Calo, de Gaetano, Prochazka, Johnson, and Gaub wells. Gas is likely migrating vertically along joints in the Cuyahoga Shale beneath these properties (Figure 3-86A, B).

- Because the source of fugitive gas was eliminated by the two cement jobs on December 16 and 17, 2007, the amount of gas able to spill under the low ridge (saddle) in the top of the Berea Sandstone surface (dashed yellow line on Figures 3-81B to 3-88B) will diminish over time as the gas dissipates upward into the Cuyahoga Shale along vertical joints. As a result, the gas zone on the east side of the saddle in the Berea Sandstone will decrease in areal extent and thickness over time (Figure 3-86B).

- Groundwater flow in the Berea Sandstone and in the Cuyahoga Shale is greatly impacted by the formation of numerous cones of depression created by the intentional overpumping of selected residential wells (Table 1-1). This pulls the gas cap in the Berea Sandstone to the west beneath Scotland Drive while also diminishing the thickness of the gas cap in this area.

Ba = Bastifell well (7981 Scotland Dr)
Ca = Calo well (17969 Kingswood Dr)
Cz = Czernicki well (17995 English Dr)
Ga = Gaub well (17939 English Dr)
Ko = Komocki well (7950 Scotland Dr)
Ma = Mason well (7941 Scotland Dr)
Oh = Ohara well (7846 Scotland Dr)
Jo = Jordan well (17990 English Dr)
Bu = Buddenhagen well (7897 Scotland Dr)
Co = Cooper well (17974 English Dr)
de = de Gaetano well (17971 Kingswood)
Jh = Johnson well (17928 Kingswood Dr)
Ku = Kukoleck well (7969 Scotland Dr)
Mc = McGee well (7859 Scotland Dr)
Pa = Payne wells (17975 English Dr)
Pr = Prochazka well (17927 Kingswood Dr)

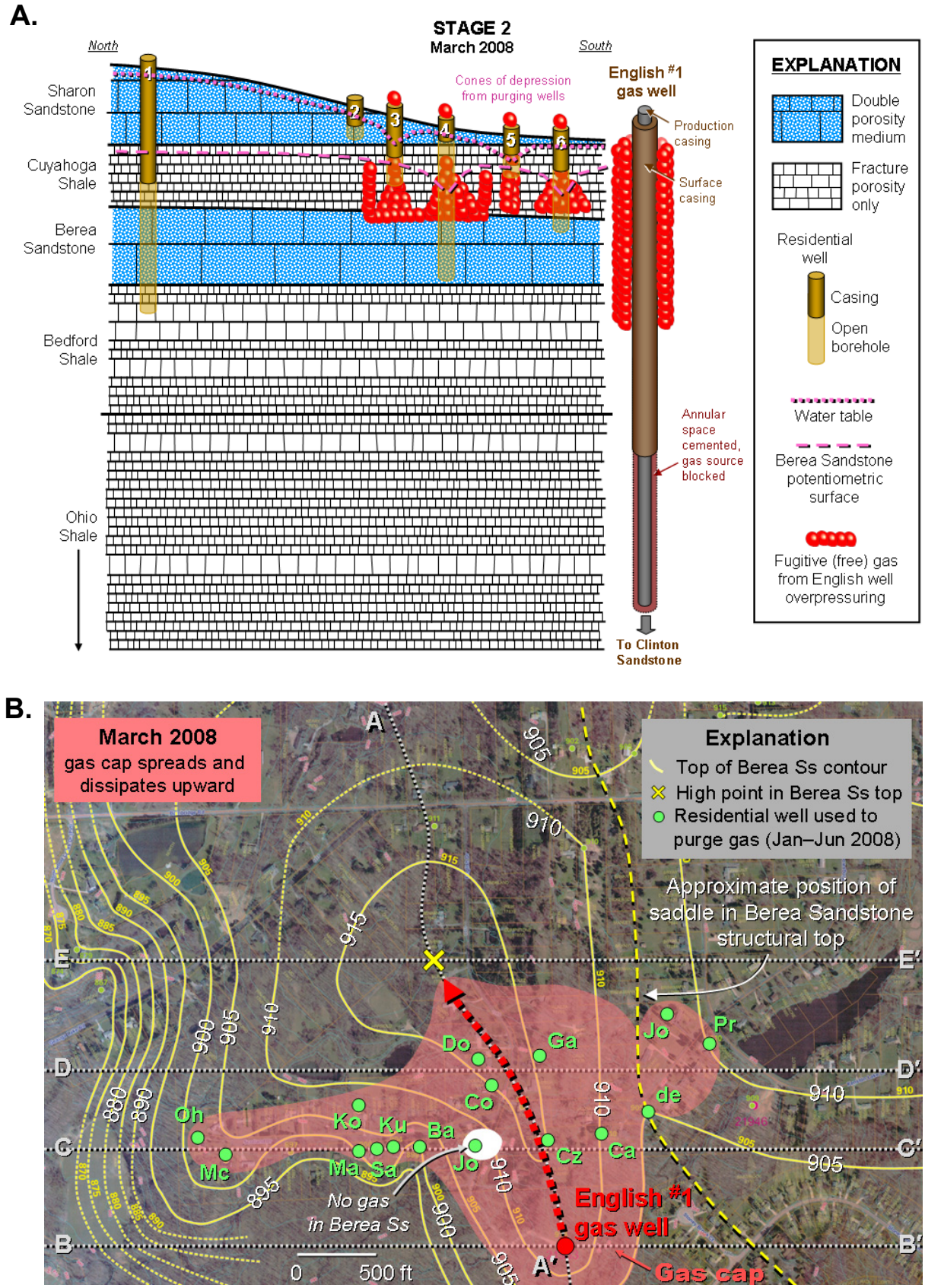

Figure 3-86. Stage 2, March 2008: A – Vertical extent of fugitive gas migration from English #1 Gas Well, B – Areal distribution of fugitive gas in Berea Sandstone.

Facing page to Figure 3-87

Stage 3
Summer 2009

- Some low pressure, fugitive gas from the English #1 well annulus continues to slowly rise up into the Berea Sandstone from vertical migration in the Ohio and Bedford shales immediately adjacent to the English #1 well (Figure 3-87A, B).

- Gas in the Berea Sandstone continues to move closer to the top of the sandstone structure. The gas cap in the Berea Sandstone thins as gas leaks upward along joints into the Cuyahoga Shale. This is detected in several borehole videos taken in the summer of 2009, which show that the deepest gas source zones are now in the Cuyahoga Shale. This is in contrast to the March 2008 borehole videos where the deepest gas source zone, in the same videotaped wells, was in the Berea Sandstone (Table 3-3).

- Intentional overpumping of residential wells ended 6 to 8 months ago. Most of the gas in the Berea Sandstone a year ago has migrated upward into the Cuyahoga Shale. The remaining portion of the gas cap in the Berea Sandstone is split into four lobes (local structural highs in the top of Berea Sandstone surface) separated by low ridges in the top of the Berea Sandstone surface (Figure 3-87A, B).

- The only borehole video showing gas emanating from bedding planes or joints in the Berea Sandstone is from the Komocki well. When the pump is turned on in the well, this gas appears to be flowing downward out of the Cuyahoga Shale and into a large bedding plane opening at the contact with the Berea Sandstone and then into the well. This indicates that the bottom of the gas zone beneath the Komocki property is just above the contact. This is called "U-tubing."

- The separate gas pool on the east side of the north-south ridge in the top of the Berea Sandstone surface (near Johnson, de Gaetano, and Prochazka) becomes isolated from the main gas cap because the thickness of gas has diminished to the point that the saddle is again an obstruction to gas migration (Figure 3-87B).

- Groundwater flow in the Berea Sandstone returns to its normal flow pattern (Figure 3-87A).

Ko = Komocki well (7950 Scotland Dr)

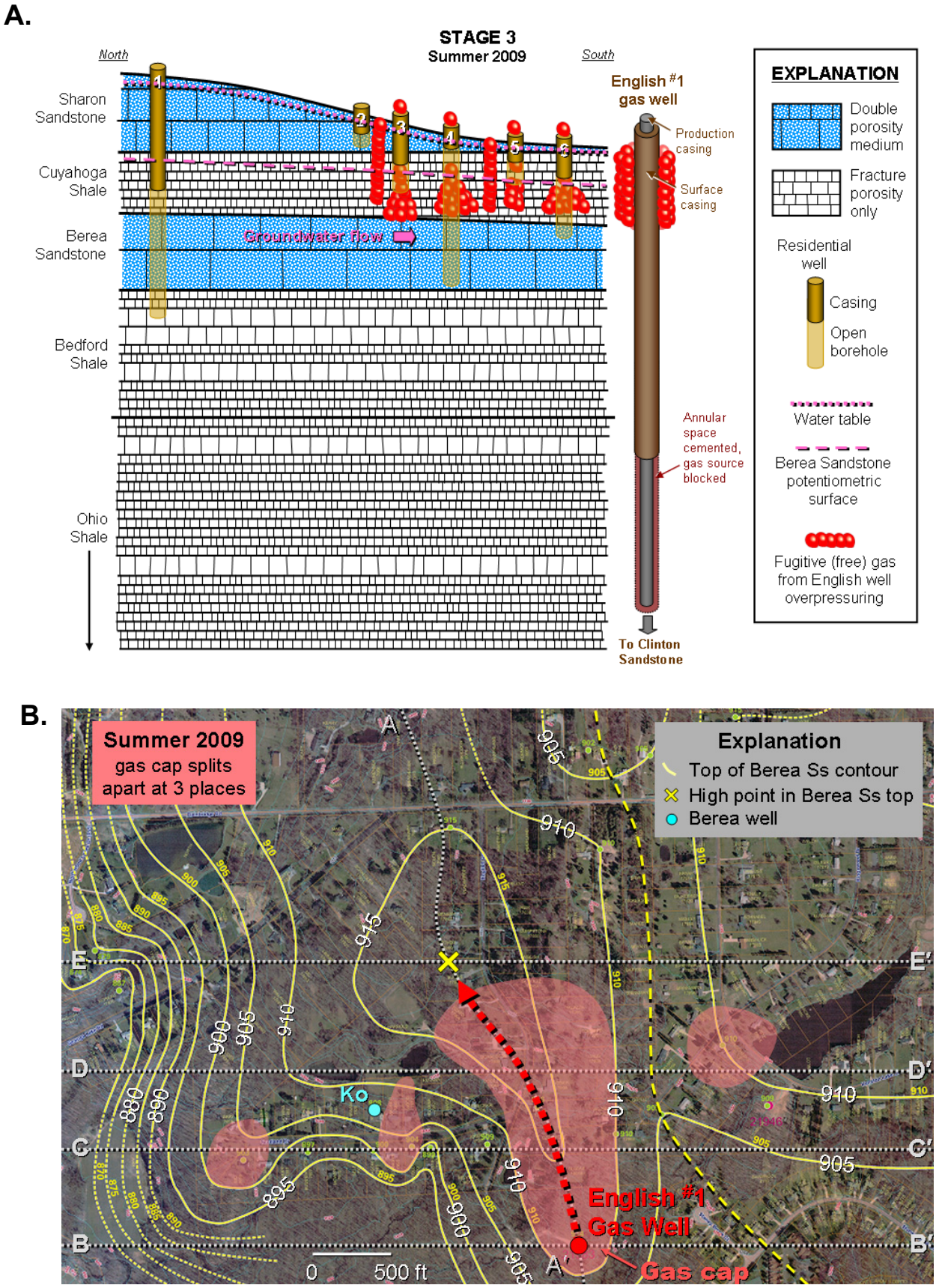

Figure 3-87. Stage 3, Summer 2009: A – Vertical extent of fugitive gas migration from English #1 Gas Well, B – Areal distribution of fugitive gas in Berea Sandstone.

Facing page to Figure 3-88

Stage 3
December 2009

- Fugitive gas emanating from the English #1 gas well annulus likely is gone from the Ohio and Bedford shales.

- No gas is seen in the Berea Sandstone in any of the borehole videos taken in December 2009 suggesting that the gas cap has migrated completely out of the Berea Sandstone and any remaining gas occurs in the Cuyahoga Shale and Sharon Sandstone.

- The lack of gas in the Berea Sandstone indicates that the postulated fractures extending downward from the Ohio Shale into deeper, commercial gas production zones were not created by overpressurization of the English #1 well in November – December 2007.

Ad = Adams well (17820 English Dr)
Ba = Bastifell well (7981 Scotland Dr)
Br = Burns well (17888 English Drive)
Bu = Buddenhagen well (7897 Scotland Dr)
Ca = Calo well (17969 Kingswood Dr)
Co = Cooper well (17974 English Dr)
Cz = Czernicki well (17995 English Dr)
de = de Gaetano well (17971 Kingswood Dr)
Jh = Johnson well (17928 Kingswood Dr)
Ko = Komocki well (7950 Scotland Dr)
Ku = Kukoleck well (7969 Scotland Dr)
Ma = Mason well (7941 Scotland Dr)
Mc = McGee well (7859 Scotland Dr)
Pa = Payne wells (17975 English Dr)
Jo = Jordan well (17990 English Dr)
St = Stover well (17860 English Dr)

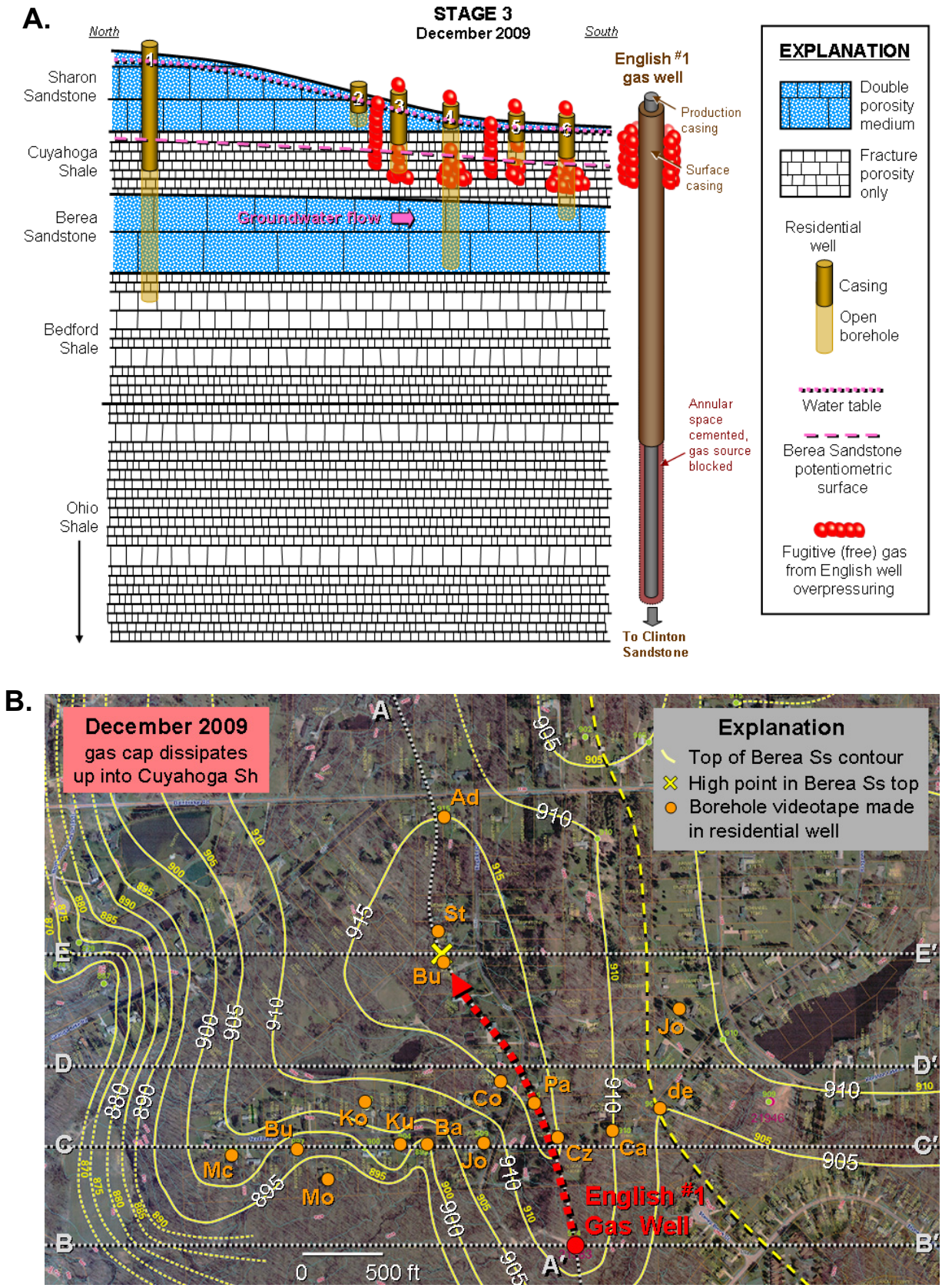

Figure 3-88. Stage 3, December 2009: A – Vertical extent of fugitive gas migration from English #1 Gas Well, B – Areal distribution of fugitive gas in Berea Sandstone.

The final series of diagrams (Figure 3-89 to 3-96) documenting the migration and dissipation of fugitive gas in Berea Sandstone is based on multiple cross sections taken along lines A-A′, B-B′, C-C′, D-D′, and E-E′ on Figures 3-81B to 3-88B. A series of cross sections was created for each snapshot in the three time stages portrayed in Figures 3-81 to 3–88. The cross sections show the contact between the Berea Sandstone and the Cuyahoga Shale, the approximate thickness and areal extent of the gas cap, and the locations of residential water wells and the English #1 well.

A facing page precedes each cross section. It lists the observations and data used to delineate the gas cap and the physical processes causing the gas to migrate in the different geologic units.

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Facing page to Figure 3-89

Stage 1
Mid-November 2007

- Panels A-A' and B-B' show fugitive gas rising out of the Bedford and Ohio shales into the Berea Sandstone and collecting along the top of Berea Sandstone surface, under the leaky caprock of Cuyahoga Shale.

- At this time the gas cap in the Berea Sandstone is very small, located on English #1 well property, and is controlled by its buoyancy within the groundwater flow in the Berea Sandstone under normal pumping stresses from residential wells, the closest of which is located several hundred feet away to the north.

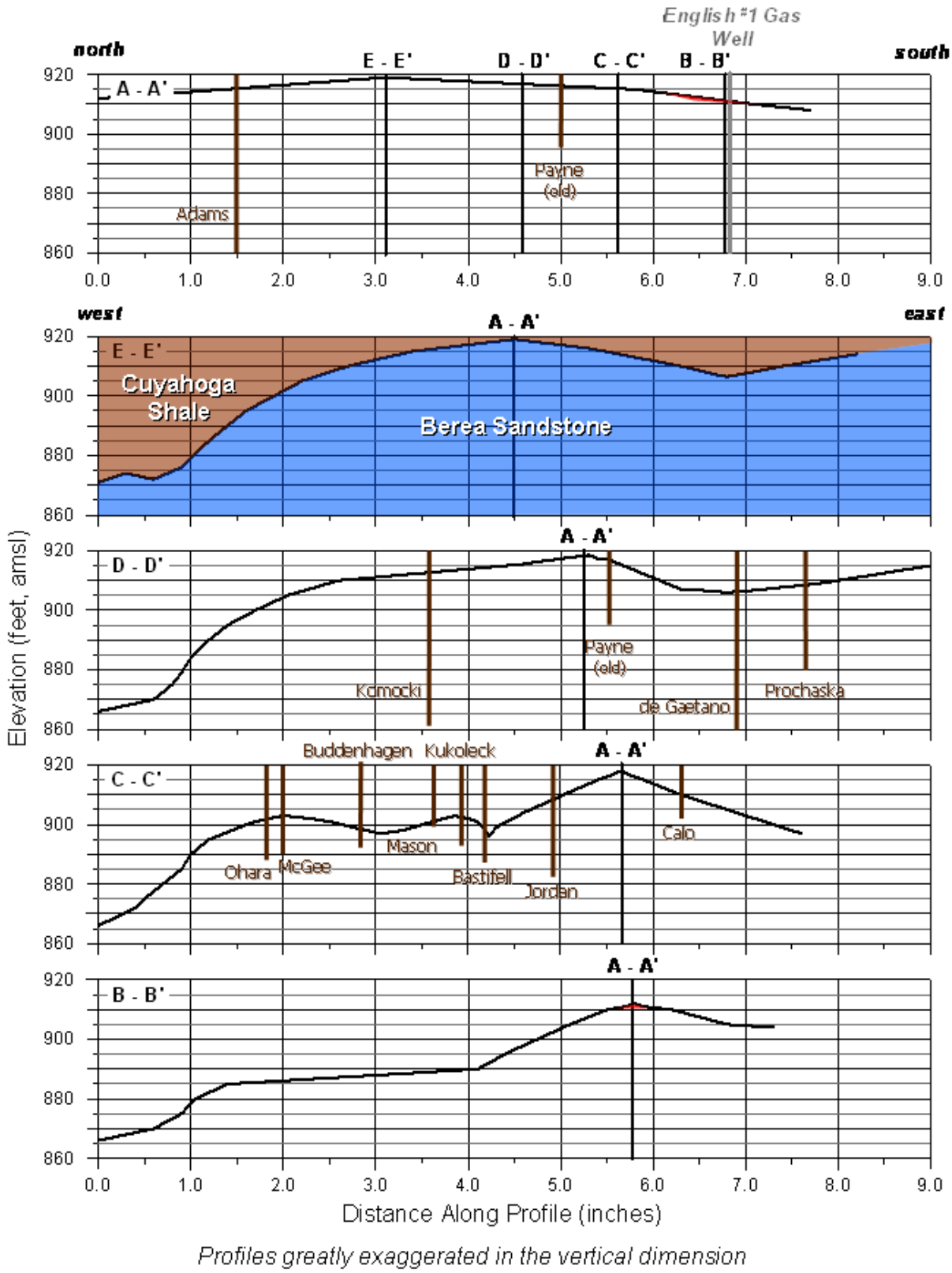

Figure 3-89. Profiles showing configuration of fugitive gas zone in Berea Sandstone, Stage 1 – Mid-November 2007 (corresponds to Figure 3-81).

Facing page to Figure 3-90

Stage 1
Late November 2007

- Approximately two later, the gas cap has grown in depth and areal extent as more fugitive gas moves upward into the Berea Sandstone from the Bedford and Ohio shales.

- The gas cap slides northward up the steepest slope (largest gradient) in the overlying Cuyahoga Shale caprock (A-A′). Along the way some gas is migrating upward through vertical joints into the basal part of the Cuyahoga Shale.

- The gas cap has migrated upslope far enough north (C-C′) to be influenced by cones of depression in local water wells completed in the Berea Sandstone. This causes the gas cap to spread out laterally to the east toward the Calo well and to the west toward the Jordan well (C-C′).

- Leakage of gas long vertical joints in the caprock directly above the gas cap enables some gas to move upward into the Cuyahoga Shale.

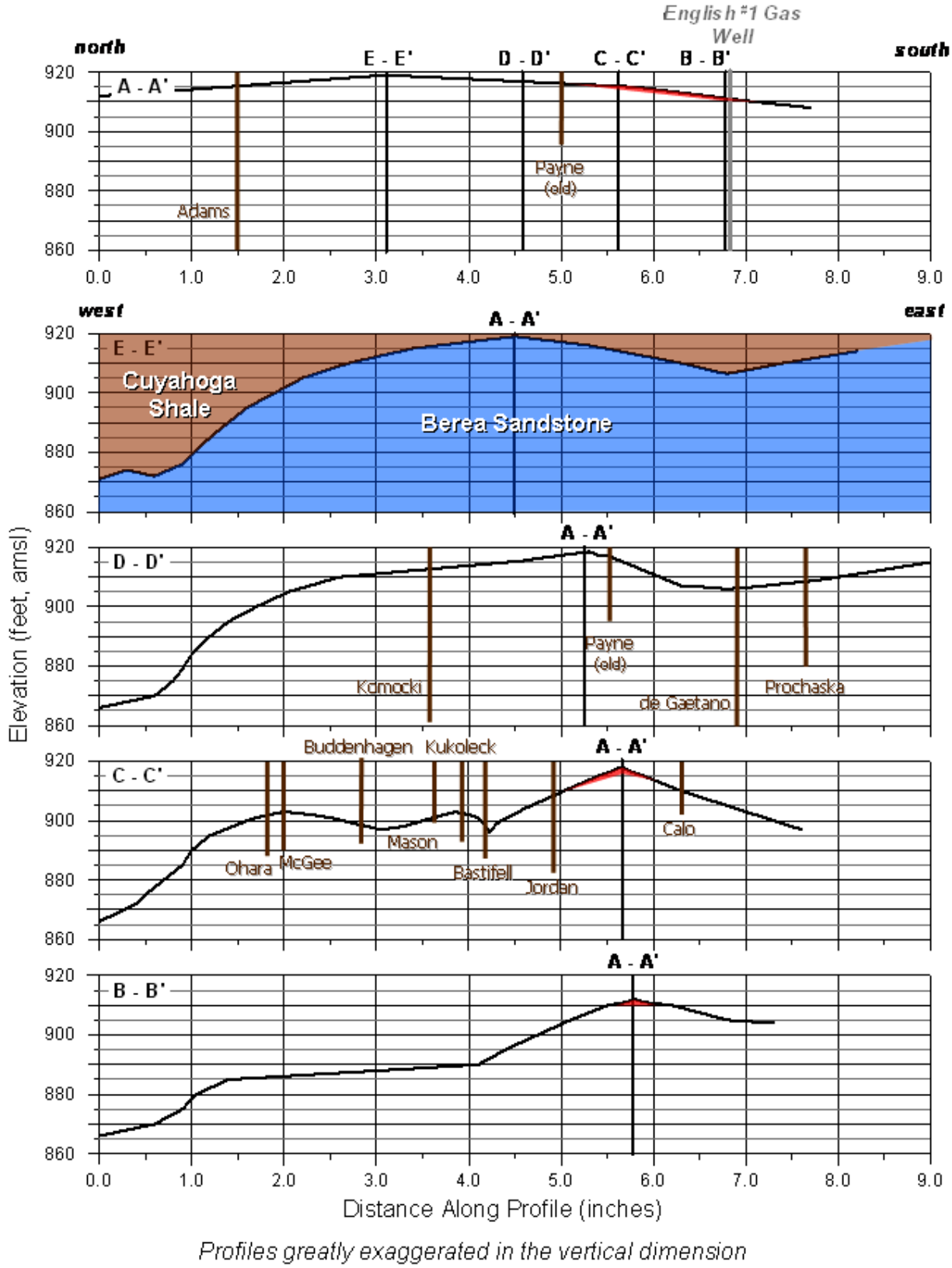

Figure 3-90. Profiles showing configuration of fugitive gas zone the Berea Sandstone, Stage 1 – Late November 2007 (corresponds to Figure 3-82).

Facing page to Figure 3-91

Stage 1
Early December 2007

- By early December, gas rising into the Berea Sandstone from the Bedford and Ohio shales near the English #1 well, has caused the gas cap to grow thicker and extend further to the north along the steepest gradient in the overlying Cuyahoga Shale caprock.

- The gas cap in the Berea Sandstone now underlies the Czernicki, Jordan, Payne, and Cooper wells and some gas is leaky upward into the Cuyahoga Shale along vertical joints. This corresponds to the early anecdotal evidence of the turbidity and gas in local water wells (Table 1-1).

- As the gas cap continues to slide upslope to the north, it is influenced more and more by residential well pumping in wells completed in the Berea Sandstone. This causes the gas cap to spread laterally in the Berea Sandstone under Scotland Drive where several wells withdraw water from the Berea Sandstone.

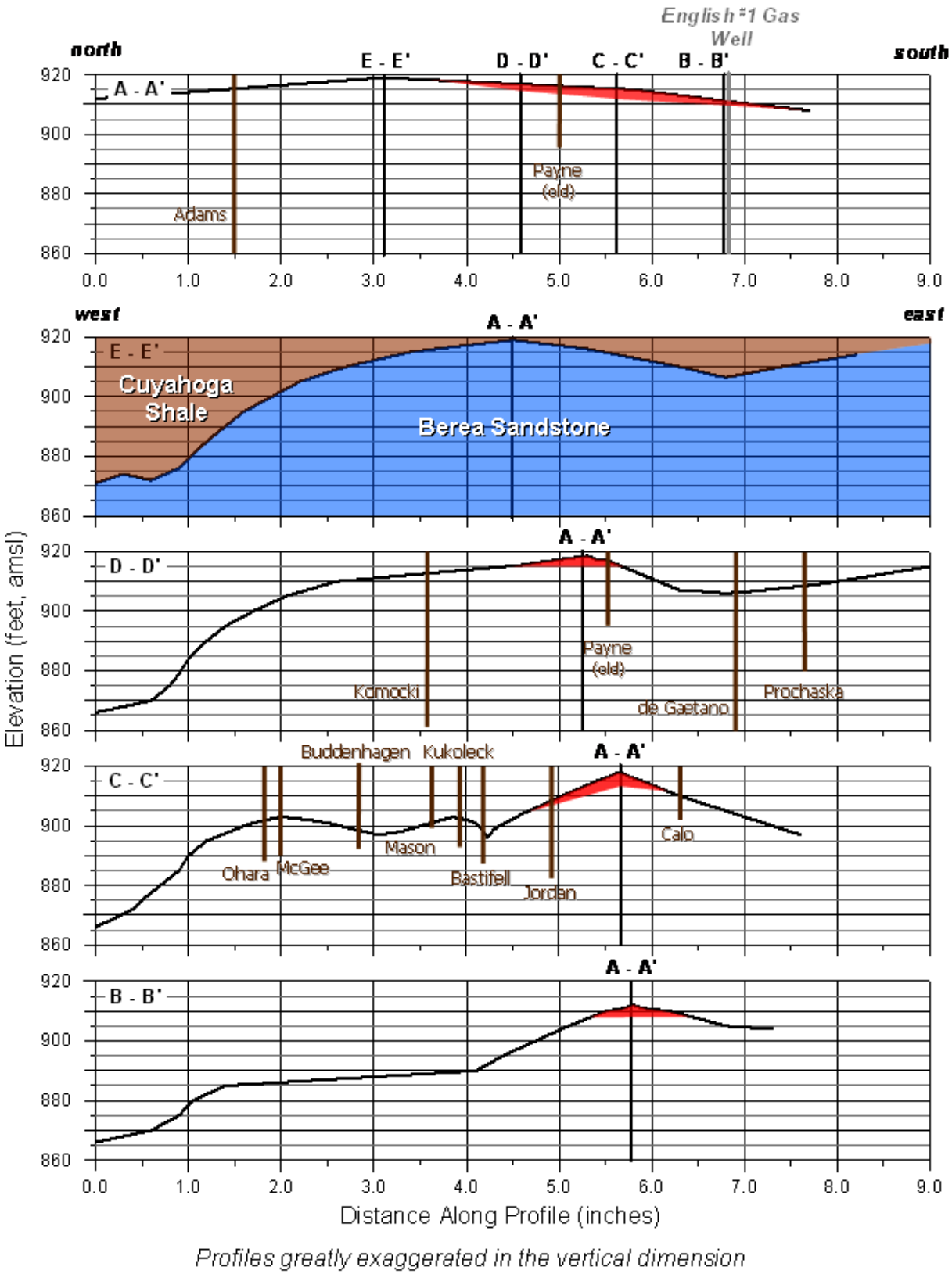

Figure 3-91. Profiles showing configuration of the fugitive gas zone in Berea Sandstone, Stage 1 – Early December 2007 (corresponds to Figure 3-83).

Facing page to Figure 3-92

Stage 1
December 15, 2007

- The gas cap in the Berea Sandstone now extends to the north so far that it directly underlies the Donaldson and Gaub properties (A-A'). It is about 4 feet thick at the English #1 well and is within a few hundred feet of the high point on the top of the Berea Sandstone surface (A-A').

- Normal pumping stresses in the Berea Sandstone pulled the gas cap to the west beneath Scotland Drive, where it now underlies properties as far west as Ohara and McGee. This is consistent with the measurements of wellhead LELs by the fire department on December 16, 2007 (Appendix E).

- The top of the Berea Sandstone (bottom of the Cuyahoga Shale) beneath the properties on Scotland Drive contains several small undulations (ridges and troughs), as seen on cross section C-C' (Figures 3-14, 3-81 to 3-88). Gas migrates upslope to the tops of these ridges as dictated by its buoyancy and the pumping stresses of the local water wells.

- Gas continues to escape upward along joints in the Cuyahoga Shale wherever the footprint of the gas cap occurs in the top of the Berea Sandstone.

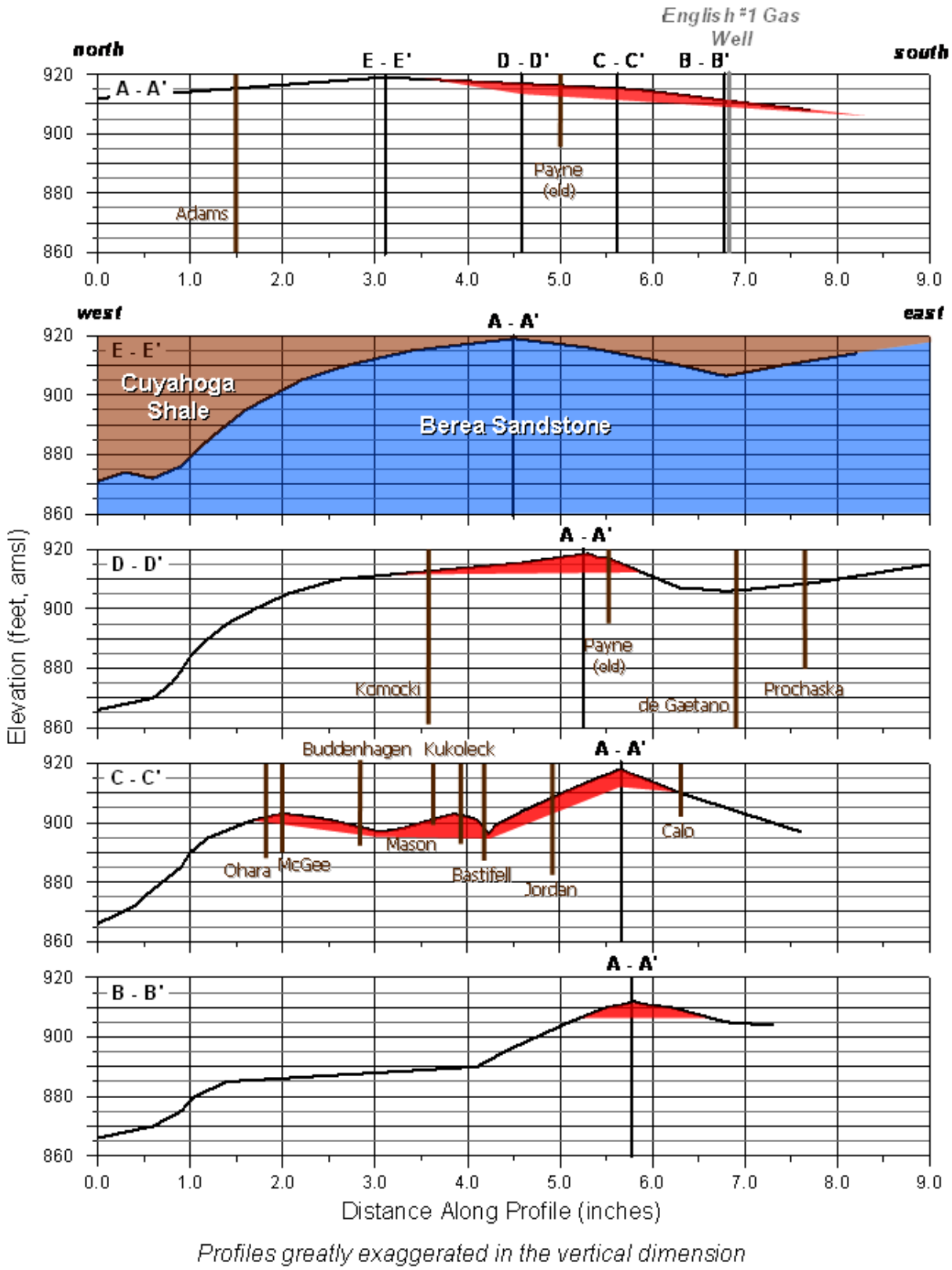

Figure 3-92. Profiles showing configuration of fugitive gas zone in Berea Sandstone, Stage 1 – December 15, 2007 (corresponds to Figure 3-84).

Facing page to Figure 3-93

Stage 2
Early January 2008

- The gas cap in the Berea Sandstone continues to grow from residual gas in the Bedford and Ohio shales migrating upward near the English #1 well is even though the annulus of the surface production casing was cemented shut on December 17, 2007.

- The gas cap now extends nearly all the way north to the high point in the top of the Berea Sandstone surface (A-A') and is thick enough to spill to the east under the north-south trending saddle in the top of the Berea Sandstone surface (D-D'). This is consistent with the delay in measuring significant wellhead LELs in the Johnson and de Gaetano wells (Appendix F).

- Due to deliberate overpumping of residential wells, especially along Scotland Drive and the southern end of English Drive (Appendix G), the gas cap begins to thin out in these areas while being pulled to the west beneath Scotland Drive.

- Some gas escapes upward into the Cuyahoga Shale along vertical joints wherever the gas cap occurs in the Berea Sandstone.

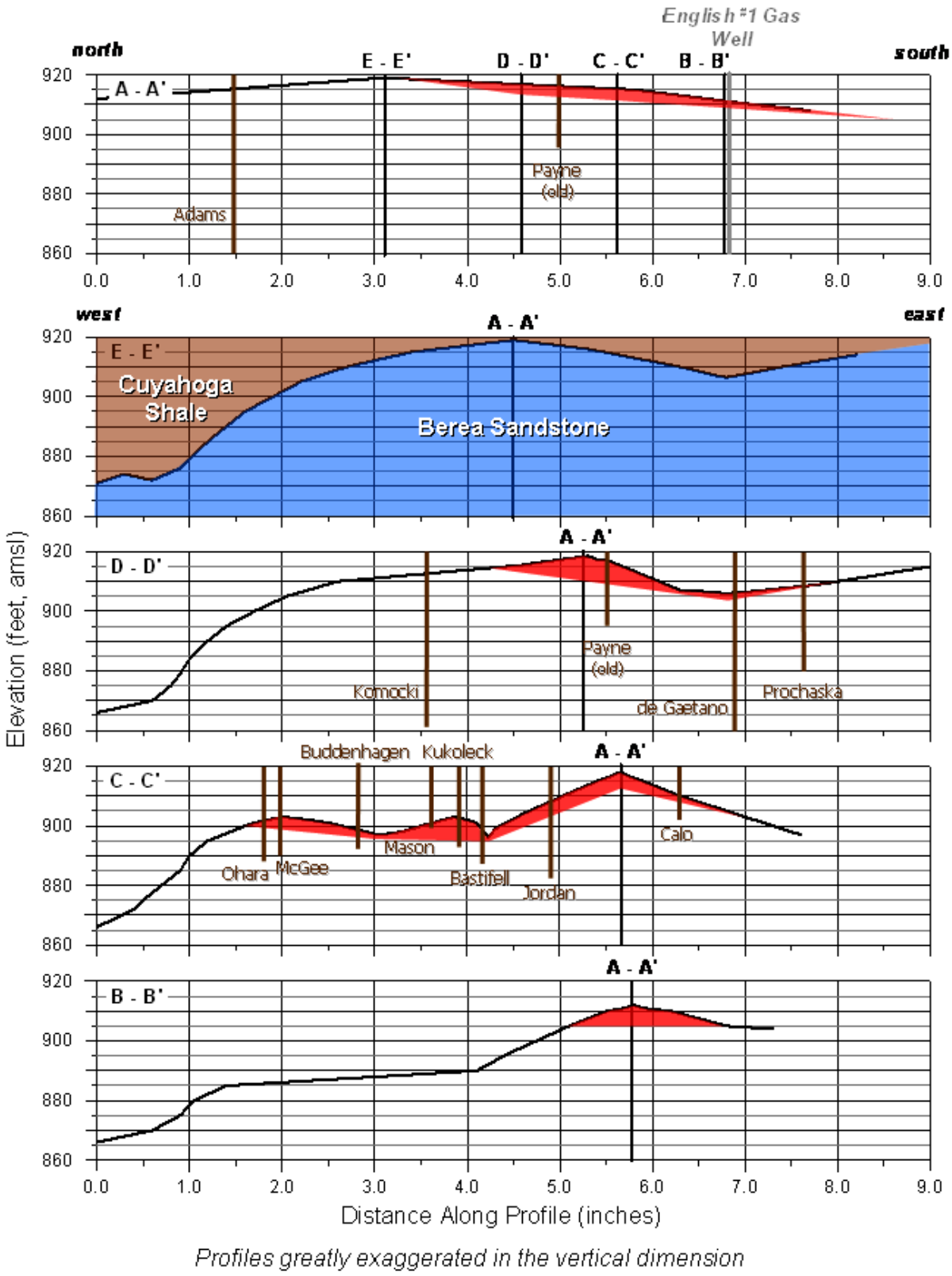

Figure 3-93. Profiles showing configuration of fugitive gas zone in Berea Sandstone, Stage 2 – Early January 2008 (corresponds to Figure 3-85).

Facing page to Figure 3-94

Stage 2
March 2008

- Some residual gas continues to rise through the Ohio and Bedford shales into the Berea Sandstone near the English #1 well (A-A').

- Due to continued deliberate overpumping of residential wells (Appendix G), the gas cap begins to thin out in these areas (C-C' and Figure 3-88).

- The aggressive overpumping effort is so effective near the Jordan well that the deepest gas source zone is in the March 17, 2008 borehole video is in the lower part of the Cuyahoga Shale (C-C'). In the January 11, 2008 borehole video, the deepest gas source zone is in the Berea Sandstone (Tables 3-3 and 3-4).

- The overpumping on the east side of the north-south trending saddle in the top of the Berea Sandstone surface also has caused the gas cap in that area to thin (D-D'), which is consistent with the lower wellhead LELs measured in the de Gaetano and Johnson wells.

- Gas continues to leaky upward from the Berea Sandstone into the Cuyahoga Shale along vertical joints in the shale, making the footprint of the gas cap in the Berea Sandstone smaller and smaller as time goes by.

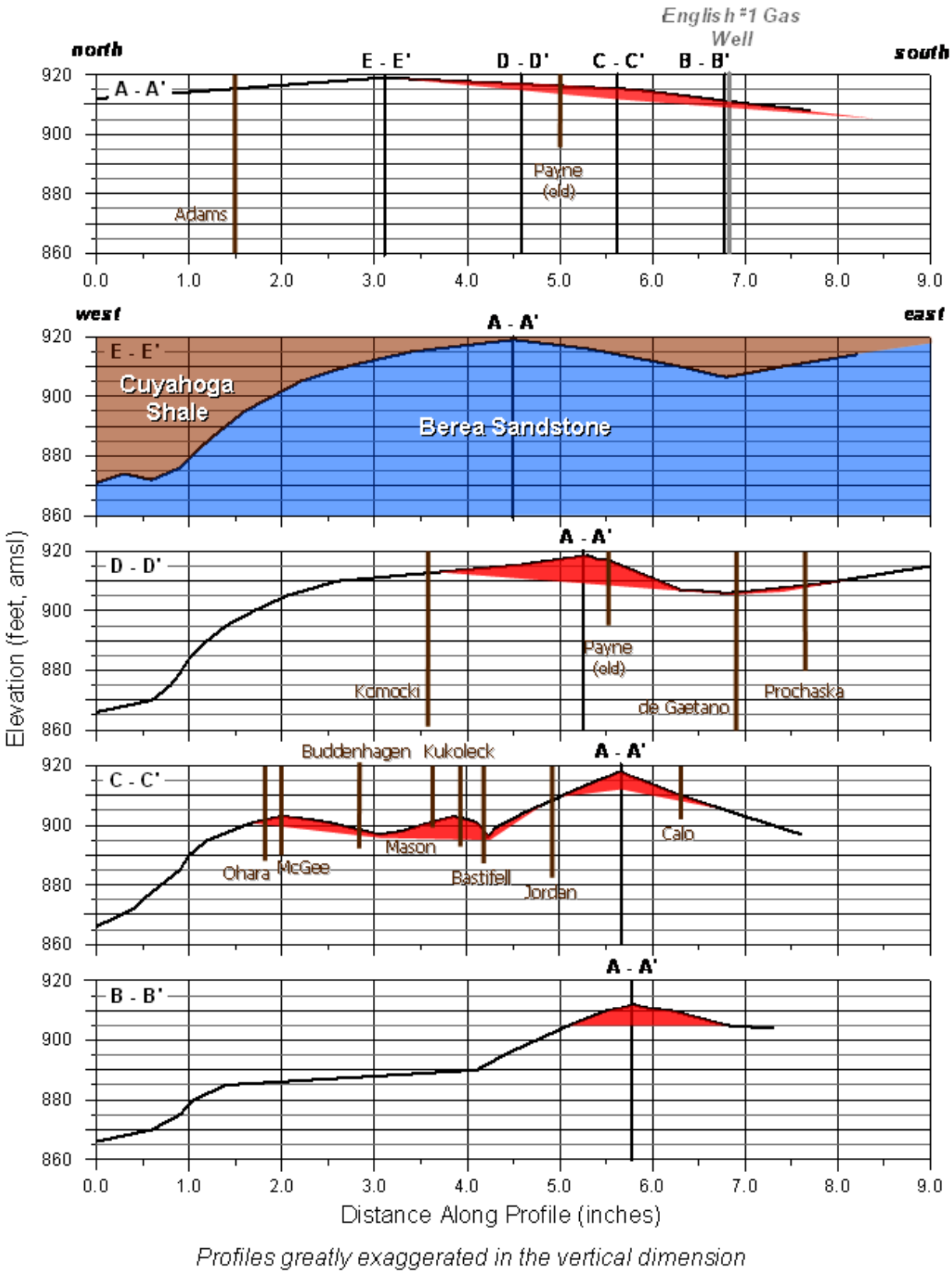

Figure 3-94. Profiles showing configuration of fugitive gas zone in Berea Sandstone, Stage 2 – March 2008 (corresponds to Figure 3-86).

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Stage 3
Summer 2009

- By the summer of 2009 there is very little residual gas entering the Berea Sandstone from the Ohio and Bedford shales near the English #1 well. The thickness of the gas cap in that area has decreased (A-A′ and B-B′).

- The footprint of the gas cap in the Berea Sandstone is much smaller than in March 2008 as more and more gas leaks upward into the Cuyahoga Shale over time (C-C′ and D-D′), which is consistent with the declining wellhead LELs measured in the Johnson, de Gaetano, Gaub, Donaldson, and Weber wells (Appendix F).

- The gas cap has become so much thinner that it now occurs as four individual gas caps separated by local troughs (saddles) in the top of the Berea Sandstone surface (C-C′ and D-D′), as seen by the lack of gas source zones in the Berea Sandstone during borehole videos taken during the summer of 2009 (Tables 3-3 and 3-4).

- Because water wells are no longer deliberately overpumping to flush fugitive gas from the subsurface, the decrease in the thickness of the gas cap in the Berea Sandstone is caused by continued upward leakage in to the Cuyahoga Shale and the lack of any gas replenishment from deeper commercial gas production zones.

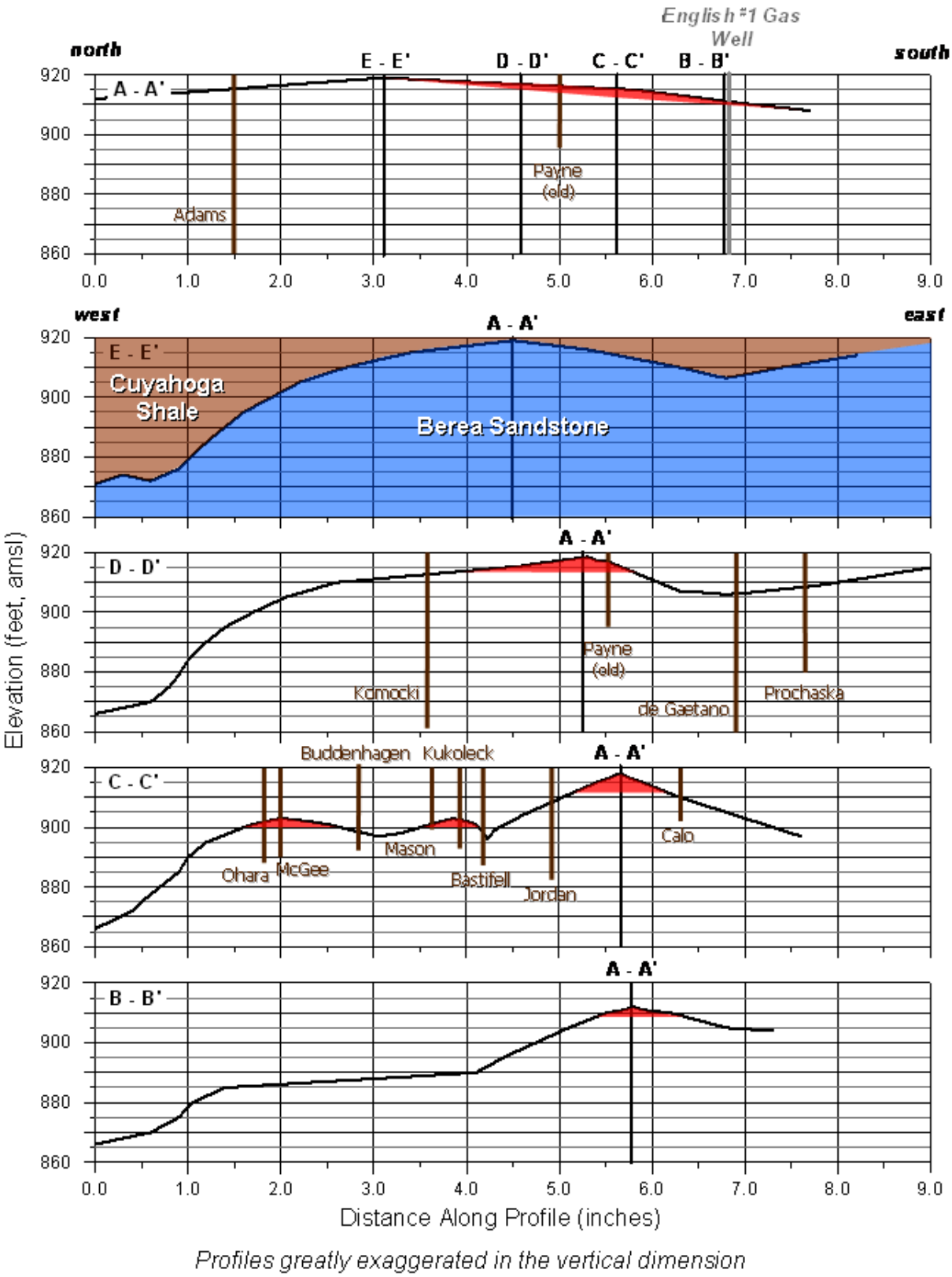

Figure 3-95. Profiles showing configuration of fugitive gas zone in Berea Sandstone, Stage 3 – Summer 2009 (corresponds to Figure3-87).

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Stage 3
December 2009

- The borehole videos taken in the old and new Payne wells and in the Czernicki well in December 2009 show no gas source zones in the Berea Sandstone. This absence, the absence of gas source zones in the Berea Sandstone in the numerous borehole videos taken in summer of 2009 (Tables 3-3 and 3-4), the rise of the bottom of the overall gas zone from the Berea Sandstone up into the Cuyahoga Shale seen in several borehole videos (Table 3-5), and the continued decline in wellhead LELs seen in almost all wells indicates that fugitive gas escaping from the annulus of the surface production casing in the English #1 well no longer occurs in the Berea Sandstone except, perhaps, at the high point in the top of Berea Sandstone surface (A-A′ and E-E′).

- All the gas in other parts of the Berea Sandstone has migrated up into the Cuyahoga Shale along vertical joints (B-B′, C-C′, D-D′).

- The absence of gas in the Berea Sandstone indicates that there is no replenishment of gas from deeper commercial production zones and that the gas invasions in water wells in the investigation area in Bainbridge Township was solely from a one-time pulse source emanating from the annulus of the surface production casing in the English #1 well.

- There is no evidence that a continuous source of gas from a deeper commercial production zone ever migrated upward along a system of deep fractures created by overpressurization of the surface production casing in the English #1 well. Had such a system of deep fractures ever existed connecting the Ohio Shale to a deep source of commercial gas, that gas would have replaced the gas escaping from the Berea Sandstone along vertical joints in the Cuyahoga Shale and by overpumping of local wells.

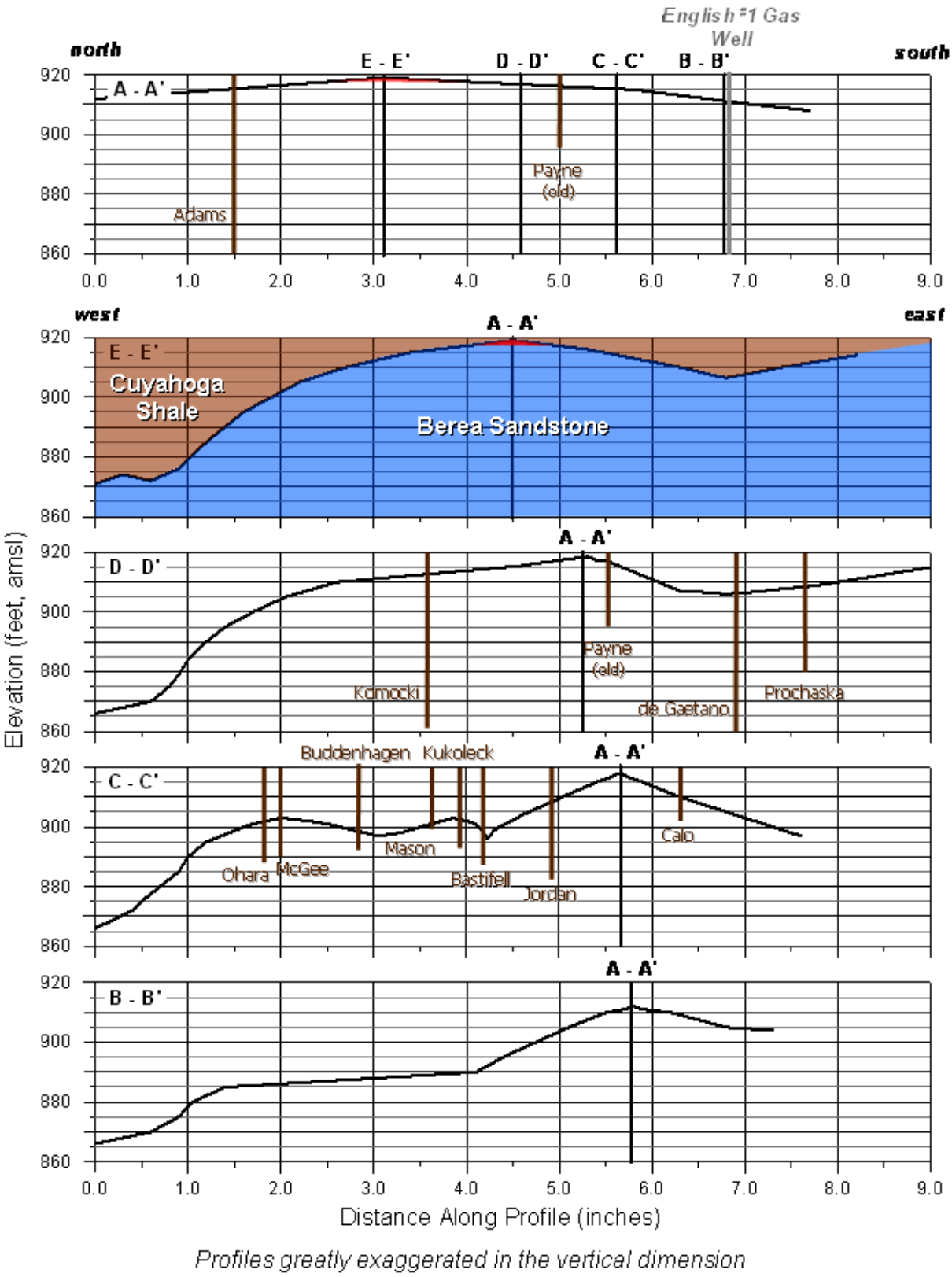

Figure 3-96. Profiles showing configuration of fugitive gas zone in Berea Sandstone, Stage 3 – December 2009 (corresponds to Figure 3-88).

The Adams Well Quandary

The wellhead LEL data and the information from the two borehole videos taken in the Adams well (17820 English Dr) are difficult to interpret and appear inconsistent with respect to the same types of information obtained from nearby wells on English Drive. The wellhead LEL data from the Adams well, which are presented in the next section in this chapter, show that natural gas was present in the Adams well on the first day wellhead LEL measurements were taken (December 19, 2007). The first borehole videotape taken in the Adams well, May 14, 2009, only showed natural gas emanating from the bottom of the wellbore in the Bedford Shale. Because the hydraulic fracture analysis (Chapter 2) ruled out creation of large, deep fractures connecting commercial gas reservoirs with the Berea Sandstone and other shallower geologic units, the gas detected in the Adams well on December 19, 2007, and perhaps thereafter, may be normal natural gas, as opposed to fugitive natural gas emanating from the annulus of the surface-production casing in the English #1 well. The likelihood of fugitive gas migrating up to the high point in the top of the Berea Sandstone surface and then filling the closed structure in the top of Berea Sandstone surface with enough fugitive gas to completely fill the structure through the entire thickness the Berea Sandstone plus the upper part of the Bedford Shale, is truly remote.

One difficulty in making this analysis is that the detection of gas in the first borehole video taken in the Adams well was severely hindered by the dense growth of bacteria along nearly the entire length of the cased and uncased borehole (Figure 3-32). As a result, it was difficult to see even large gas bubbles, let alone gas source zones. Another difficulty in making this analysis is that the second borehole video taken in the Adams well was taken the day after the well was cleaned by a professional contractor (Harper Well & Pump Services) to remove bacteria. The well cleaning may have temporarily purged the natural gas from the deeper source previously detected in the Bedford Shale. The second borehole video, taken on April 1, 2010, only shows gas emanating from a small bedding plane opening in the Cuyahoga Shale.

By April 1, 2010, fugitive gas could have reached the Adams well, but it is not likely. The most likely source of the gas detected in the Adams well is natural gas (not fugitive gas) derived from the Ohio Shale, but there are not sufficient data to make this interpretation with certainty. Nor are there sufficient data to make any other interpretation as to the source of the gas in the Adams well. It is a quandary. Worth noting is that natural gas also is present in the police station well (8353 Bainbridge Rd), the Pierce well (8139 Bainbridge Rd), and the Cloninger well (7780 Bainbridge Rd), but these the wells are all outside the closed structure on the top of the Berea Sandstone (Attachment 4), which is consistent with the occurrence of natural gas (not fugitive gas) in these wells.