Assessment of Hydrocarbon Seepage on Fort Peck Reservation, Northeast Montana: A comparison of surface exploration techniques.

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ABSTRACT: Surface exploration techniques have been employed in separate study areas on the Fort Peck Reservation in northeastern Montana. Anomalies associated with hydrocarbon seepage are documented in all three areas and a variety of surface exploration techniques can be compared. In a small area with established production, headspace gas and thermal desorption methods best match production; other methods also map depletion. In a moderate-size area that has prospects defined by 3D seismic data, headspace gas along with microbial, iodine, and Eh soil anomalies are all associated with the best hydrocarbon prospect. In a large area that contains many curvilinear patterns observed on Landsat images, that could represent micro-seepage chimneys, results are preliminary. Reconnaissance mapping of magnetic susceptibility (MagSus) identified a potential prospect; subsequent soil probe gas and head gas surveys suggest hydrocarbon potential. DOE Contract #DE-FG26-00BC15192.

Oil has been produced on the Fort Peck Indian Reservation for 50 years. The Fort Peck Tribes have been actively engaged in exploration and production activity during the past 17 years. A recent grant from the United States Department of Energy has provided an opportunity to assess the utility of surface exploration technology in prospect characterization. The primary objective of the DOE grant is to conduct surface geochemical and non-seismic, geophysical sampling of soils above geologic or geophysical anomalies that have hydrocarbon potential.

The small Palomino Oil Field has production that provided a test of utility for the various surface exploration techniques. The Wicape Prospect Area is intermediate in size. Despite no established production, this area does have 3D seismic structural prospects. The largest study area is Smoke Creek and has a variety of anomalies documented by stratigraphy, structure, geophysics, and remote sensing. Some of these anomalies have potential to be hydrocarbon prospects in an area with sparse drilling.

To compare a variety of **surface exploration techniques**, a number of independent labs were employed for analysis. Soil probe gas analyses were done in-house for the Smoke Creek Area.

Table 1 lists the methods used in this study. Direct techniques measure hydrocarbons liberated from soil particles or interstitial space. Propane is used to map the correlation of soil gas anomalies with structural features believed to contain underlying oil reservoirs. Indirect techniques measure indicators that theoretically are related to the distribution of hydrocarbon gases. When gases migrate vertically along seeps, geochemical changes occur in the mineralogy of the surface soils. The resulting signatures are thus the tops of diagenetic "chimneys" that are rooted in a subsurface oil accumulation. In order to apply a uniform methodology across all data, an anomaly index was calculated (1.5 times the mean). All values for each area were then divided by the anomaly index in that area, to create a ratio. Any ratio greater than 1.0, is thus an anomaly, indicating hydrocarbon seepage.

The **Palomino Oil Field** produces from the Nisku Formation (Devonian). This six-well field was discovered in 1980 and has a EUR of 2.8 MM Bbls. The field is located on a structural high (Fig. 2) that is somewhat elongate to the northeast. The sample array covers less than 4 sq mi (10 sq km) and the data sets are summarized in Table 2.

Two direct techniques are mapped Fig. 2. Propane values are contoured because they display patterns similar to the other direct techniques and are not altered by biogenic surface processes. Head gas propane contours match oil production and structure well (Fig. 2A). Acid extract propane patterns show a similar northeast orientation (Fig. 2B), but the low values indicate depletion over the main area of production. Figures 2A and 2B display the anomaly ratio for each respective method in relation to an estimated drainage area labeled "oil closure". The inner black line is the

Table 1: Surface Hydrocarbon Exploration Methods Employed

Technique	Theoretical Basis	Anomaly	Analytical	Data Reported
Direct				
Head Space Gas	Water in sample jar dissolves adsorbed light gases.	Apical	FID GC	C1-5 (ppm)
Acid Extract	Acid frees occluded light soil gases.	Apical	FID GC	C1-4
Thermal Desorption	Heat frees adsorbed light soil gases.	Apical	FID GC	C1-5
Soil Gas Probe	In-situ sampling of soil light gases.	Apical	FID GC	C1-4
Soil UVF I, II	Soil fluorescence of med. weight gases.	Linear (Fracture)	FID GC	Naphthalene Phenanthrene
Indirect				
Soil Microbial I, II	Hydrocarbon-feeding bacteria in soil.	Apical	Butane Growth Cultures	Density, avg., %.
Iodine	Soil H/C attracts iodine.	Apical	Titration and colorimetric.	Iodine
Eh	Reducing soil Eh above seep.	Apical Low	Ion electrode probe.	mVolts
PH	Relatively greater pH above seep.	Weak Apical with Strong Halo	Ion electrode probe.	pH
K	Salts precipitated in high pH soils.	Halo	Ion electrode probe.	microhos
Magnetic Susceptibility	Easily magnetized ferrous minerals precipitated in low Eh environment.	Apical	Meter measures magnetic susceptibility.	cgs

structural crest of the field. In an effort to confirm the anomaly type observed on the maps, ratio data for each method was gridded both inside and outside the oil closure line. This comparison is summarized in Table 2.

Essentially the correlation index compares the average ratio inside and outside the oil producing area. Again, a ratio of 1.0 or greater means the data is anomalous, indicating hydrocarbon micro-seepage. No ratio in Table 2 is > 1.0 because not all of the gridded values fall entirely within the oil closure (apical) or entirely outside (halo). This is due to insufficient structural control and soil sampling density. However some ratios vary by at least 50% and thus are used as an indication of whether the anomaly is apical (ratios higher) or halo/depletion (ratios lower) inside the oil closure area. Ratios that are similar indicate uncertainty in determining the anomaly type. This procedure confirms that head gas propane is apical and acid extract propane is a Depletion or Halo anomaly.

The **Wicape Prospect Area** is one of the largest blocks of unexplored land owned by the Fort Peck Tribes (25 sections). Within the survey area of about 8 sq mi (21 sq km), 210 sample sites are distributed along 18 east-west profiles. Data for this area is summarized below in Table 3. Propane data maps for two direct techniques are shown in Figure 3. The head gas data clearly mark both the eastern and western seismic prospect. Outlines of the seismic anomalies are plotted in Figure 3 and shown in relation to the anomaly Index lines (ratio of 1.0 or greater). There is excellent correspondence between the two for the head gas method. The acid extract map shows a general halo anomaly around the eastern prospect, but has no distinctive patterns near the western prospect. A correlation index was applied to the Wicape data in similar fashion as described above for Palomino Field. However, Table 3 goes a step farther by addressing whether observed halo patterns were verifiable by statistical analysis.

Table 2. Palomino Oil Field Data Summary

| Technique | Field Data: 27 sample sites | | | | Correlation Index | | | |
	Minimum Value*	Maximum Value*	Mean Value*	Anomaly Type (Map)	Anomaly Factor (1.5 x mean)	Oil Closure Ratio	Outside Ratio	Anomaly Type (Index)
Direct								
Head Gas-propane	0.23	9.43	4.30	Apical	6.45	0.74	0.56	Apical
Acid Extract-propane	0.17	28.38	11.05	Depletion	16.57	0.49	0.79	Depletion
Thermal Desorption-propane	3.22	12.96	8.74	Partial apical	13.12	0.65	0.64	None
Soil Gas-propane	0.14	1.64	0.70	Both	1.05	0.52	0.37	Apical
UV Soil Fluorescence I	11	35	23	Apical	34	0.72	0.67	Partial Apical
UV Soil Fluorescence II	122	577	253	Partial apical	380	0.67	0.69	None
Indirect								
Soil Microbial I	0	43	10	Partial apical	15	0.66	0.79	Depletion
Soil Microbial II	12	62	38	Depletion	57	0.71	0.64	Both
Iodine	0.1	6.8	1.7	Depletion	2.5	0.46	0.84	Depletion
Eh	-295	-7	-140	Apical Poor	-209	0.72	0.66	Apical Poor
PH	6.47	7.87	7.44	Halo	7.83	0.95	0.94	None?
Conductivity	392	6460	1151	Apical	1727	0.56	0.68	Partial Halo
Mag Susceptibility	29	98	56	Partial Halo	84	0.65	0.69	Poor Halo

*See Table 1 for description of techniques and units
Correlation Index Ratio = mean of data divided by Anomaly Factor.

Table 3. Wicape Area Data Summary

Technique	Mean Value*	East Anomaly Type (Map)	Correlation Index Anomaly Factor (1.5 x mean)	West 3D Ratio	East 3D Ratio	Outside Ratio	East Anomaly Type (Index)	East Core Ratio	East Halo Ratio	East Halo to Core Ratio	!East Halo Confirm
Direct											
Head Gas-propane	3.97	Apical	5.96	0.93	**1.84**	0.53	**Apical Only**				
Acid Extract-propane	8.69	Halo	13.03	0.16	0.59	0.74	Halo	0.60	0.76	1.27	Yes
Soil Gas-propane	0.51	Both	0.76	0.38	0.37	0.56	Halo	0.41	0.45	1.10	Weak
UV Soil Fluorescence	33	Halo/Linear	49	0.81	0.49	0.70	Halo	0.52	0.54	1.04	Very Weak
Indirect											
Soil Microbial II	20.66	Apical	30.99	0.55	**1.04**	0.67	Apical				
Iodine	0.87	V. Sm. Apical	1.31	1.18	0.38	0.059	None				
Eh	47.08	Apical	70, -155	0.38	0.79	0.58	Small Apical				
PH	7.41	Halo	7.91	0.94	0.91	0.93	None	0.92	0.9	0.98	No
Conductivity	1376	None	2065	0.93	0.26	0.76	False Halo				
Mag Susceptibility	52	Halo	77	0.53	0.82	0.65	Halo Ring				

See Table 1 for description of techniques and units. Correlation Index Ratio = mean of data / anomaly Factor.

Table 3 attempts to confirm two map observations; 1) Are apical anomalies present over the two seismic prospects? Or, 2) Are there halo anomalies associated with the seismic prospects? Depletion is not relevant here because there has been no oil production. The head gas method has a correlation index of 1.84 over the eastern 3D anomaly and is therefore definitely confirmed. The other three direct hydrocarbon measurements listed in Table 3 appeared to have

halo and other anomaly types on the maps. Haloes were verified in all three by gridding the data inside the core of the seismic anomaly (1/2 the radius) and comparing it to a halo ring area. The area from .5 − 1.5 the radius was used because most halo anomalies are not outside the geologic prospect, but rather near the margins of the feature. The East core acid extract C3 ratio is .60 and the halo ratio is .76. Halo confirmation of the other two direct measurements is weaker.

The large **Smoke Creek Area** has no established oil production and few wells, but does have many H/C prospects. These may be associated with a large aeromag anomaly located at the intersection of regional Landsat lineament zones that have influenced strat and structural features below. In addition, Landsat tonal curvilinears are concentrated in the vicinity of the large aeromagnetic anomaly. This evidence suggests the possibility of many H/C micro-seepage chimneys in the area (Monson and Shurr, 1993) and corresponds to a model proposed by Land in 1991. As a consequence, portions of the Smoke Creek Area were evaluated using surface exploration techniques that were most useful in the other two areas. Because the total area is large, > 250 sq mi (648 sq km), MagSus measurements were made in a reconnaissance survey. 1200 observations were taken in a series of profiles that sampled the core of the major aeromag anomaly, as well as the surrounding townships. Three areas of high susceptibility values emerged from this reconnaissance (Fig. 4): SC Core, Lobo West, and Site 26.

The first two prospect areas have been surveyed with single traverses only. However, the Site 26 Prospect Area was surveyed with a 100-200 meter grid. The MagSus anomaly is on the southeastern end of a structural nose documented in a 3D seismic survey. Figure 4B maps propane contours on soil Gas probe data that mirrored those for the head gas measurements. Indirect techniques had a wide range of utility: soil microbes and iodine (apical), Eh (weak apical), pH and conductivity (partial haloes). Data is summarized in Table 4. Anomaly ratios were calculated over the center of the Site 26 MagSus anomaly (NW/4 of sec.15). This prospect is significant because it lies outside the Smoke Creek Aeromag Anomaly and was initially sampled as a background data, but hydrocarbon seepage anomalies were detected by all of the methods employed.

Table 4. Smoke Creek Area Site 26 Data Summary

Technique	Field Data: 61 sample sites.				Correlation Index: Relative to Mag. Sus.				Comment
	Minimum Value*	Maximum Value*	Mean Value*	Anomaly (Map)	Anomaly Factor (1.5 x mean)	Closure Ratio	Outside Ratio	Anomaly (Index)	
Direct									
Head Gas-propane	0.05	8.21	1.46	Apical	2.20	0.96	0.67	Apical	Good correlation west.
Soil Gas-propane	0.00	0.84	0.23	Apical	0.35	0.68	0.48	Apical	Extends farther east.
Indirect									
MagSus	**0.09**	**3.26**	**1.27**	**Apical**	**2.11**			**Apical**	
Soil Microbial II	14.00	80.00	39.00	Apical	59	0.70	0.63	Apical	Extends farther east.
Iodine	0.9	10.7	2.9	Apical	4.3	0.74	0.68	Apical	Extends farther southeast.
Eh	-223.5	294.0	181.9	Apical?	270.3 (1)	0.72	0.74	None	
pH	6.20	8.00	7.20	Partial halo	<2>	0.29	0.37	Partial Halo	
Conductivity	317	1292	727	Partial halo	1091	0.63	0.71	Partial Halo	

*See Table 1 for description of techniques and units. (1)Minimum subtracted from all data to make numbers positive. Mean then divided by 1.5 for factor. <2>anomaly Factor calculated by subtracting 7 from pH values and multiplying by 2. Correlation Index Ratio = mean of data divided by anomaly Factor.

Much work remains on going in the Smoke Creek Area. Reconnaissance MagSus data will be further evaluated. Measurements of the magnetic total field along three profile lines will be integrated with other data and interpretations. High frequency data, which was removed from the aeromagnetic data to model deep structure, is being re-examined as a possible indicator of surface hydrocarbon micro-seepage. And, curvilinear features mapped on Landsat images will be closely compared with a variety of data sets. All of this activity is aimed at evaluating the curvilinears as signatures for diagenetic chimneys and at further defining and refining potential hydrocarbon prospects.

A **summary** of map observations in each of the 3 study areas is presented in Table 5. Surface exploration techniques are arranged in an approximate order of usefulness. Head gas emerges as the most functional of the direct techniques. Acid extract and thermal desorption measurements are also generally useful. Soil gas works well if sampling density is sufficient. UV soil fluorescence is of limited utility in evaluating structural trap reservoirs, but has usefulness in designating faults or fractures associated with a petroleum system. Among the indirect observation techniques, soil microbial and iodine data are most useful. Eh, pH, and conductivity also show some utility and should be used only in a multi-disciplinary program. MagSus appears to be helpful, but needs more evaluation. Although surface exploration techniques did not all have equal utility, almost all had some kind of pattern that mapped the location potential oil traps.

Table 5: Comparative Summary of Surface Exploration Methods

Technique	Palomino	Wicape	Smoke Creek
Direct			
Head Gas	Best correspondence	Corresponds with prospects	Corresponds
Acid Extract	Depletion signature	Halo on east prospect	Not surveyed
Thermal Desorption	Partial correspondence	Not surveyed	Not surveyed
Soil Gas	Partial correspondence	Possible halos	Corresponds
UV Soil Fluorescence	Partial correspondence	No correspondence	Not surveyed
Indirect			
Soil Microbial	Inconclusive	Apical on east prospect	Good correspondence
Iodine	Depletion signature	Weak Apical on east prospect	Good correspondence
Eh	Partial correspondence	Apical on east prospect	Inconclusive
pH	Inconclusive	Possible halo on east	Partial Halo
Conductivity	Inconclusive	No correspondence	Partial Halo
Magnetic Susceptibility	Partial Halo	Halo on east prospect	Defines prospect

CONCLUSIONS: Surface exploration techniques clearly document hydrocarbon seepage on the Fort Peck Reservation. Among the direct detection techniques, head gas and acid extract methods are most useful in mapping production and potential prospects; thermal desorption was only tested at Palomino Oil Field and correlated well to production; and the soil gas method has less understandable utility. Indirect techniques that are useful include soil microbial, iodine, and Eh soil analyses. UV soil fluorescence, pH, and conductivity are all relatively inconclusive. Evaluation continues on the utility of MagSus. Hydrocarbon seepage has been assessed in three separate study areas on the reservation. Palomino Oil Field is a small area with established oil production. The Wicape Prospect Area is larger and has at least two 3D seismic prospects. The Smoke Creek Area is very large and appears to have several potential prospects. This sequence of three study areas provides a spectrum of hydrocarbon flux sources that range from small and simple to large and complex. In general, surface exploration techniques are effective aids in mapping production and prospects in all three areas of the reservation.
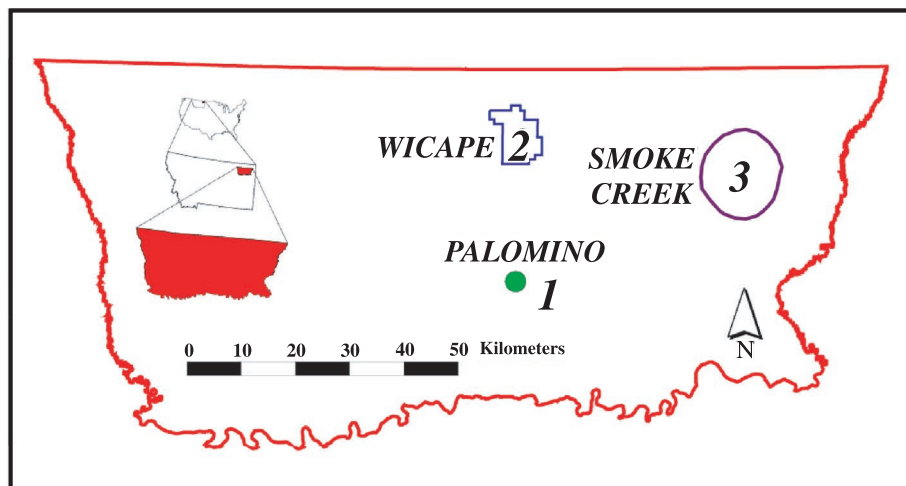
Figure 1. Location of Fort Peck Reservation in Montana, U.S. with surface hydrocarbon study areas: 1 – Palomino Oil Field, 2 – Wicape 3D Seismic Prospect Area, 3 – Smoke Creek AeroMag Anomaly.
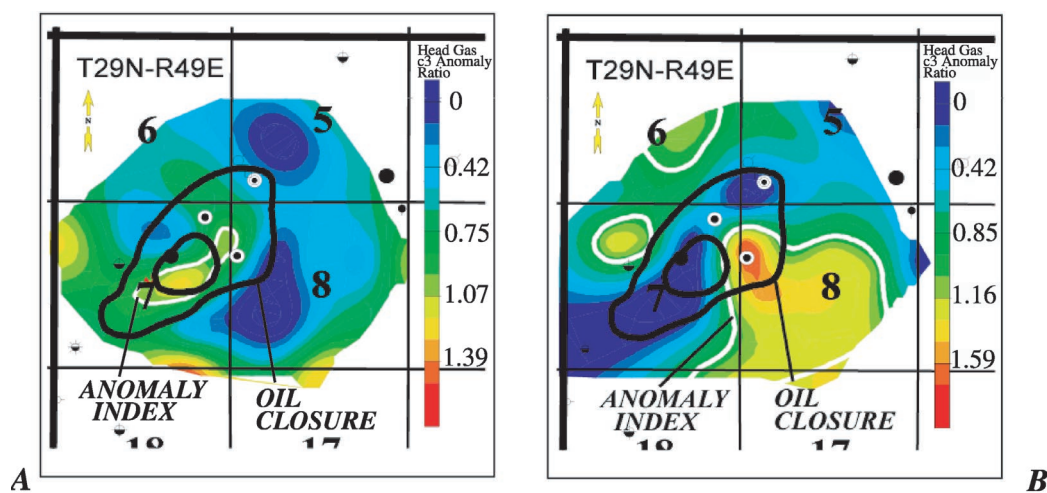

Figure 2. Palomino oil producing closure and structural crest compared to soil head gas anomaly ratio (A) and acid extract anomaly ratio (B).
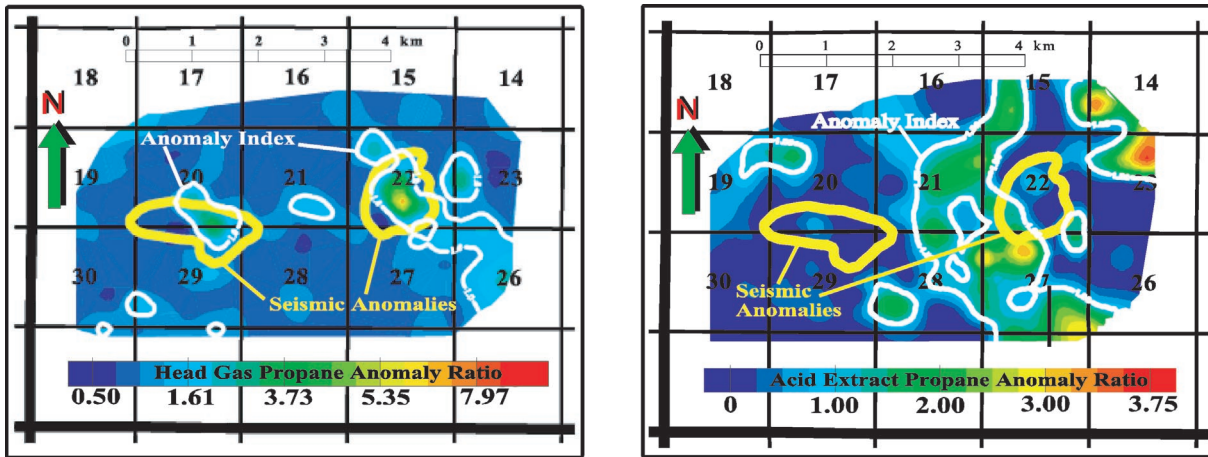
Figure 3. Wicape 3D Prospect Area comparison of seismic closures (yellow) and anomaly index areas (white) for head gas propane anomaly ratio (A) and acid extract propane anomaly ratio (B).

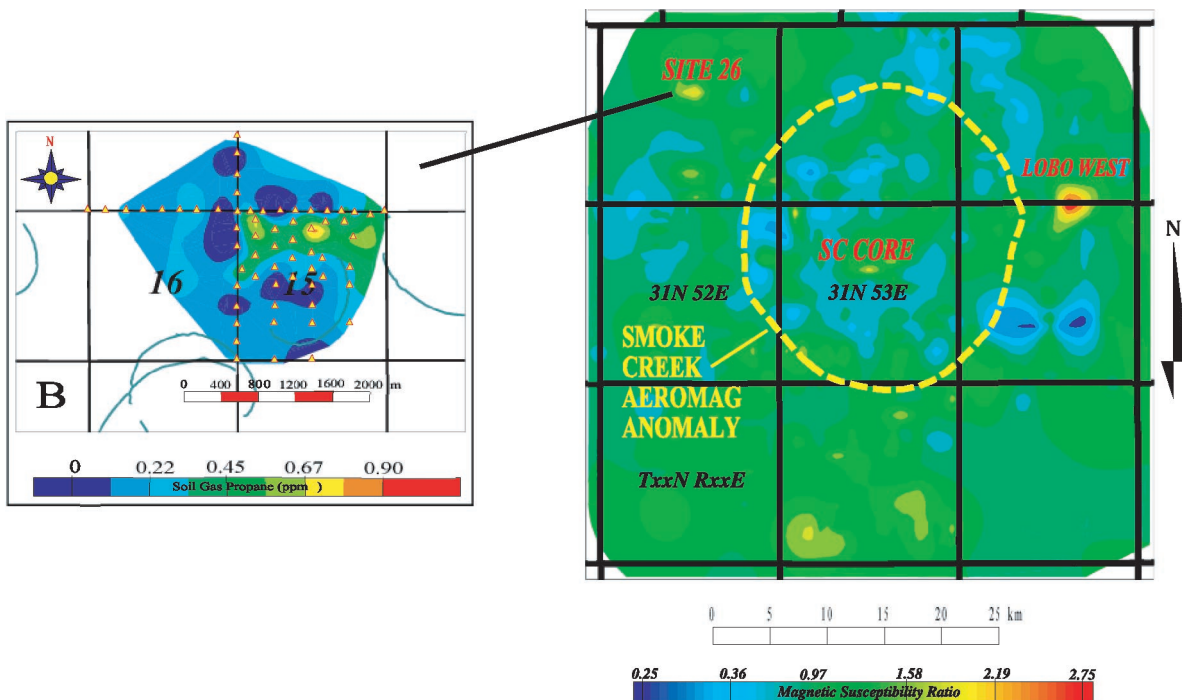**Figure 4.** Smoke Creek Magnetic Susceptibility Ratio (right map) with anomalous areas labeled. Site 26 soil Gas probe propane contoured in B.