Mature Basin Exploration: Detailed Geochemical Surveys Lead to New Pays*

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Abstract

Detailed surface geochemical surveys document that hydrocarbon microseepage from oil/gas accumulations is common, is predominantly vertical, and is dynamic. These characteristics create applications for surface geochemical surveys that are well suited for mature basins: early delineation of field limits, field development, reservoir characterization, identification of by-passed pay, near-field exploration, and monitoring patterns of hydrocarbon drainage. Combined with other uses of surface geochemistry like high-grading leads, and prospects based on likely hydrocarbon charge, these new applications show great promise for better prospect evaluation and risk assessment in mature basins. Because microseepage is predominantly vertical, the extent of an anomaly at the surface approximates the productive limits of the reservoir at depth. The detailed pattern of microseepage over a producing field can reflect reservoir heterogeneity and distinguish hydrocarbon-charged compartments from drained or uncharged compartments. Additionally, since hydrocarbon microseepage is dynamic, seepage patterns change rapidly in response to production-induced changes in fields and waterfloods. Determining the depth or identity of the reservoir responsible for the surface anomaly is challenging but can sometimes be inferred from hydrocarbon composition, from detailed anomaly shape, and from passive electromagnetic data. These applications require close sample spacing and are most effective when results are integrated with subsurface data, especially 3-D seismic data. The need for such integration cannot be overemphasized. Seismic data will remain unsurpassed for imaging trap and reservoir geometry, but only detailed geochemical or microbial surveys can reliably image hydrocarbon microseepage from those same reservoirs. This presentation will be illustrated with examples from the USA, Canada, and South America.

Introduction

High-resolution surface geochemical surveys and research studies document that hydrocarbon microseepage from petroleum accumulations is common and widespread, is predominantly vertical, and is dynamic (responds quickly to changes in reservoir conditions). These characteristics create a suite of applications for surface geochemical surveys that are well suited for mature basins: early delineation of field limits, field development, reservoir characterization, identification of by-passed pay, near-field exploration, and monitoring patterns of hydrocarbon drainage. Combined with other uses of surface geochemistry like high-grading leases, leads, and prospects, these new applications show great promise for better prospect evaluation and risk assessment in mature basins.

Because hydrocarbon microseepage is predominantly vertical, the extent of an anomaly at the surface can approximate the productive limits of the reservoir at depth. The detailed pattern of microseepage over a producing field can also reflect reservoir heterogeneity and distinguish hydrocarbon-charged compartments from drained or uncharged compartments. Additionally, since hydrocarbon microseepage is dynamic, seepage patterns change rapidly in response to production-induced changes. Determining the depth or identity of the reservoir responsible for the surface anomaly is not always possible, but can sometimes be inferred from its chemical and isotopic composition, from detailed anomaly shape, and from passive electromagnetic data.

Hydrocarbon Seepage Characteristics

A seepage continuum exists from visible oil and gas seeps at one extreme, to invisible but analytically detectible at the other extreme. The term Macroseepage refers to the visible oil and gas seeps. Faults, fractures, and outcropping carrier beds are common migration paths for fluid flow in macroseepage. Microseepage is defined as high concentrations of detectible volatile or semi-volatile hydrocarbons in soils, sediments, and waters, chiefly consisting of hydrocarbon gases and aromatic hydrocarbons. The existence of microseepage is supported by a large body of empirical evidence, including (1) increased concentration of light hydrocarbons and hydrocarbon-utilizing microbes in soils and sediments above oil/gas reservoirs, (2) increase in key light hydrocarbon ratios in oil gas above hydrocarbon reservoirs, (3) sharp lateral changes in these concentrations and ratios at the edges of the surface projection of these reservoirs, (4) similarity of the stable carbon isotope ratios for the light hydrocarbon gases in soil gas to those found in underlying reservoirs, (5) and the disappearance and reappearance of soil gas and microbiologic anomalies in response to reservoir depletion and re-pressuring (Price, 1986; Klusman, 1993; Klusman and Saeed, 1996; Matthews, 1996a).

Virtually all effective onshore surface geochemical exploration methods rely on microseepage and its predominantly vertical migration from reservoir to surface. Figure 1 shows the predominantly vertical nature of hydrocarbon microseepage as seen on these two seismic sections. The image on the left is from the Neuquen basin (Connolly et al., 2013), and the image on the right shows the gas chimney over Ekofisk field in the North Sea (Van den Bark and Thomas, 1981). The dominant migration mechanism for microseepage is a continuous phase, buoyancy-driven gas flow. Theoretical studies and empirical observations support the buoyancy of microbubbles as the most logical mechanism for hydrocarbon microseepage, and measured rates for microseepage are commonly 1-3 meters/day (Klusman, 1993; Klusman and Saeed, 1996).

Hydrocarbon Detection Methods

The surface expression of petroleum seepage can take many forms, and these include: (1) anomalous hydrocarbon concentrations in soils, sediments, waters, and atmosphere; (2) microbiological anomalies; (3) mineralogical changes such as the formation of calcite, pyrite, uranium, elemental sulfur, and certain magnetic iron oxides and sulfides; (4) bleaching of red beds; (5) clay mineral changes; (6) acoustic anomalies; (7) electrochemical changes; (8) radiation anomalies; and (9) spectral, biogeochemical and geobotanical anomalies (Schumacher, 1996; 1999). The activities of bacteria and other microbes are directly or indirectly responsible for many of the surface and near-surface expressions of hydrocarbon seepage and microseepage. Their activities, when coupled with long-term migration of hydrocarbons, lead to development of oxidation-reduction zones that favor the formation of such a wide variety of seep-induced geochemical, mineralogical, and geophysical changes in soils and sediments. These varied expressions of hydrocarbon seepage have led to the development of an equally diverse number of hydrocarbon detection methods. Some of these methods are geochemical, some are non-seismic geophysical methods, and some come under the category of remote sensing (Klusman, 1993; Schumacher, 1999; Schumacher and LeSchack, 2002). A detailed discussion of these methods is beyond the scope of this paper, but the more commonly used hydrocarbon detection methods are listed below and on Figure 2. Some of these methods are geochemical, some are biological, some are mineralogical, and some are non-seismic geophysical methods (Schumacher, 1999).

REMOTE SENSING, SATELLITE IMAGERY ANALYSIS
- Detect hydrocarbon-induced alteration of soils and sediment; spectral and hyperspectral signatures; oil slicks; atmospheric hydrocarbon anomalies

AEROMAGNETICS, MICROMAGNETICS
- Detects seep-induced magnetic anomalies in shallow subsurface

SOIL GAS, FLUORESCENCE, HEAVIER HYDROCARBONS
- Measures concentration and composition of hydrocarbon gases, aromatic hydrocarbons, C10+ hydrocarbons in soils and sediments

MICROBIOLOGICAL
- Measures concentration and distribution of hydrocarbon-utilizing bacteria

BIOGEOCHEMICAL, GEOBOTANICAL
- Measures trace elements, vegetation stress, spectral anomalies

ELECTROMAGNETIC, TELLURIC
- Hydrocarbon presence; depth to hydrocarbon-bearing formations

Survey Design

Equally important as selecting the best exploration method(s) for a specific survey – and one could argue even more important – is to properly design the survey for the exploration objectives. Figure 3 lists the main issues that must be considered when designing a surface geochemical survey. Hydrocarbon microseepage data – whether soil gas or microbial or other measurements – are inherently noisy and require ample sample density to distinguish between anomalous and background areas. Matthews (1996b) has reviewed the importance of survey design and sample density in target recognition, and states that under-sampling is probably the major cause of ambiguity and interpretation failures involving surface geochemical studies.

To optimize the recognition of an anomaly, the sampling pattern and sample number must take into consideration the objectives of the survey, the expected size and shape of the anomaly (or geologic target), the expected natural variation in surface measurements, and the probable signal-to-noise ratio (Matthews, 1996b). Defining background values adequately is an essential part of anomaly recognition and delineation; Matthews suggests that as many as 80% of the samples collected be obtained outside the area of interest. We concur with these recommendations for reconnaissance and prospect evaluation surveys; however, for field development surveys optimum results are obtained when numerous samples are collected in a closely spaced grid pattern over the feature of interest. Sample spacing is routinely 100 – 200 meters (330 - 660 feet) or less. Grid designs keep the spatial density of sampling approximately constant and enable more direct correlation with subsurface data, an essential objective in field development or production applications. Figure 4 lists geochemical survey objectives and illustrates various sampling patterns for a Pennsylvanian channel sandstone prospect in Osage County, Oklahoma, and the 3D time slice of the Layton Sand prospect (Schumacher (1999), GeoMicrobial Technologies, and Reeves et al. (1999)).

Survey Objectives in Mature Basins

Specific exploration objectives in mature basins range from (1) reconnaissance surveys to identify geochemical leads for further geologic and seismic evaluation, (2) high-grading exploration leads and prospects on basis of likely hydrocarbon charge, (3) delineation of probable field limits for new discoveries, (4) identification of by-passed pay or undrained reservoir compartments, (5) evaluate infill or step-out drilling locations, (6) document hydrocarbon drainage over time in producing fields, waterflood, or CO_2-flood operations, and (7) identify near-field exploration and development opportunities.

Hydrocarbon microseepage anomalies are identified with detailed soil gas, fluorescence, and/or other geochemical analyses. When such surveys are repeated over the life of a field or waterflood project, the changes in seepage patterns can reflect patterns of hydrocarbon drainage (Tucker and Hitzman, 1994; Rice et al., 2002). The results of such high-resolution surface geochemical surveys nicely complement geochemical analyses of reservoir fluids and their implications for establishing reservoir continuity and reservoir compartmentalization.

These applications require close sample spacing and are most effective when results are integrated with subsurface data, especially 3-D seismic data. The need for such integration cannot be overemphasized. Seismic data will remain unsurpassed for imaging trap and reservoir geometry, but only detailed soil gas or microbial surveys or certain non-seismic methods can reliably image hydrocarbon microseepage from those same reservoirs is shown on Figure 5, Figure 6 and Figure 7.

Figure 5 illustrates a microseepage profile across La Palma field, a recent oil discovery in Venezuela, and clearly shows that the hydrocarbon anomaly extends to the west several kilometers beyond the discovery wells. Figure 6 shows the of hydrocarbon microseepage over Los Manueles field in western Venezuela. The field has been producing since the 1930's and is near the end of its life. A detailed geochemical survey identified a number of strong seepage anomalies shown in dark orange, which could represent areas of bypassed pay. After the survey, two successful new well were drilled in the northeast anomaly. Figure 7 illustrates a hydrocarbon microseepage anomaly map from over Grimes Field in the Sacramento basin. The highest microseepage values are highlighted in yellow, orange, and red colors and occur primarily between wells or over undrilled parts of the field. Lower microseepage values occur near producing wells and are highlighted in blues and greens. Areas of elevated microseepage represent either undrained parts of the reservoir or areas not yet effectively drained. The strong anomaly in the NE corner of the left-hand figure includes two well locations; however, these are directional wells producing from under a pond several hundred meters to the northeast, and not from the reservoir below the surface location.

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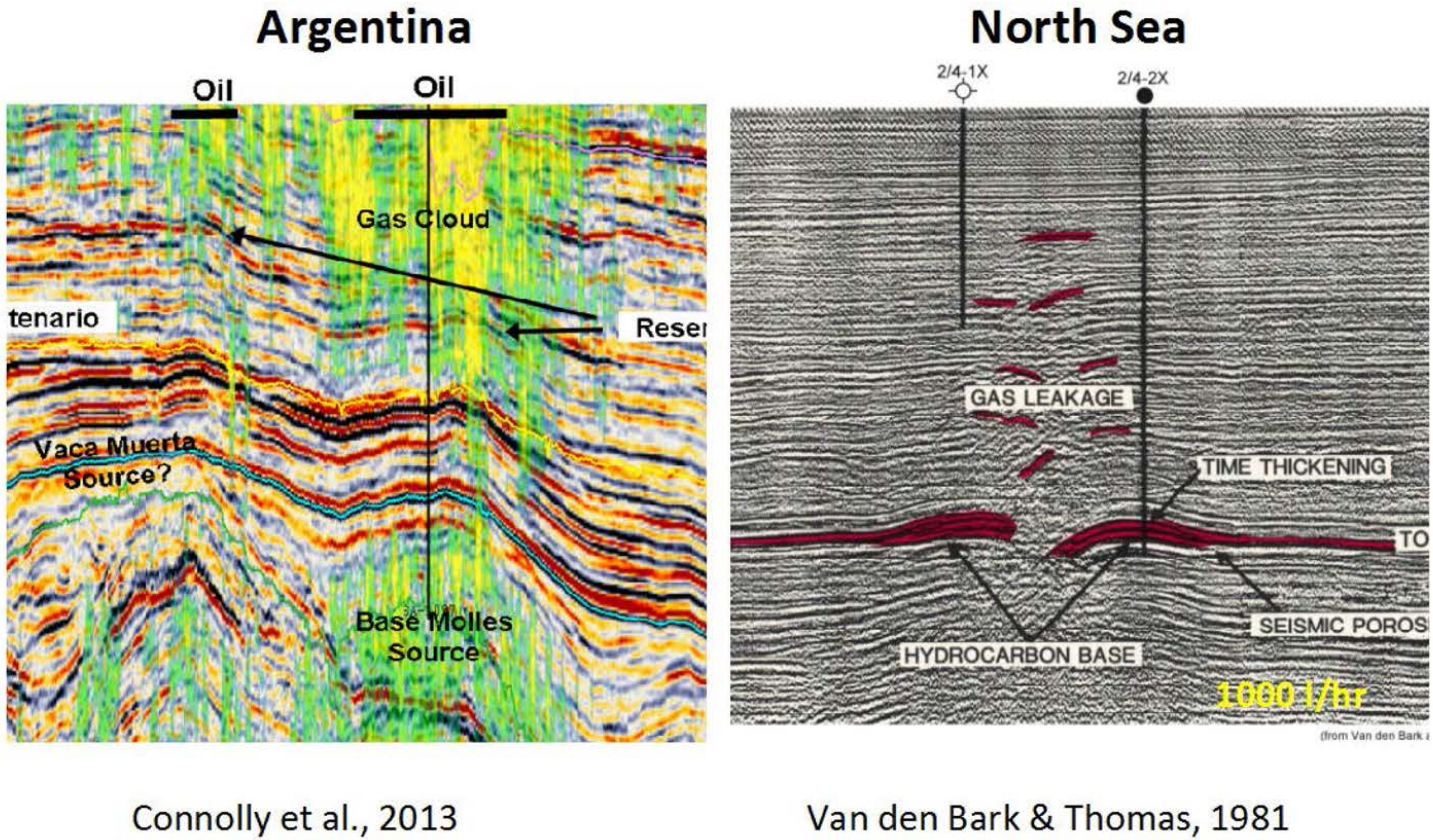


Figure 1. The predominantly vertical nature of hydrocarbon microseepage is illustrated on these two seismic sections. The image on the left is from the Neuquen basin (Connolly et al., 2013), and the image on the right shows the gas chimney over Ekofisk field in the North Sea (Van den Bark and Thomas, 1981).

Geochemical Exploration Methods

Direct Detection

- Soil Gas
  - Interstitial, Headspace
  - Acid Extracted
- Aromatics/Fluorescence
- Passive Soil Vapor
- Heavy Hydrocarbons
- Remote Sensing
  - Spectral Signatures of HCs

Indirect Detection

- Microbial
- Radiometrics
- Helium, Radon
- Iodine
- Trace Elements
- Remote Sensing
- Electrical. EM
- Aeromagnetic

Figure 2. Hydrocarbon detection methods in common usage for oil and gas exploration (Schumacher, 1999).

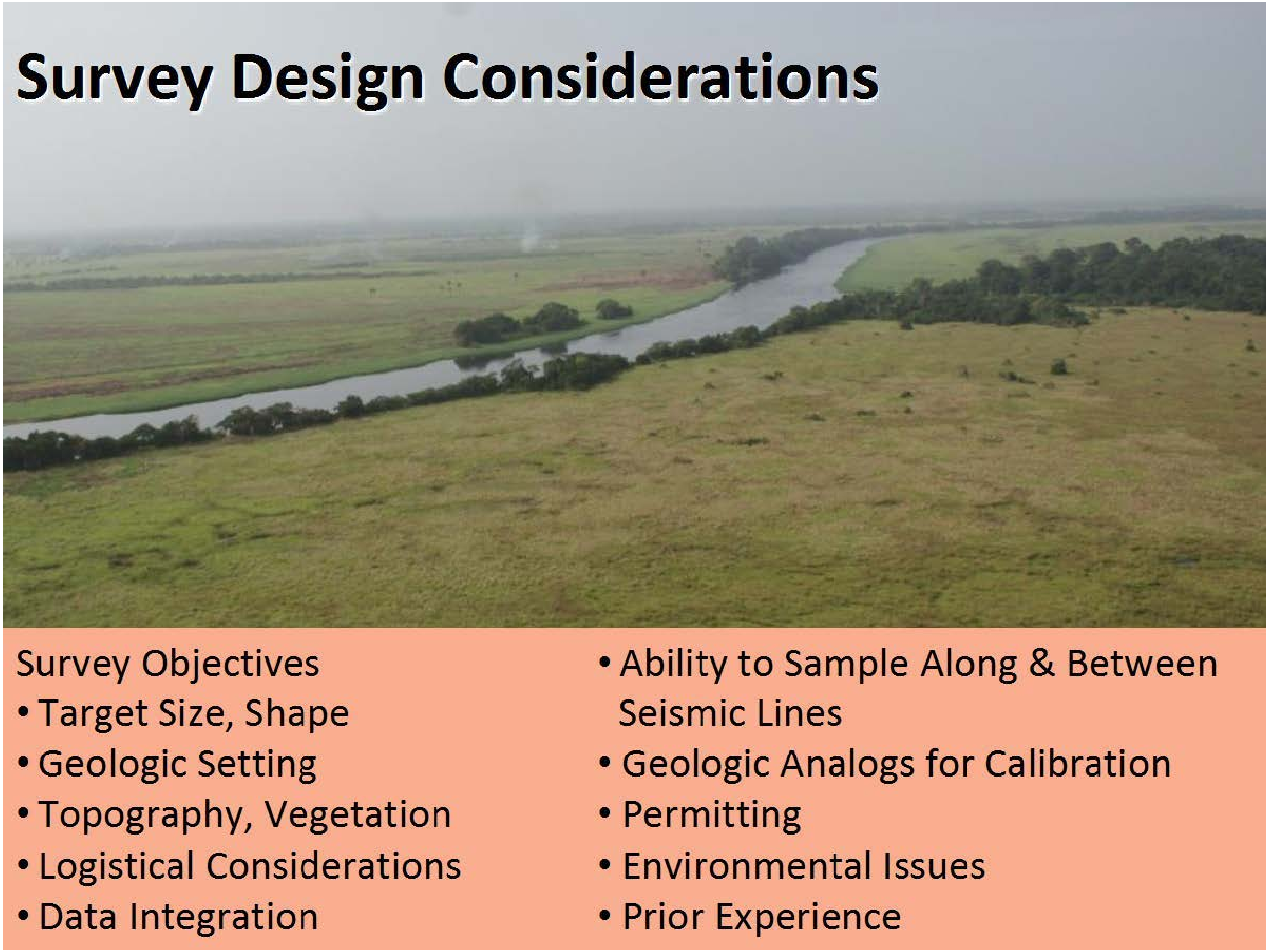


Figure 3. Survey design considerations for surface geochemical surveys for oil and gas exploration (Schumacher, 1999).

Survey Objectives

Reconnaissance
Prospect Generation, Prospect Evaluation
Field Development
Production Monitoring

Images from Schumacher 1999, GMT, and Reeves et al., 1999

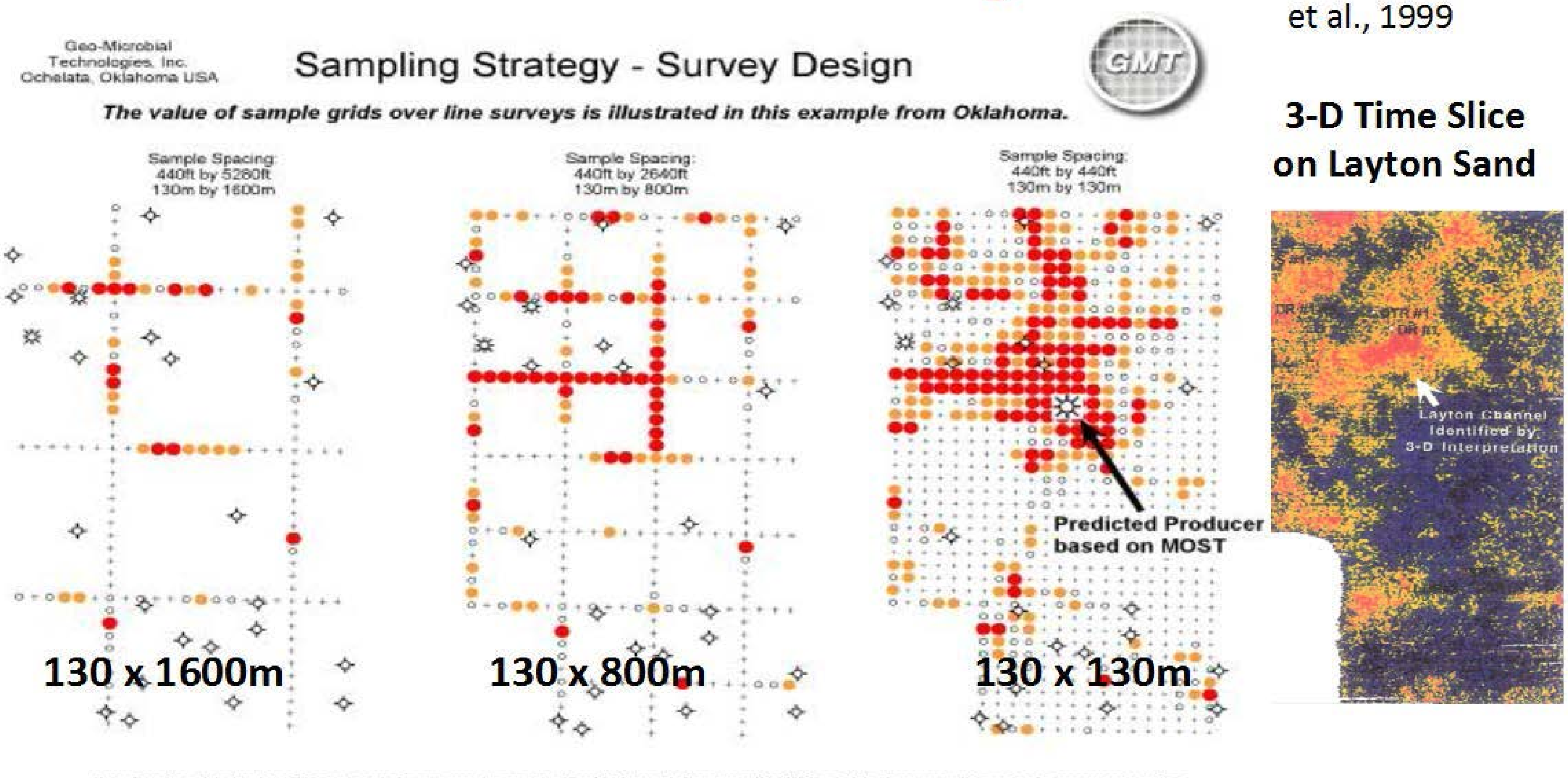
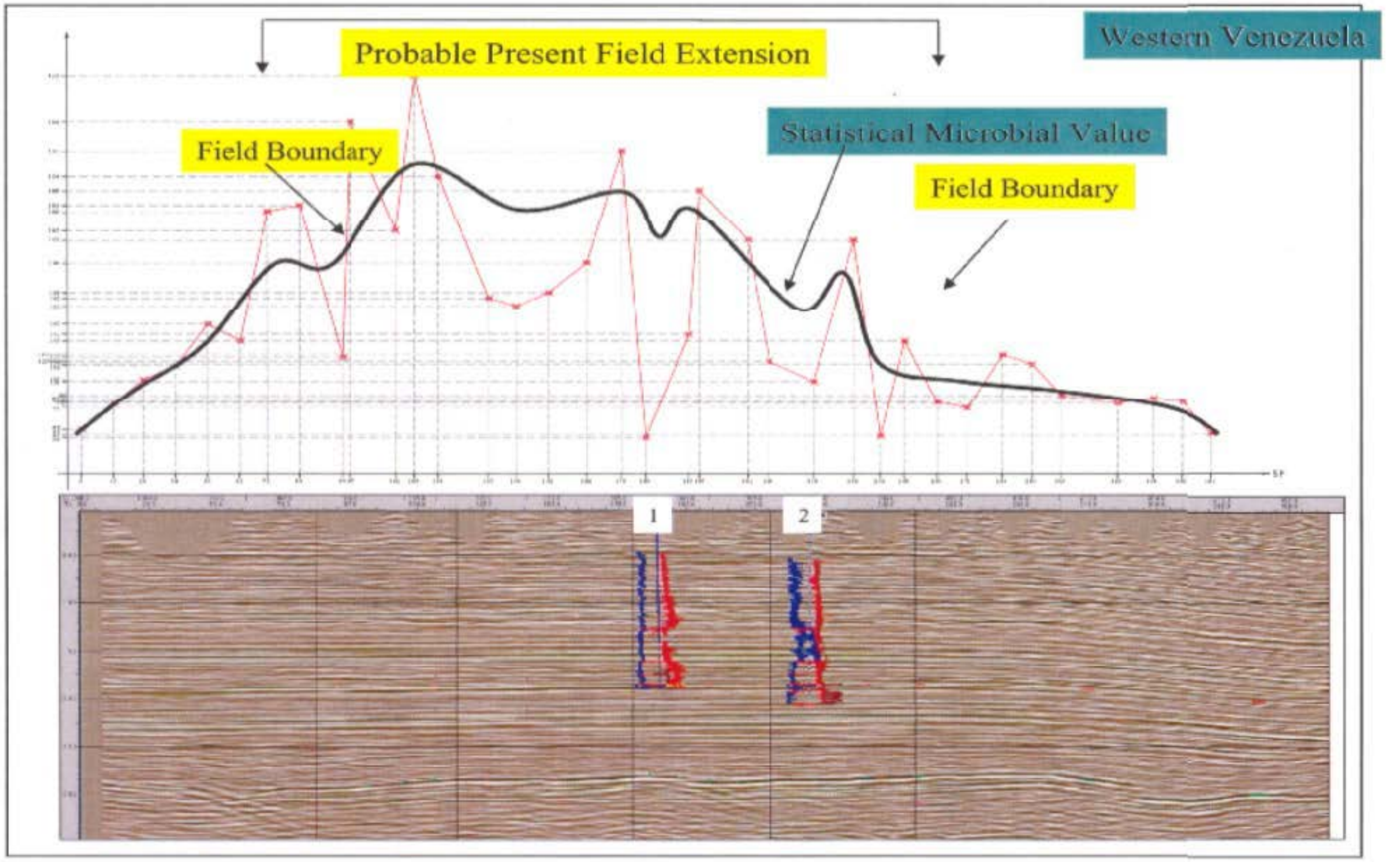


Figure 4. Geochemical survey objectives and various sampling patterns for a Pennsylvanian channel sandstone prospect in Osage County, Oklahoma. Data and images from Schumacher (1999), GeoMicrobial Technologies, and Reeves et al. (1999).

Venezuela, New Field Discovery



Example of a geochemical anomaly associated with a recent discovery in western Venezuela. Microbial samples were collected at 300m intervals along seismic lines to identify the probable limits of the oil/gas field. The most prospective area occurs west of the wells. Also note the low seepage values in the immediate vicinity of the two producing wells; this is due to depressurization of the reservoir due to production.

Figure 5. Hydrocarbon microseepage profile across La Palma field. a recent field discovery in western Venezuela. Although only two wells had been drilled at the time of the survey, the likely extent of the productive reservoir is evident from the microseepage data and extends several kilometers to the west along this seismic line (Schumacher, 2013).

Los Manueles Field, Venezuela

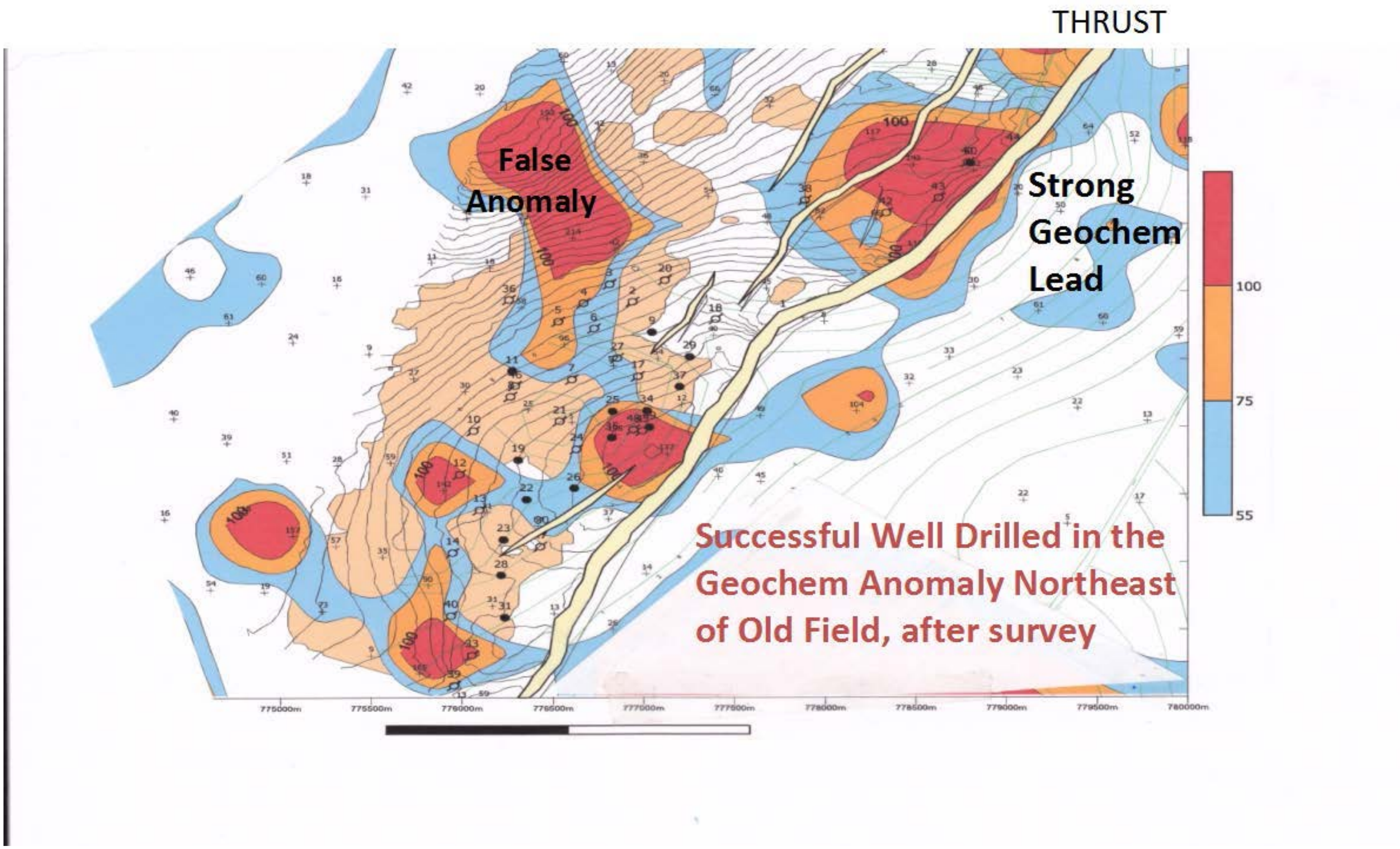


Figure 6. Distribution of hydrocarbon microseepage over Los Manueles field in western Venezuela. The field has been producing since the 1930's and is near the end of its life. A detailed geochemical survey identified a number of strong seepage anomalies shown in dark orange, which could represent areas of bypassed pay. After the survey, two successful new well were drilled in the northeast anomaly (Schumacher, 2013).

Geochemical Expression of Bypassed Pay
Grimes Field, Sacramento Basin, California

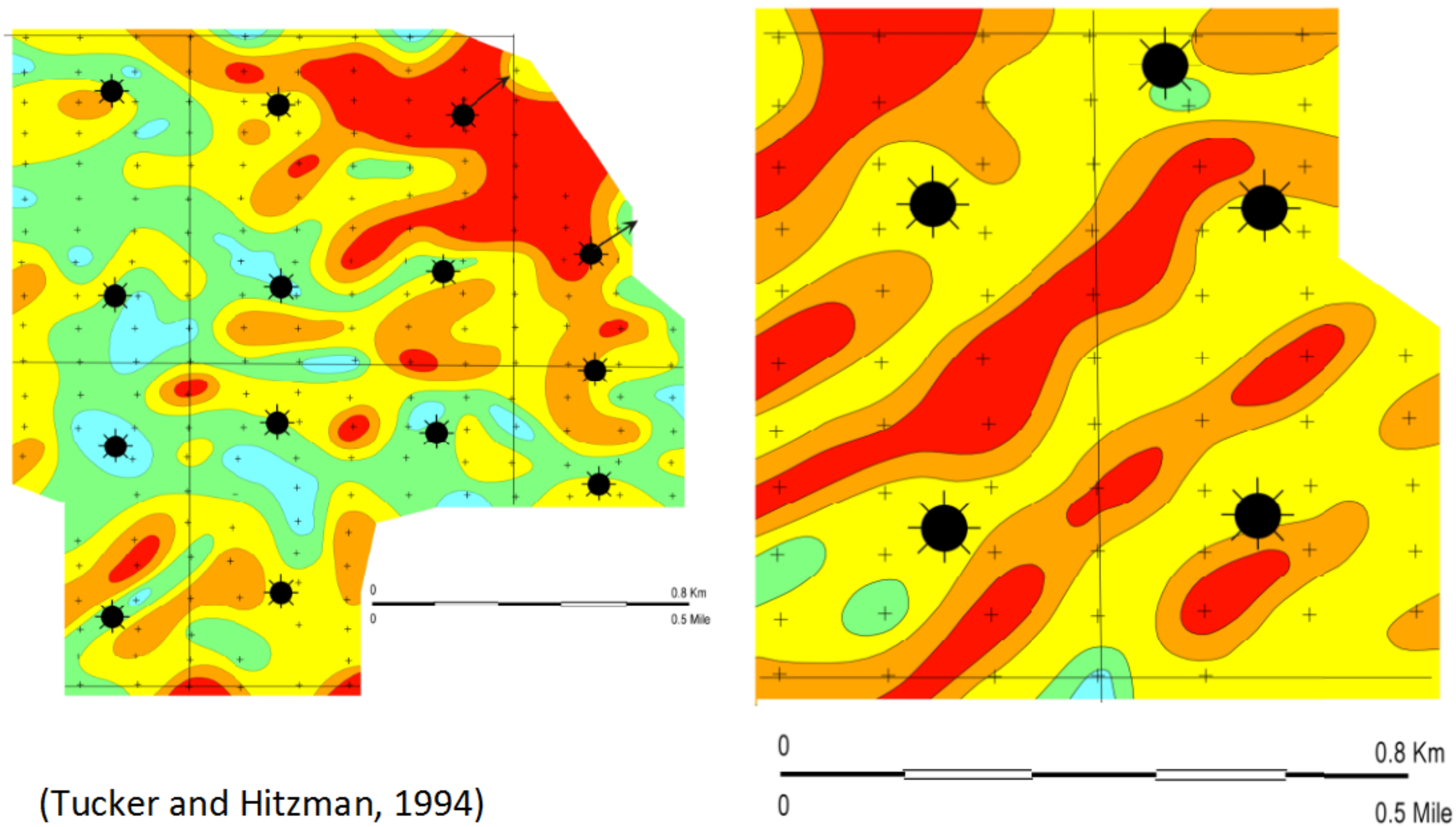


Figure 7. A hydrocarbon microseepage anomaly map from over Grimes Field in the Sacramento basin. The highest microseepage values are highlighted in yellow, orange, and red colors and occur primarily between wells or over undrilled parts of the field. Lower microseepage values occur near wells and are highlighted in blues and greens. Areas of elevated microseepage represent either undrained parts of the reservoir or areas not yet effectively drained (Tucker and Hitzman, 1994).