本多媒体仅用于学术交流，任何单位、个人无权用于其他目的！

页岩气测井技术

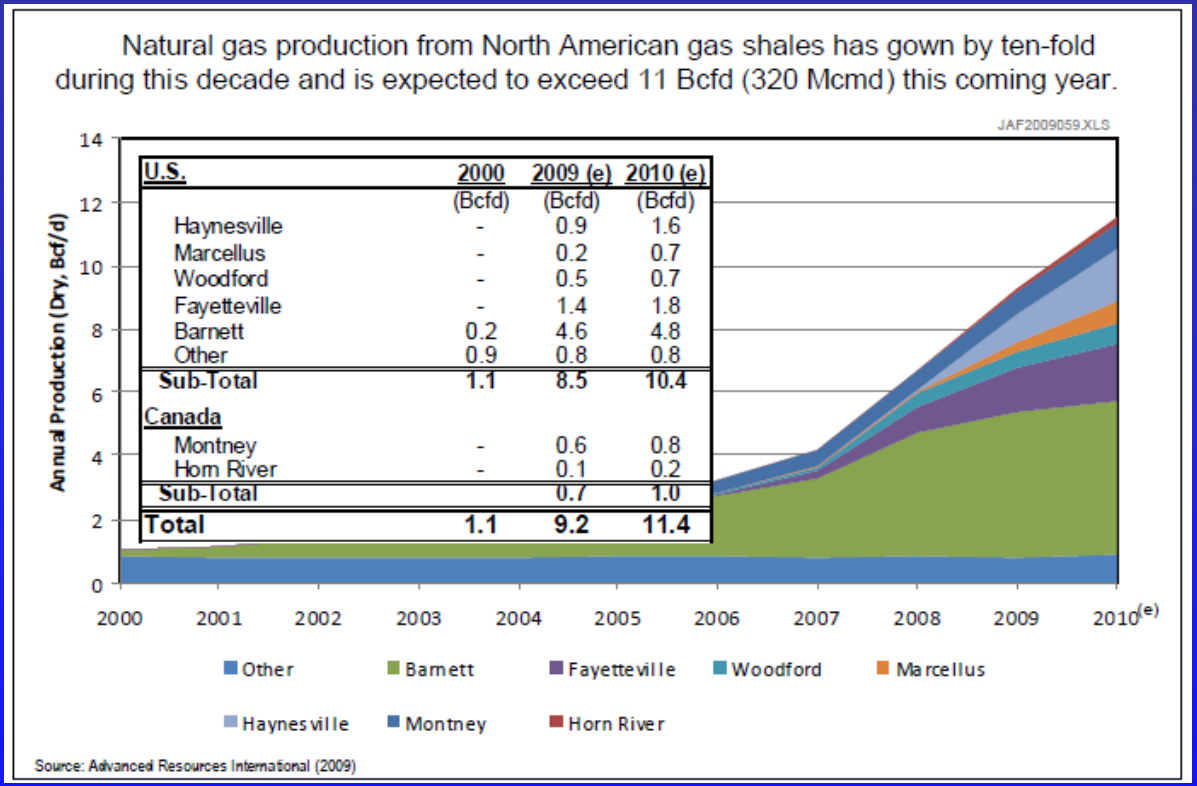
邹长春

中国地质大学(北京)

地球物理与信息技术学院

2011.3.8

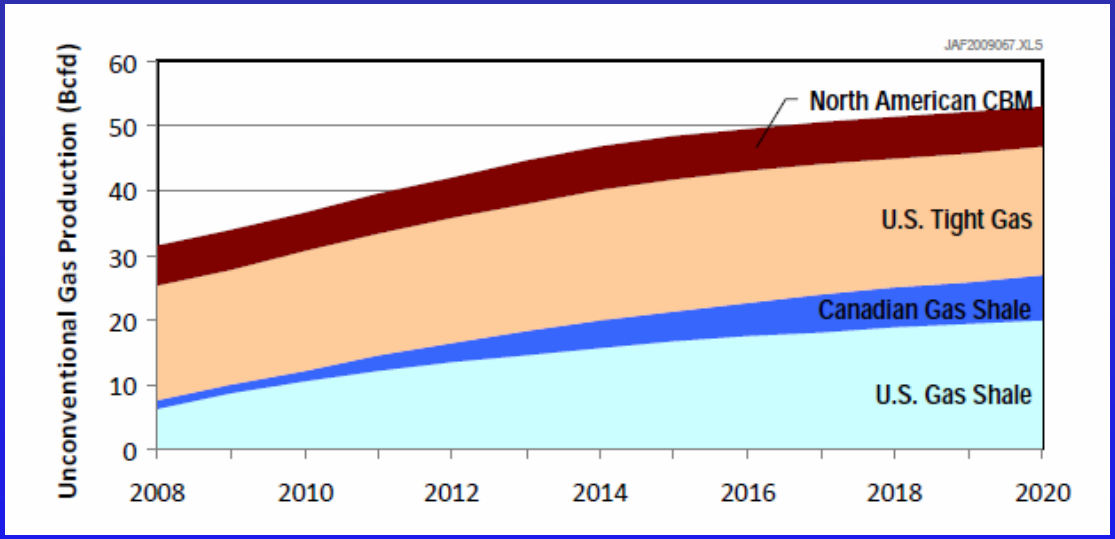
二、研究现状



U.S.	2000 (Bcfd)	2009 (e) (Bcfd)	2010 (e) (Bcfd)
Haynesville	-	0.9	1.6
Marcellus	-	0.2	0.7
Woodford	-	0.5	0.7
Fayetteville	-	1.4	1.8
Barnett	0.2	4.6	4.8
Other	0.9	0.8	0.8
Sub-Total	1.1	8.5	10.4
Canada			
Montney	-	0.6	0.8
Horn River	-	0.1	0.2
Sub-Total		0.7	1.0
Total	1.1	9.2	11.4

世界页岩气资源丰富，资源预测量为$456 \times 10^{12} m^3$（Rogner，2007）。在过去的十年里，北美的页岩气开发取得了飞速的发展，图为美国和加拿大2000~2010年的几个主要页岩气田的产量图（Advanced Resources International, Inc, 2009）。

二、研究现状



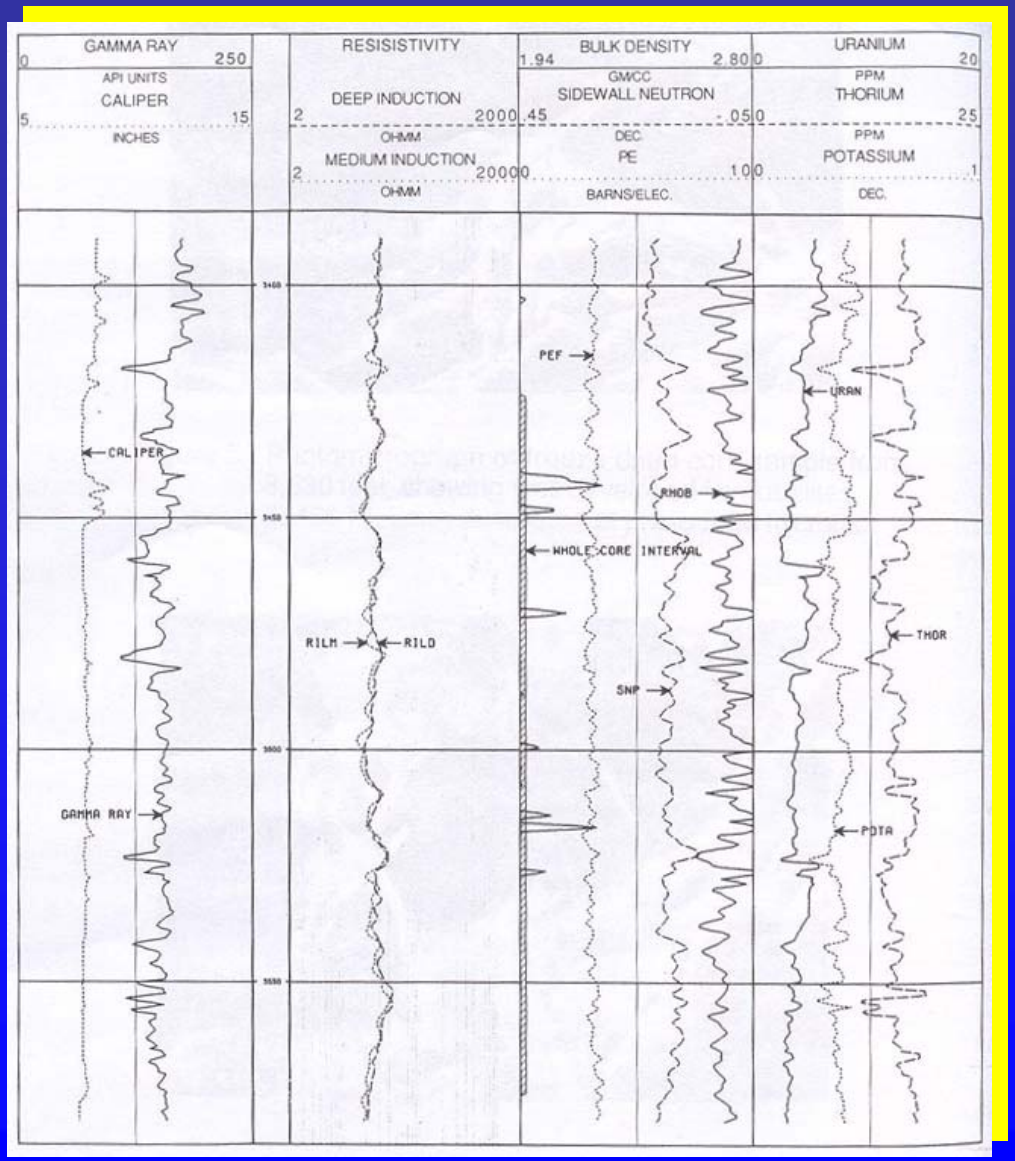
页岩气的发展是解决能源供应不足的一个有效途径。页岩气的快速勘探开发使美国天然气储量增加了40%，预计2010年页岩气产量将占全美天然气产量的15%以上，如图2所示(Advanced Resources International, Inc, 2009)。

二、研究现状

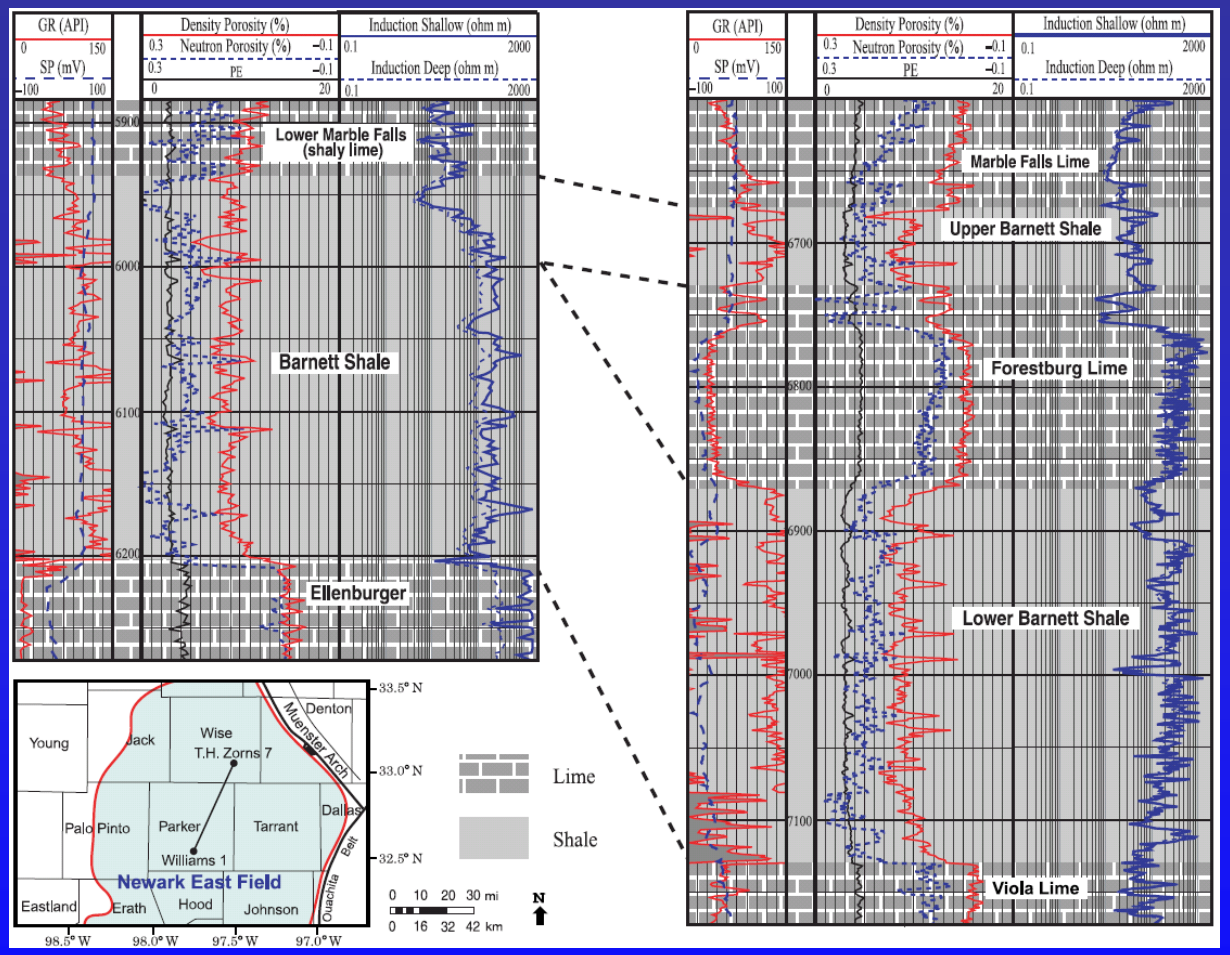
(1)页岩气主要测井方法系列

测井是页岩气勘探不可缺少的技术手段，发挥着十分重要的作用。数十年来，大多数页岩气田均进行了测井数据采集，以满足页岩气储层评价的需要。

根据**Luffel**和**Guidry(1989)**的文献，**Appalachian**盆地大多数采用空气钻井，采用测井系列包括双感应、岩性密度测井、井壁中子、自然伽马能谱。还包括井下电视和温度测井。

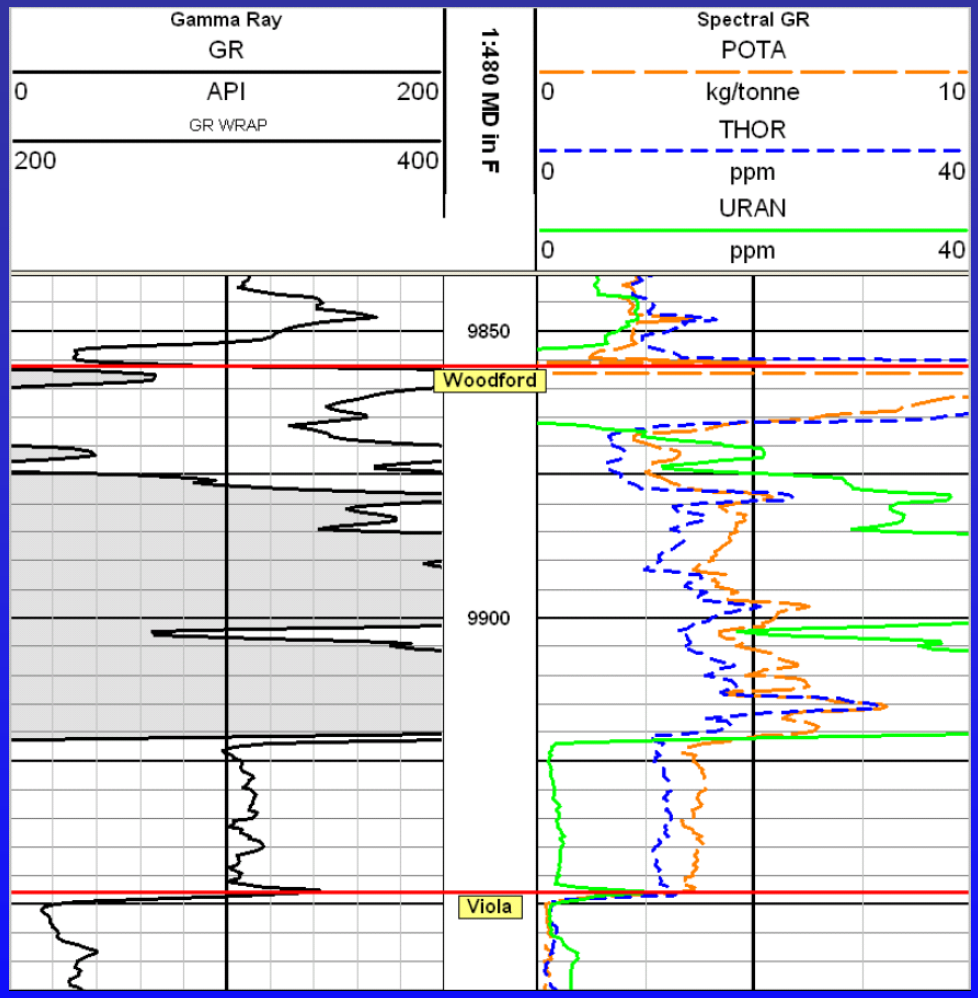


二、研究现状



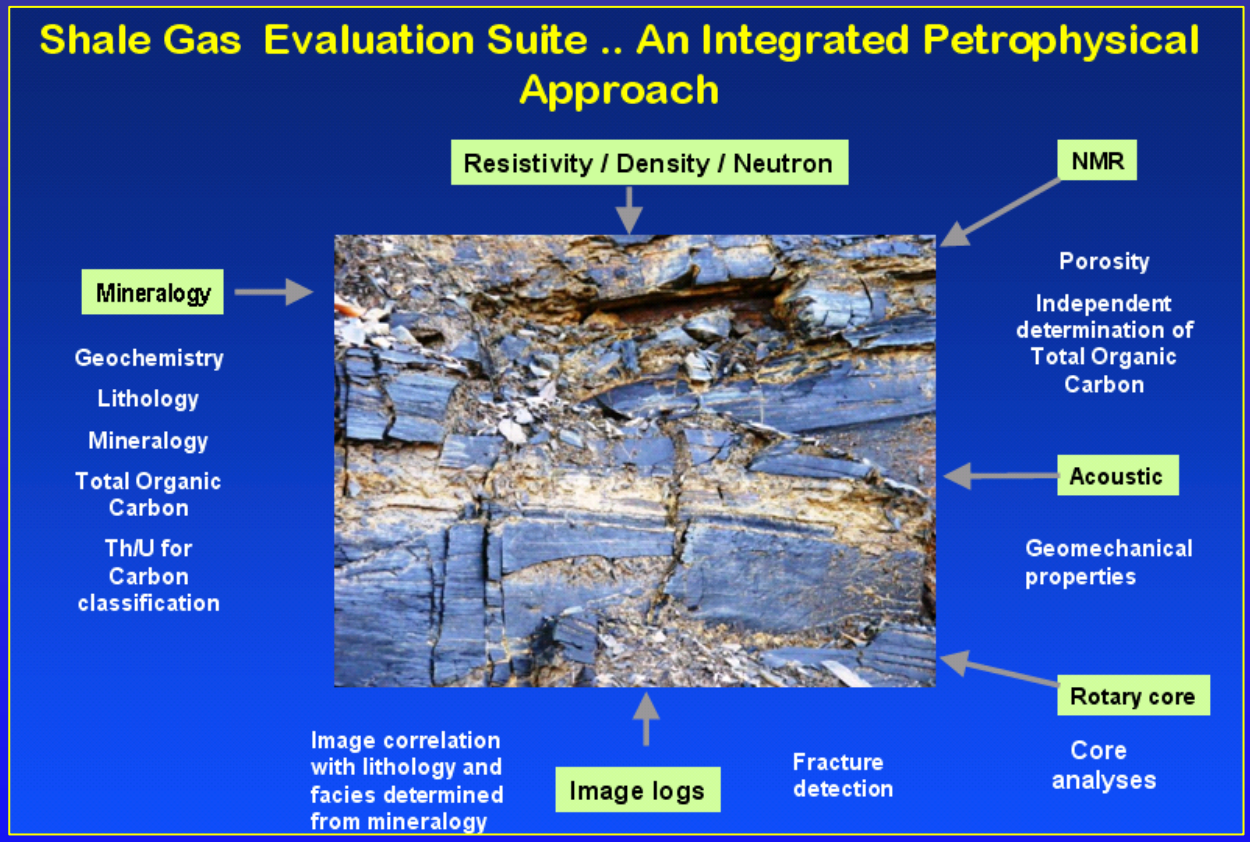
Zhao等(2007)报道了北美Fort Worth盆地泥盆系Barnett页岩典型测井系列，包括自然伽马、密度、中子、岩性密度和感应测井。

二、研究现状



Arkoma盆地Woodford页岩层自然伽马能谱测井实例(Cluff和Miller，2010)，页岩气层总GR和U的数值明显高值。

二、研究现状

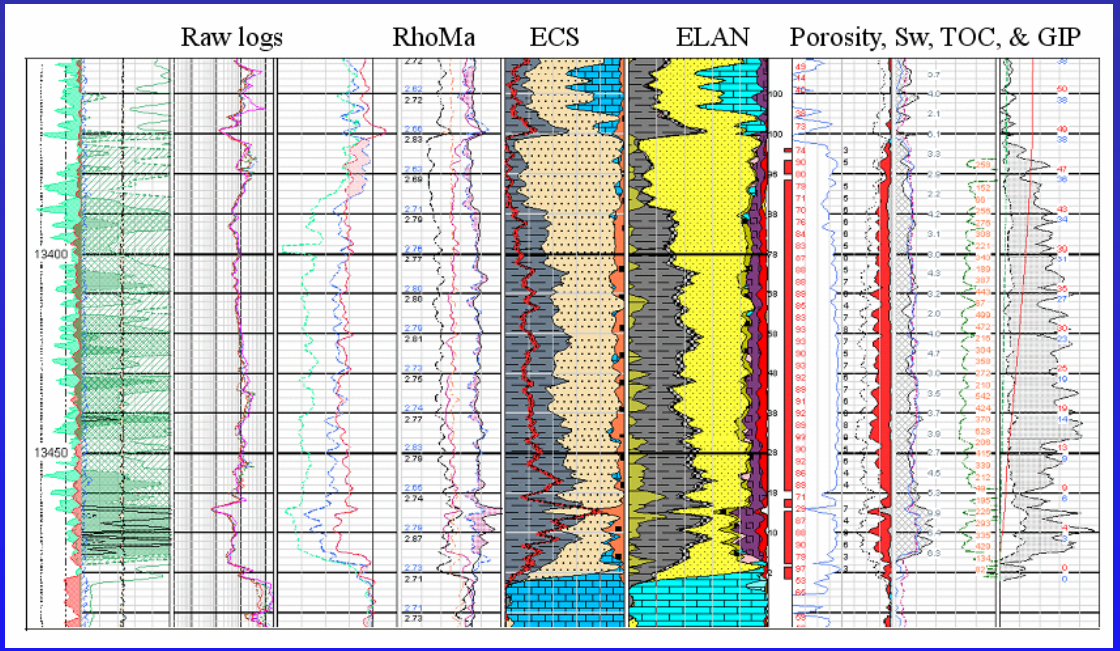


墨菲石油公司(Murphy Oil) LeCompte等（2010）根据页岩气储层评价需求，提出了较为全面的页岩气测井系列，见上图，包括：1)电阻率测井、密度、中子测井；2）核磁共振测井，用于确定页岩孔隙度（不受TOC影响）；3）声波测井，用于岩石力学性质分析；4）成像测井，用于识别裂缝。

二、研究现状

(2)页岩气测井资料处理技术进展

Lewis等（2004）报道了Schlumberger公司的页岩气测井资料处理技术，基于该公司的Platform Express测井软件平台和ECS测井技术，开发了专门的处理软件包。ECS处理模块称为SpectroLith或WALK2，结合密度、中子、Pe、NGS等测井资料，通过随机求解方法可计算出岩性成分、孔隙度、含水饱和度、干酪根含量、TOC、GIP等参数。



上图给出了含气页岩储层的测井资料ELAN程序处理结果（Cluff和Miller，2010）。

二、研究现状

(3)页岩气测井资料解释技术进展

在页岩气储层评价中，测井资料可以进行定性和定量解释。

定性解释内容包括识别岩性，判断含气页岩层，识别裂缝等。

定量解释内容包括:

确定矿物成分;

计算孔隙度、渗透率;

计算干酪根含量/总有机碳含量(TOC)、吸附气和游离气含量;

计算热成熟度和热成熟度指数(MI);

计算储层厚度;

计算弹性参数;

评价天然气地质储量(GIP)等。

二、研究现状

1)识别岩性和计算矿物成分

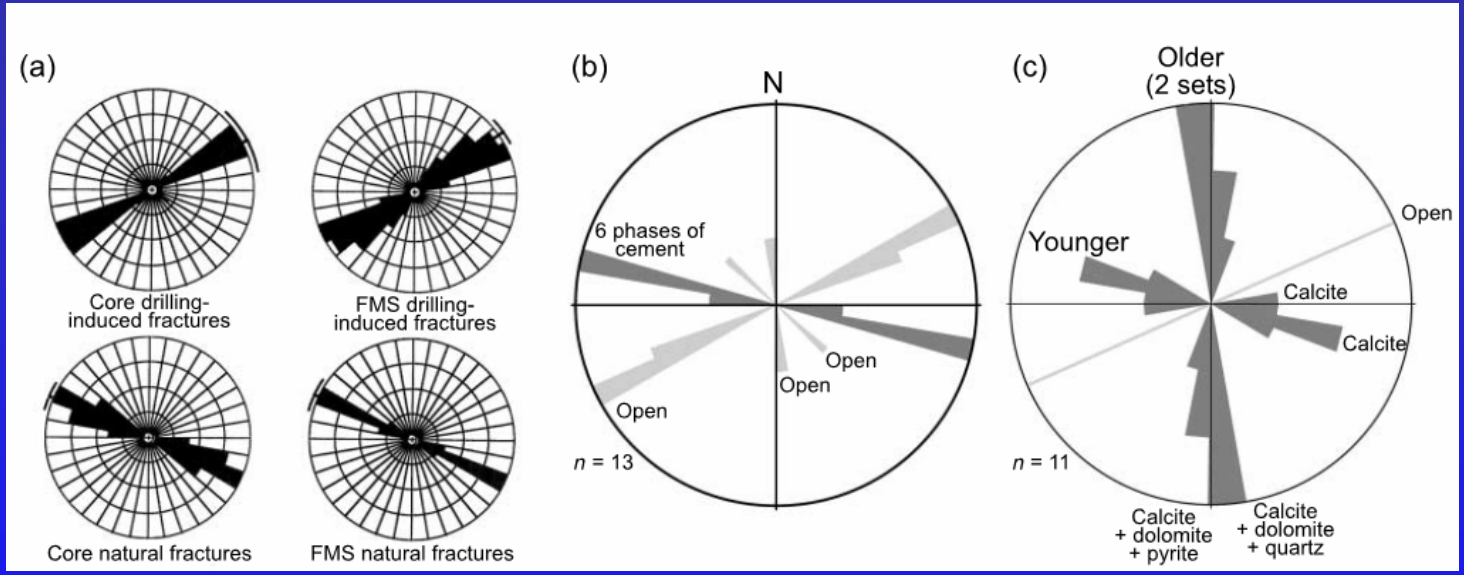
Gary等2011年Appalachian盆地中泥盆系Marcellus地层的页岩气储层进行了识别。Scott等2008年利用测井资料划分了德克萨斯Fort Worth盆地密西西比纪Barnett页岩气储层岩性。Travis J. Kinley等2008年利用测井资料识别了德克萨斯特拉华盆地密西西比纪页岩气储层。

Richard等2007年利用自然伽马测井、电阻率测井资料识别了德克萨斯Fort Worth盆地密西西比纪Barnett页岩气储层及其厚度。Luffel等1992年综合分析测井资料、岩心资料，识别Appalachian盆地泥盆纪页岩气储层的岩性，并计算了其矿物成分。

Walter等1990年利用自然伽马能谱等测井资料识别了俄克拉荷马和德克萨斯Woodford页岩气储层等。Ross等2008年综合利用测井资料分析了加拿大西部沉积盆地泥盆纪-密西西比纪页岩气储层的矿物成分。Flower于1983年利用声波测井、电阻率测井资料，快速直观地识别了俄亥俄泥盆纪页岩储层。

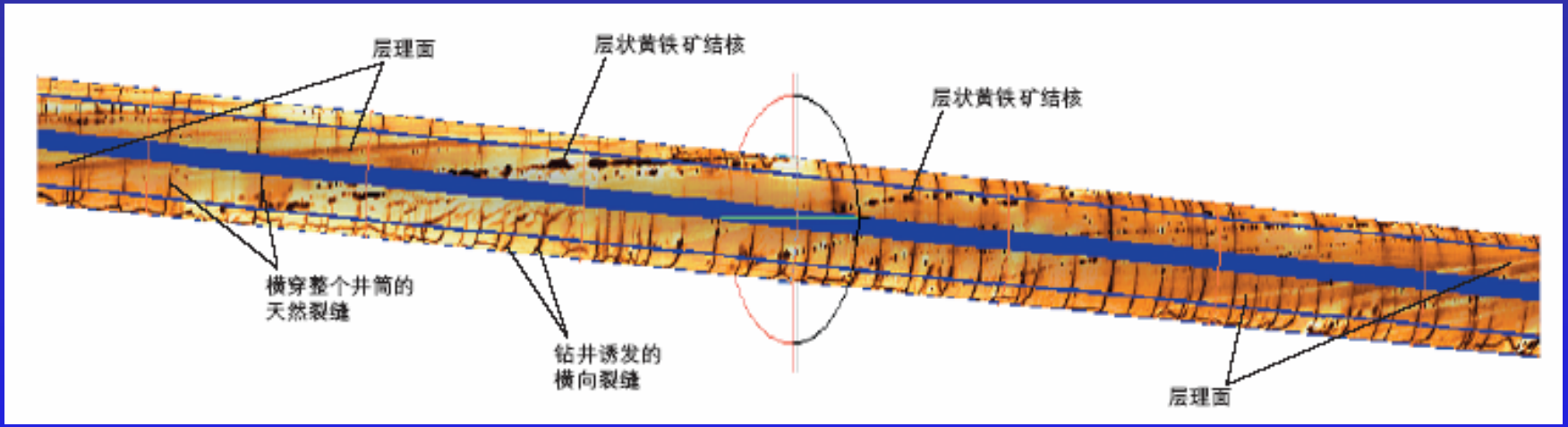
二、研究现状

2)裂缝识别与评价



Gale等**2007**年综合成像测井和岩心资料对**Fort Worth**盆地密西西比纪**Barnett**页岩气储层的裂缝体系进行了评价。

二、研究现状

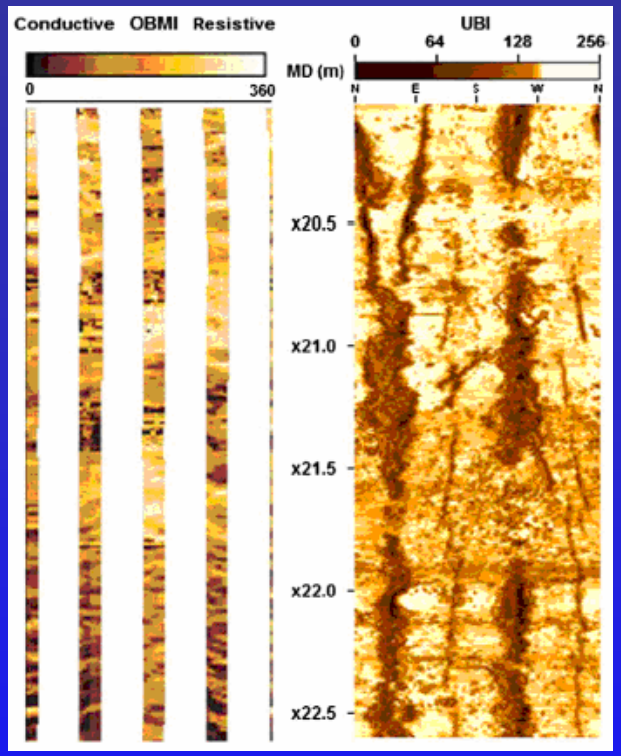


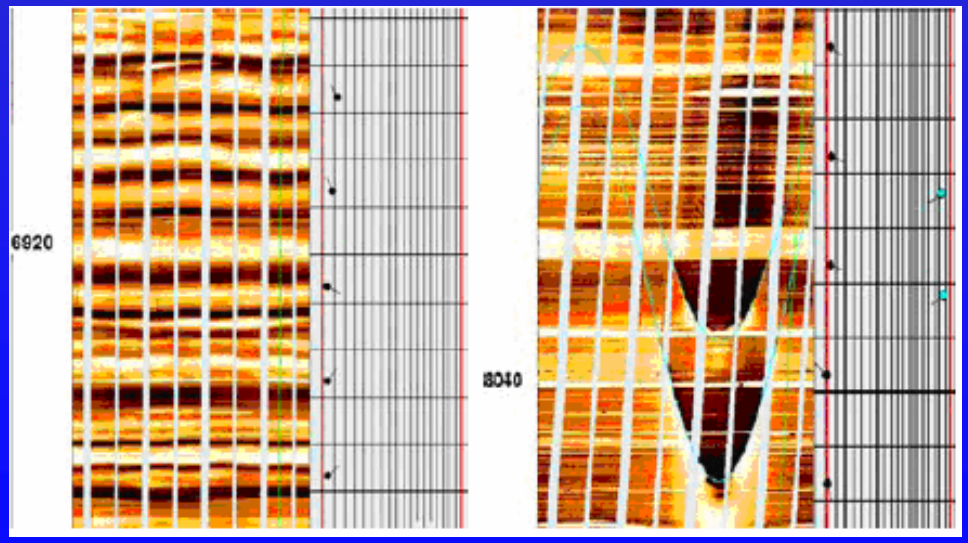
Charles Boyer等（**2010**）指出，在页岩气水平井的开发中，随钻成像测井系统已被应用于解决水平井测井存在的一些问题。

应用该系统可以在整个井筒长度范围内进行电阻率成像和井筒地层倾角分析。成像能够将地层天然裂缝和钻井诱发裂缝进行比较，帮助作业者确定射孔和油井增产的最佳目标。利用测井得到的成像资料来识别地震资料无法识别的断层。

二、研究现状

Hamed Soroush等指出，在页岩气储层测井为了防止井眼垮塌，通常采用油基泥浆钻井，为了评价裂缝通常油基泥浆电阻率成像测井**(OBMI)**和超声成像测井**(UBI)**，右图为**Barnett**层的**OBMI**与**UBI**的比较。



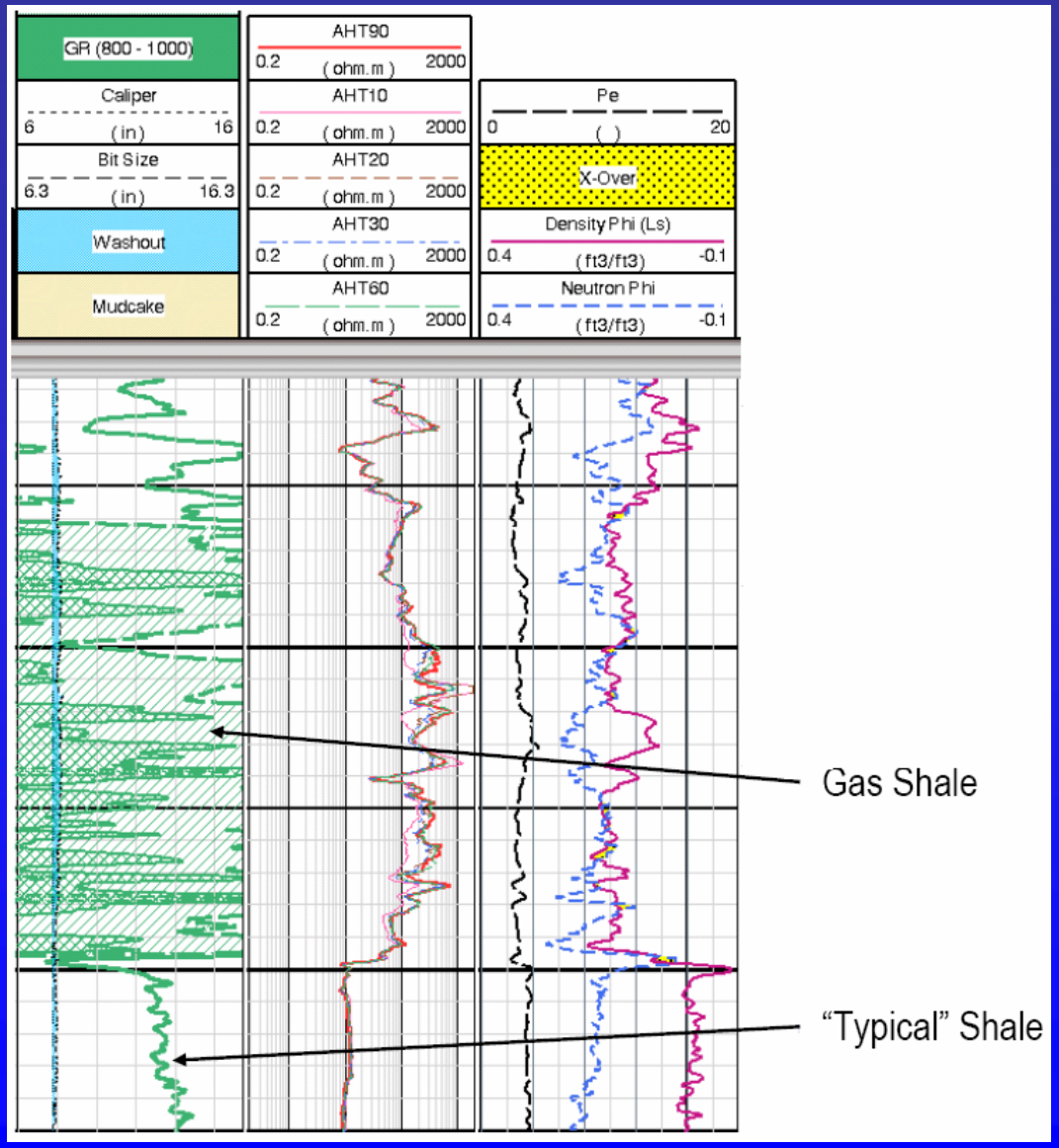


Waters等论述了页岩气水平井钻井中成像测井应用，识别层理和裂缝。左图为成像测井在水平井中识别页岩气储层层理和裂缝实例。

二、研究现状

3)判断含气页岩

Lewis等（**2004**）给出了含气页岩的典型测井曲线图，上部含气页岩为**Oklahoma**州泥盆-密西西比系**Woodford**页岩，表现为伽马、电阻率高值，密度、**Pe**低值；下部为**Sylvan**地层，不含气。测井曲线差异明显。



二、研究现状

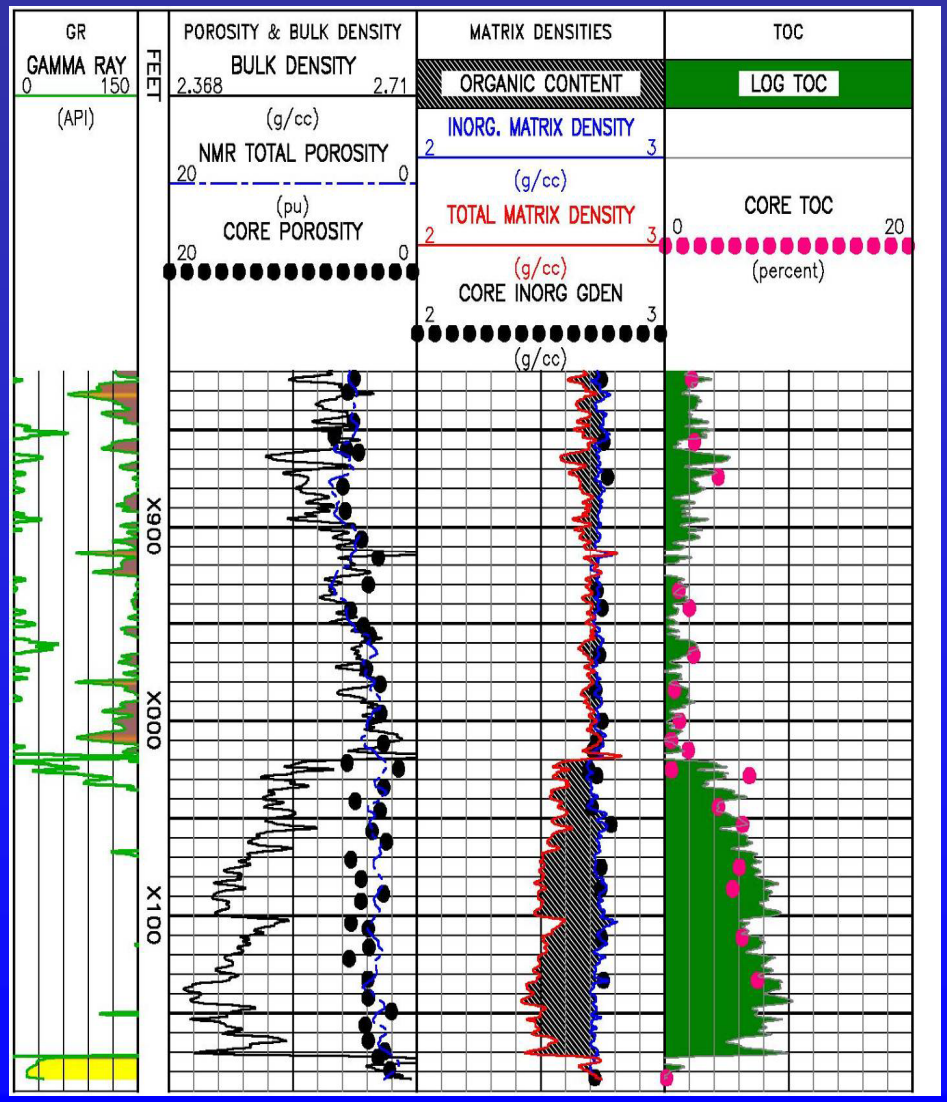
4)计算孔隙度、渗透率、饱和度

Ross等**2008**年综合利用测井资料计算了加拿大西部沉积盆地泥盆纪-密西西比纪页岩气储层总孔隙度、渗透率。

Luffel等**1989**年综合利用测井资料、岩心资料，计算了**Appalachian**盆地泥盆纪页岩气储层的孔隙度、有效孔隙度及含气饱和度，并分析了其渗透率。

Soeder于**1984**年计算了**Appalachian**盆地泥盆纪页岩气储层的孔隙度及渗透率。

LeCompte等（**2010**）最新报道中，核磁共振测井**(NMR)**也被用于计算孔隙度，计算结果与岩心分析孔隙度非常一致(右图)。



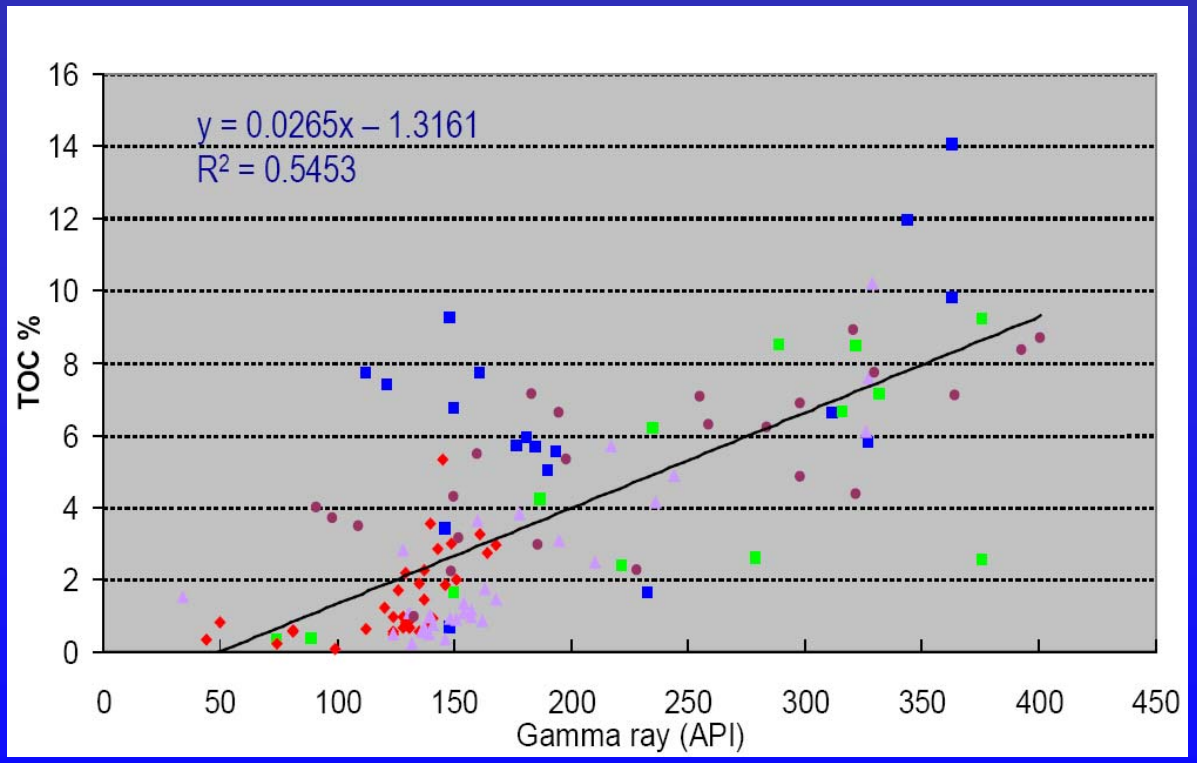
二、研究现状

5)确定总有机碳含量(TOC)

有研究表明，页岩气储层的含气量主要取决于其总有机碳含量。

根据自然伽马测井资料计算TOC。

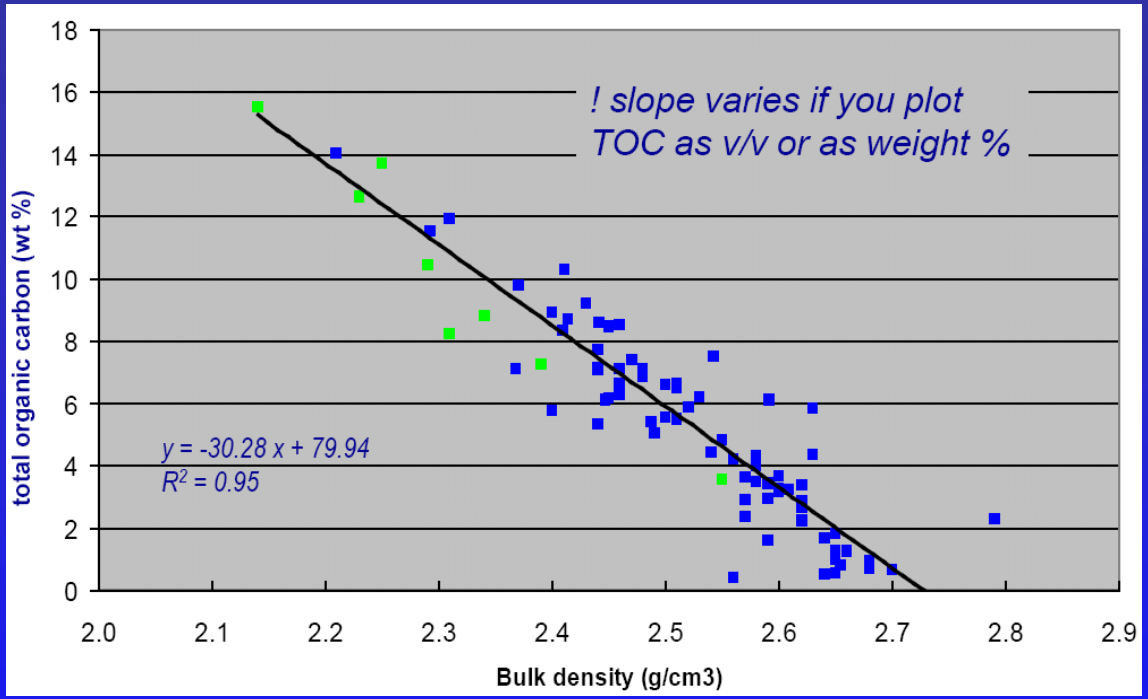
Schmoker于1981年对美国Illinois州New Albany页岩岩心进行研究，发现自然伽马测井值与TOC呈线性关系。



二、研究现状

根据密度测井资料计算TOC。

Schmoker于1979年对美国Illinois的New Albany页岩岩心进行研究，发现TOC与密度测井值之间具有良好的相关性，因此利用密度测井资料计算总有机碳含量。

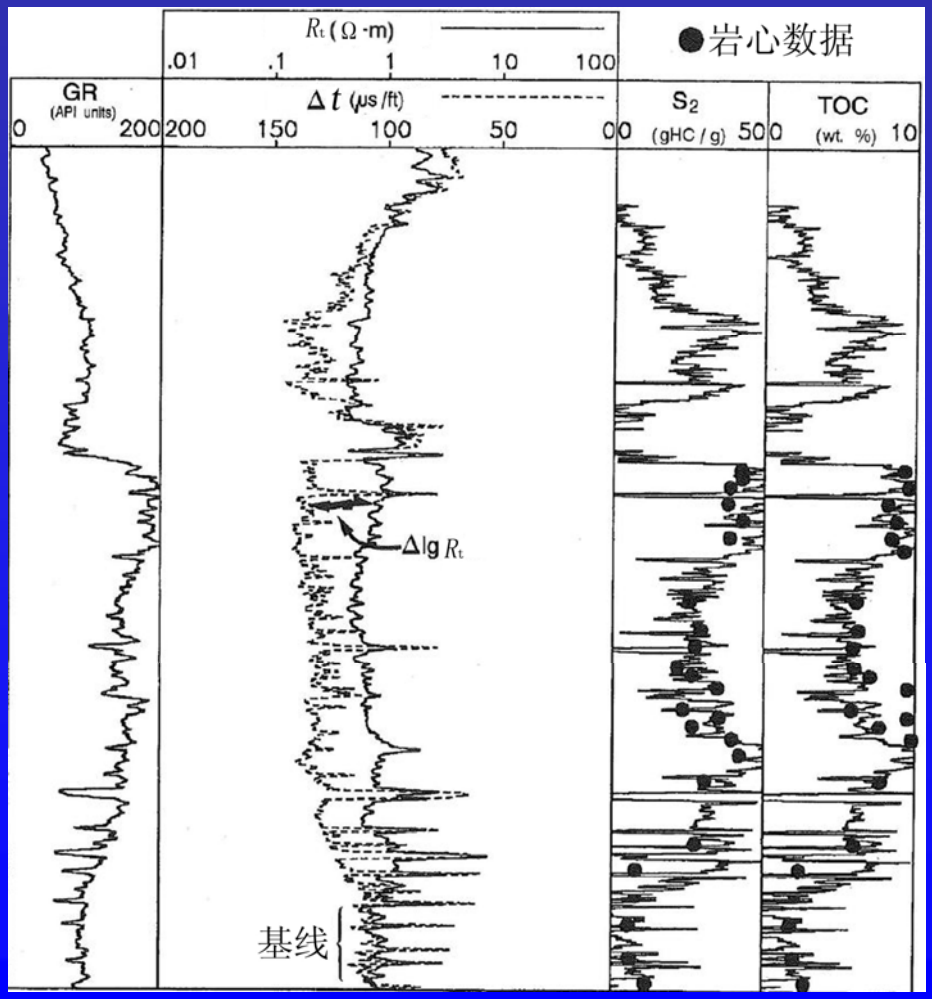


Schmorker和Hester (1979)、Hester和Schmorker(1987)的文献均有相关内容的报告。Schmorker和Hester (1979)在Anadarko盆地Woodford页岩层分析中，TOC计算结果的置信度达到90%，误差约为±1.6wt%(重量百分数)。

二、研究现状

电阻率-孔隙度曲线叠合图也可以用于确定TOC，这种方法也称为 $\Delta \lg R_t$法。

Passey等(1990)给出了利用声波时差和地层电阻率计算TOC的数学表达式:

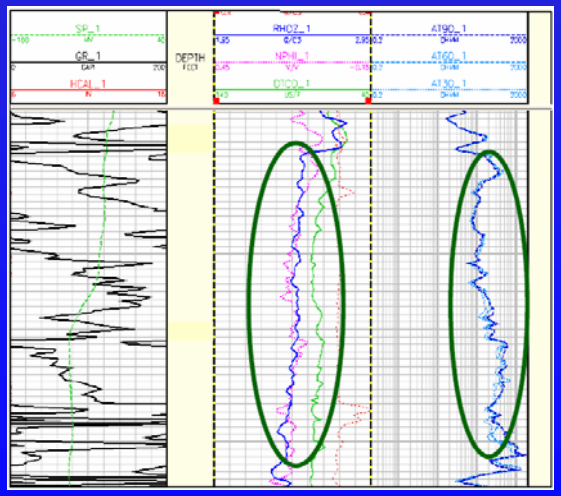


二、研究现状

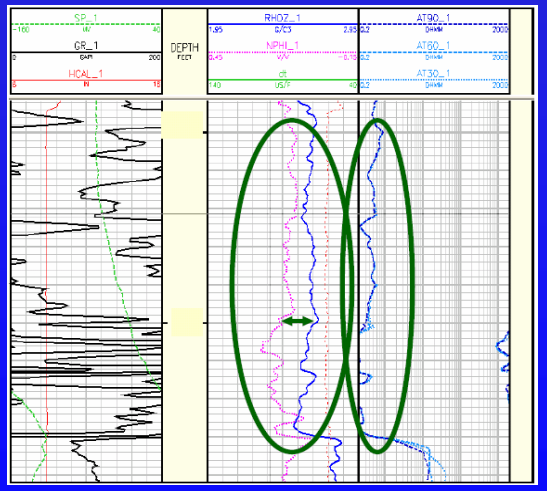
6)确定热成熟度指数(MI)

当页岩中TOC达到一定指标后，有机质的成熟度则成为页岩气源岩生烃潜力的重要预测指标，含气页岩的成熟度越高表明页岩生气量越大，页岩中可能赋存的气体也越多。

Miller(2010)对比了页岩层不同镜质体反射率R_O的各种测井曲线响应特征，认为R_O影响测井曲线的变化：当Ro在1.8~2.0范围内时，密度低值，密度和中子曲线重叠，地层电阻率高值达到(100Ω.m)；当Ro>4.5时，密度高值，密度和中子曲线分开，地层电阻率非常小(小于1Ω.m)。



(a) R_O在1.8~2.0之间



(b) R_O >4.5

二、研究现状

Zhao Hank等(2007)研究了Fort Worth盆地Barnett页岩气层的热成熟度指数MI，给出了利用测井资料计算MI的公式:

$$MI = \sum_{i=1}^{N} \frac{N}{\phi_{n9i}(1-S_{w75i})^{1/2}}$$

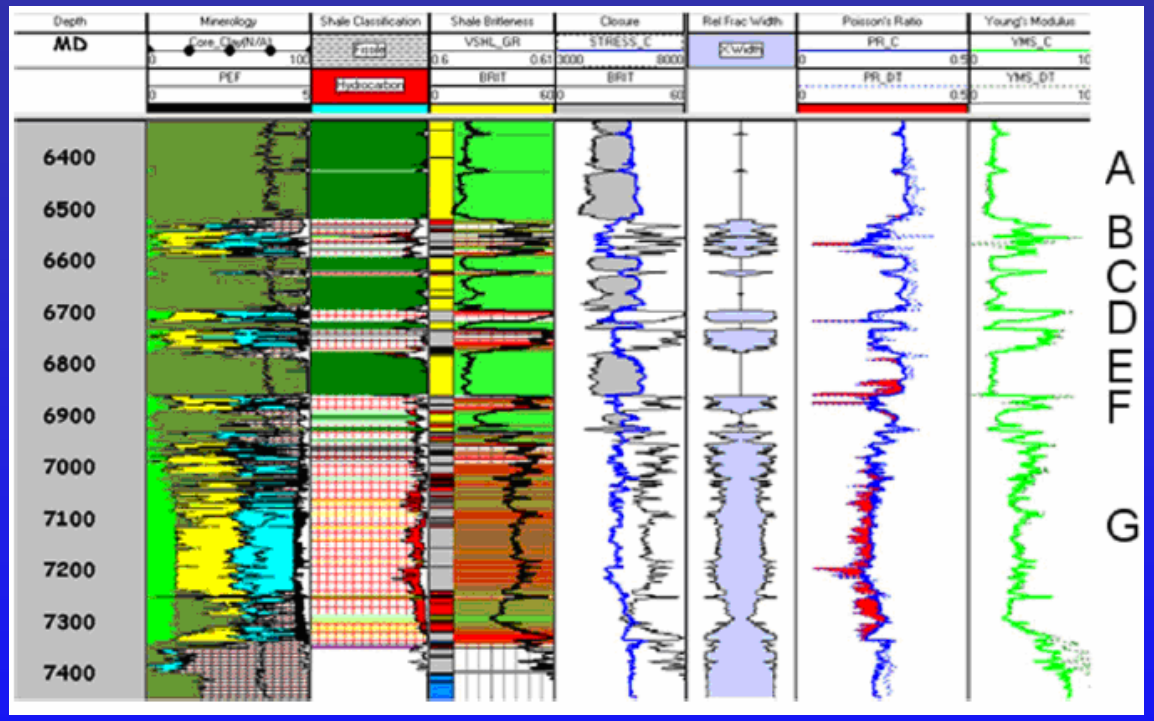
$$S_{wi} = \left(\frac{R_w}{\phi_{d9i}^m R_t} \right)^{1/2}$$

$$\phi_{n9} = \phi_d - 90\%$$

二、研究现状

7)计算储层岩石力学参数

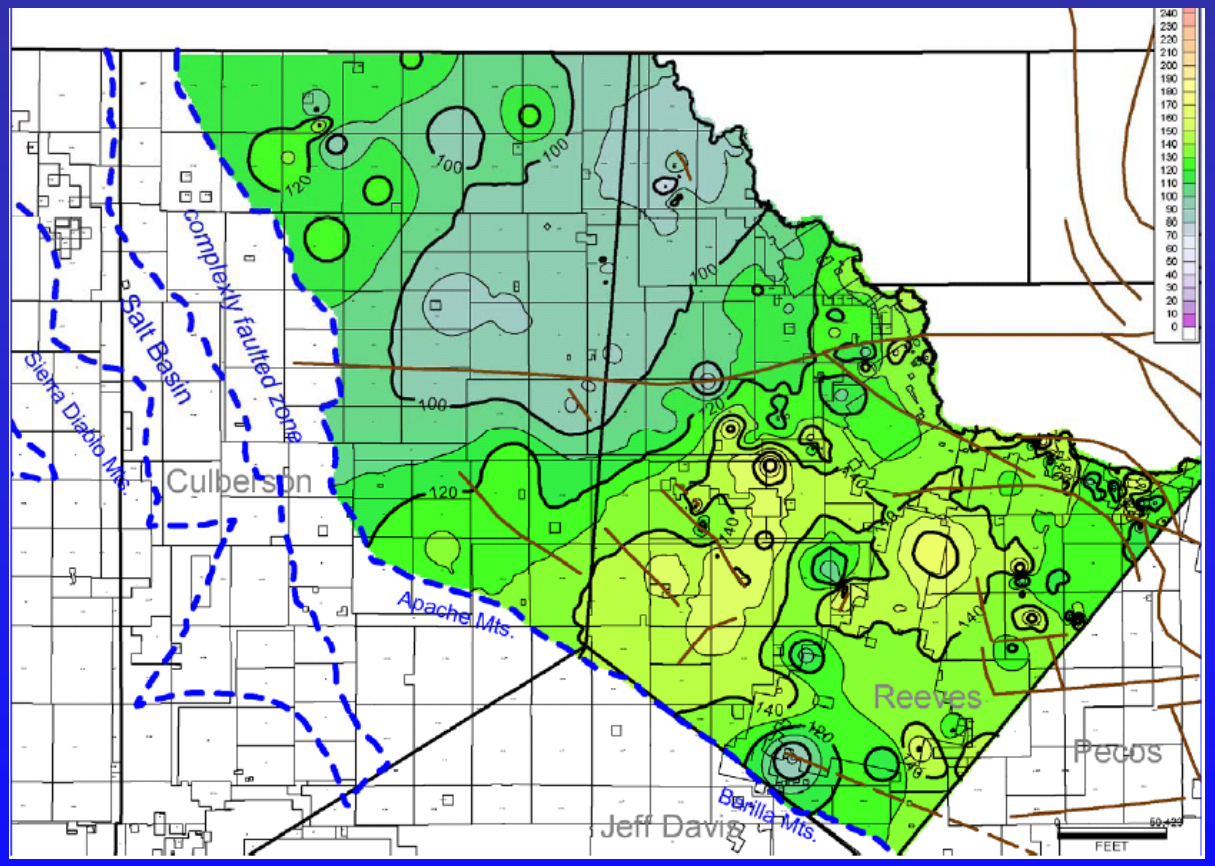
Rick Rickman等（**2008**）针对页岩气储层的压裂问题论述了每一种页岩气储层不见得都与**Barnett**地层相同。在压裂中必须进行优化设计，为此必须进行演示物理参数的计算，在这篇文献中他提出了脆性、闭合压力、压裂宽度、杨氏模量、泊松比等计算方法，并给出了实例。



Gatens等**1990**年利用声波测井资料、原位应力数据计算了**Appalachian**盆地页岩气储层的力学参数，绘制了地应力剖面。

二、研究现状

8)确定天然气地质储量(GIP)等



Cluff(2006)利用Langmuir公式计算了Woodford页岩气储层的平均地质储量，并绘制成平面图。

二、研究现状

已收集的部分参考文献:

[1] Buckner, N., R.M. Slatt, B. Coffey, and R.J. Davis, 2009, Stratigraphy of the Woodford Shale from behind-outcrop drilling, logging, and coring: AAPG Annual Convention, San Antonio, TX. AAPG Search and Discovery Article No. 50147, 24 slides. http://www.searchand discovery.net/documents/2009/50147buckner/ndx_buckner.pdf

[2] Cluff B. and Miller M., 2010, Log evaluation of gas shales: a 35-year perspective, April 2010 DWLS luncheon

[3] Cluff B., 2006, Barnett Shale-Woodford Shale play of the Delaware basin – is it another giant shale gas field in Texas? The Discovery Group, Inc.

[4] Daniel J. K. Ross and R. Marc Bustin. Characterizing the shale gas resource potential of Devonian–Mississippian strata in the Western Canada sedimentary basin: Application of an integrated formation evaluation.AAPG Bulletin; January 2008; 92; p. 87-125

[5] Decker, A., D. Hill, and D. Wicks, 1993, Log-based gas content and resource estimates for the Antrim Shale, paper SPE-25910, Michigan basin: SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium, p. 659-669

[6] Decker, A. D., D. Wicks, and J.-M. P. Coates, 1993, Gas content measurements and log based correlations in the Antrim Shale. Topical report., in G. R. Institute, ed., Chicago, IL, p. 51 p. + appendices. OSTI ID: 7203859

[7]Dorsch, J., and T. J. Katsube, 1996, Effective porosity and pore-throat sizes of mudrock saprolite from the Nolichucky Shale within Bear Creek Valley on the Oak Ridge Reservation: Implications for contaminant transport and retardation through matrix diffusion, p. 81 p. OSTI ID: 285464

[8]Dorsch, J., 1995, Determination of effective porosity of mudrocks: a feasibility study, p. 70 p. OSTI ID: 204203

[9]Evans, K. F., T. Engelder, and R. A. Plumb, 1989, Appalachian stress study 1. A detailed description of in situ stress variations in Devonian shales of the Appalachian plateau: Journal of Geophysical Research, v. 94, p. 7129-7154

[10]Evans, K. F., G. Oertel, and T. Engelder, 1989, Appalachian Stress Study 2. Analysis of Devonian Shale Core: Some Implications for the Nature of Contemporary Stress Variations and Alleghanian Deformation in Devonian Rocks: Journal of Geophysical Research, v. 94, p. 7155-7170

二、研究现状

[11]Fertl, W., and G. Chilingarian, 1990, Hydrocarbon resource evaluation in the Woodford Shale using well logs: Journal of Petroleum Science and Engineering, v. 4, p. 347-357
[12]Flower, J. G., 1983, Use of sonic-shear-wave/resistivity overlay as a quick-look method for identifying potential pay zones in the Ohio (Devonian) Shale: Paper SPE-10368, Jour Petroleum Technology, p. 638-642. DOI: 10.2118/10368-PA
[13]Gatens, J. I., C. W. Harrison, D. E. Lancaster, and F. K. Guidry, 1990, In-Situ Stress Tests and Acoustic Logs Determine Mechanical Properties and Stress Profiles in the Devonian Shales: Paper SPE-18523-PA, SPE Formation Evaluation, v. 5, p. 248-254. DOI: 10.2118/18523-PA
[14]Gas_Research_Institute, 1991, Formation evaluation technology for production enhancement: log, core, geochemical analyses in Barnett shale, in G. R. Institute, ed., Chicago, IL, p. 125 p. GRI 5086-213-1390
[15]Hester, T.C., and J.W. Schmoker, 1987a, Determination of organic content from formation-density logs, Devonian-Mississippian Woodford Shale, Anadarko basin, Oklahoma: U.S. Geological Survey Open-File Report 87-20, 11p
[16]Hester, T.C., and J.W. Schmoker, 1987b, Formation resistivity as an indicator of oil generation in black shales [abstract]: AAPG Bulletin, v. 71, p. 1007
[17]Hester, T.C., H.L. Sahl, and J.W. Schmoker, 1988, Cross sections based on gamma-ray, density, and resistivity logs showing stratigraphic units of the Woodford Shale, Anadarko basin, Oklahoma: U.S. Geological Survey Miscellaneous Field Studies Map MF-2054, 2 sheets
[18]Hester, T.C., J.W. Schmoker, and H.L. Sahl, 1990, Log-derived regional source-rock characteristics of the Woodford Shale, Anadarko basin, Oklahoma: U.S. Geological Survey Bulletin 1866-D, 38p
[19]Hester, T.C., J.W. Schmoker, and H.L. Sahl, 1992, Structural controls on sediment distribution and thermal maturation of the Woodford Shale, Anadarko basin, Oklahoma, in K.S. Johnson and B.J. Cardott, eds., Source rocks in the southern Midcontinent, 1990 symposium: OGS Circular 93, p. 321-326.
[20]Hester, T.C., J.W. Schmoker, and H.L. Sahl, 1992, Tectonic controls on deposition and source-rock properties of the Woodford Shale, Anadarko basin, Oklahoma; loading, subsidence, and forebulge development, in C.H. Thorman, ed., Application of structural geology to mineral and energy resources of the central and western United States: U.S. Geological Survey Bulletin 2012, p. B1-B11

二、研究现状

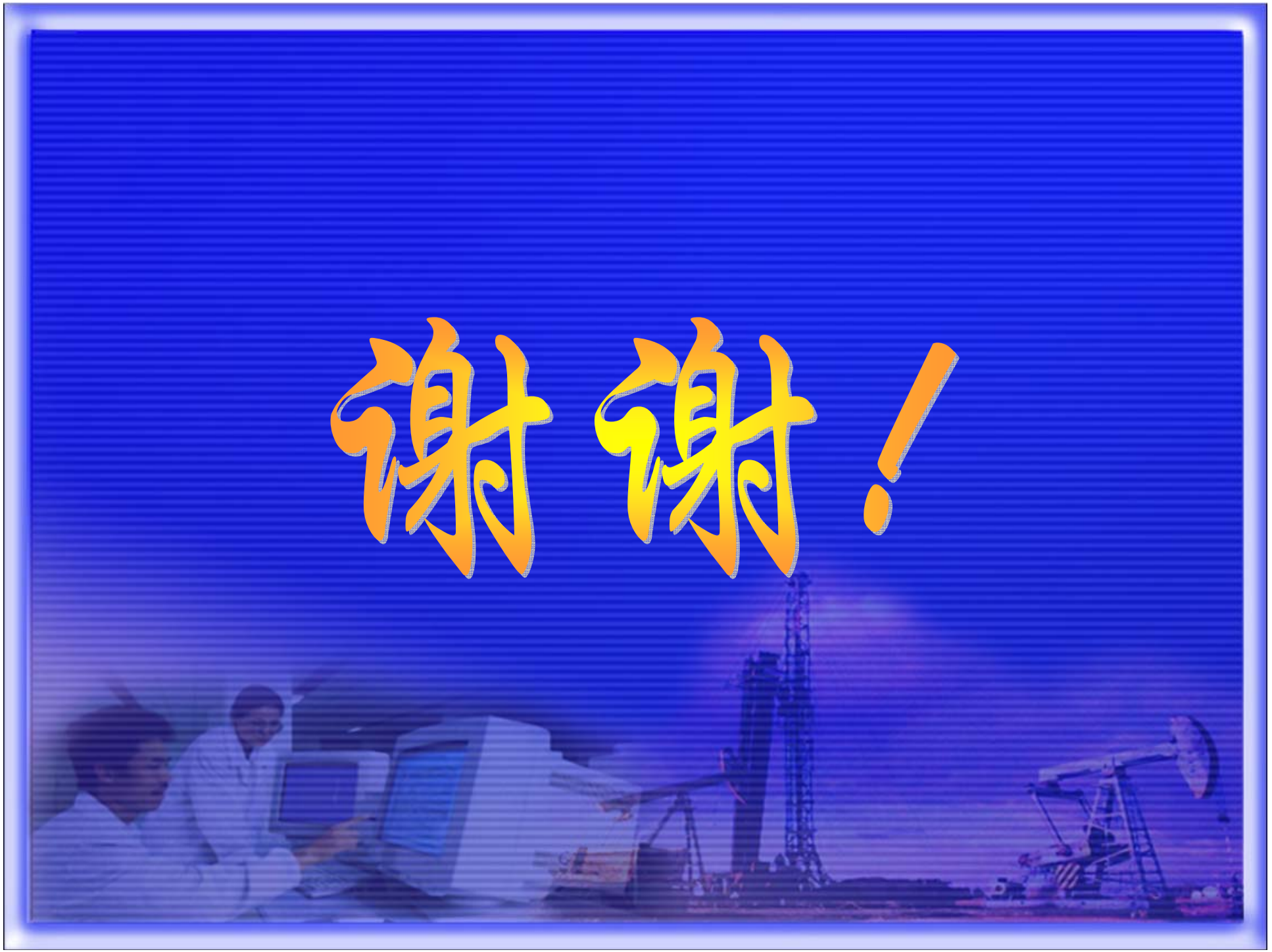
[21]Hester, T.C., and J.W. Schmoker, 1993, Regional geology of the Woodford Shale, Anadarko basin, Oklahoma—an overview of relevance to horizontal drilling, in K.S. Johnson and J.A. Campbell, eds., Petroleum-reservoir geology in the southern midcontinent, 1991 symposium: OGS Circular 95, p. 74-81
[22]Julia F. W. Gale, Robert M. Reed and Jon Holder. Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments. AAPG Bulletin，2007，91(4):603-622
[23]Kinley Travis J., Lance W. Cook, John A. Breyer,et al. Hydrocarbon potential of the Barnett Shale (Mississippian), Delaware Basin, west Texas and southeastern New Mexico.AAPG Bulletin,August 2008; v. 92; no. 8; p. 967-991
[24]Kuuskraa V. A. and Stevens S. H., 2009, Worldwide Gas Shales and Unconventional Gas: A Status Report, Advanced Resources International, Inc.
[25]LeCompte B.，2010，Comprehensive Resource Play Evaluation for Well Completion Decisions - Mineralogy, Acoustic, and NMR Integration, Murphy Oil Inc.
[26]Lewis R., Ingraham D. and Pearcy M. et al., 2004, New Evaluation Techniques for Gas Shale Reservoirs, Resservoir Symposium, 2004
[27]Luffel, D. L., F. K. Guidry, and J. B. Curtis, 1992, Evaluation of Devonian Shale with new core and log analysis methods: Paper SPE-21297, Journal of Petroleum Technology, v. 44, p. 1192-1197. DOI: 10.2118/21297-PA
[28]Luffel, D. L., and F. K. Guidry, 1992, New core analysis methods for measuring reservoir rock properties of Devonian shale: paper SPE-20571, Jour Petroleum Technology, v. 44, p. 1184-1190. DOI: 10.2118/20571-PA.
[29]Luffel, D. L., and F. K. Guidry, 1989, Reservoir rock properties of Devonian shale from core and log analysis: Soc Core Analysts 3rd Annual Technical Conference, p. 13 p
[30]Luffel, D. L., 1993, Advances in shale core analyses, Chicago, Il, Gas Research Institute, p. 138

二、研究现状

[31]Mullen, M., 2005, Reservoir characterization and analysis of shale gas methane (SGM) plays using wireline logs, in P. Lufholm and D. Cox, eds., 2005 WTGS Fall Symposium: West Texas Geological Society, Publication No. 05-115, p. 109-114
[32]ResTech_Houston_Inc, 1996, Development of laboratory and petrophysical techniques for evaluating shale reservoirs, Chicago, IL, Gas Research Institute
[33]Rickman R., Mullen M., Petre E. et al., 2008, A Practical Use of Shale Petrophysics for Stimulation Design Optimization: All Shale Plays Are Not Clones of the Barnett Shale, SPE 115258
[34]Rogner, H. H., 1997, An Assessment of World Hydrocarbon Resources, Annual Review of. Energy Environment, 22:217-262
[35]Schmoker, J.W., 1993, Use of formation-density logs to determine organic-carbon content in Devonian shales of the western Appalachian Basin and an additional example based on the Bakken Formation of the Williston Basin: U.S. Geological Survey Bulletin 1909, p. J1-J14
[36]Soeder, D. J., 1986, Porosity and permeability of eastern Devonian gas shale: Paper SPE-15213, Unconventional Gas Technology Symposium, Louisville, KY, SPE, p. 75-81
[37]Schmoker, J. W., 1981, Determination of organic-matter content of Appalachian Devonian shales from gamma-ray logs: AAPG Bulletin, v. 65, p. 1285-1298
[38]Schmoker, J. W., 1980, Organic content of Devonian Shale in western Appalachian basin: AAPG Bulletin, v. 64, p. 2156-2165
[39]Schmoker, J. W., 1979, Determination of organic content of Appalachian Devonian shales from formation-density logs: AAPG Bulletin, v. 63, p. 1504-1537
[40]Scott L. Montgomery, Daniel M. Jarvie, Kent A. Bowker, et al. Pollastro Mississippian Barnett Shale, Fort Worth basin, north-central Texas: Gas-shale play with multi-trillion cubic foot potential.AAPG Bulletin, 2005;v89: 155 - 175

二、研究现状

[41]Soroush H., Rasouli V. and Tokhmechi B., 2010, A data processing algorithm proposed for identification of breakout zones in tight formations: A case study in Barnett gas shale, Journal of Petroleum Science and Engineering. 2010
[42]Truman, R. B., and R. L. Campbell, 1986, Devonian-shale well-log interpretation. Annual report, 1985, p. Pages: 111. OSTI ID: 5511050
[43]Vanorsdale, C., and P. Boring, 1987, Evaluation of initial reservoir data to estimate Devonian shale gas reserves: Paper SPE-16862, SPE 62nd Annual Technical Conference, p. 283-288
[44]Vanorsdale, C., 1987, Evaluation of Devonian shale gas reservoirs: Paper SPE-14446, Jour Petroleum Technology, p. 209-216
[45]Waters G., et. al., 2010, Use of horizontal well image tools to optimize Barnett shale reservoir exploration. 2010, SPE.
[46]White, J., 2008, Shale plays soar: An Investor's Guide to Unconventional Gas: Shales and Coalbed Methane, Supplement to Oil & Gas Investor, 2008, 2-8
[47]Work, P.L., 1975, Digitized well logs can help boost success in exploring shale intervals: Oil and Gas Journal, v. 73, no. 7, p. 84-88
[48]Zhao, Hank, N. B. Givens, and B. Curtis, 2007, Thermal Maturity of the Barnett Shale Determined from Well-Log Analysis: AAPG Bulletin, v. 91, p. 535-549


谢谢！