

我国富含有机质泥页岩发育特点与页岩气战略选区*

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摘 要 我国页岩气勘探才刚刚起步, 目前研究主要集中在页岩气成藏条件和有利区评价方面。页岩气有利区优选还处于富含有机质泥页岩优选阶段, 优选出的主要是页岩气发育远景区。受复杂地质背景和多阶段演化过程的影响, 我国含油气盆地类型多、盆地结构复杂, 盆地的不同演化规律直接控制着富含有机质泥页岩的发育与分布。为此, 依据形成环境将富含有机质泥页岩划分为海相厚层富含有机质泥页岩、海陆交互相及陆相煤系地层富含有机质泥页岩、湖相富含有机质泥页岩这 3 种类型, 并分别探讨了其页岩气勘探开发前景。结论认为: ①海相厚层富含有机质页岩是我国近期页岩气勘探的首选; ②海陆交互相及陆相煤系地层富含有机质泥页岩单层厚度较薄, 但与致密砂岩气和煤层气有共生条件, 发展页岩气与致密砂岩气等多类型天然气资源多层合采技术具有十分现实的意义; ③湖相富含有机质泥页岩成岩程度普遍不高, 需要进一步优选岩石强度较大、具备裸眼完井条件的层位进行勘探开发。

关键词 中国 页岩气 泥页岩 富集区 海相 海陆交互相 陆相煤系 湖相

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目前, 不同的研究者对页岩气的界定有着一定的差别。张金川等将页岩气定义为: “主体位于暗色泥页岩或高碳泥页岩中, 以吸附或游离状态为主要存在方式的天然气, 在页岩气藏中, 天然气也存在于夹层状的粉砂岩、粉砂质泥岩、泥质粉砂岩甚至砂岩地层中, 为天然气生成之后在源岩层内就近聚集的结果, 表现为典型的‘原地’成藏模式”^[1]。笔者认为, 这种界定方式突出了生成并保存天然气的富含有机质泥页岩层系, 而不是限定在某一单纯的富含有机质泥页岩层, 与国际上对页岩气的界定相似, 同时也有利于页岩气的勘探实施。

1 我国页岩气勘探与研究现状

我国在页岩气勘探方面才刚刚起步。2008 年 11 月, 中国石油天然气股份有限公司在四川盆地长宁构造实施了一口深度为 200 m 的页岩取心井——长芯 1 井, 获取了志留系页岩岩心样品^[2]。2009 年, 国土资源部油气资源战略研究中心启动了“我国重

点地区页岩气资源潜力及有利区优选研究”项目。该项目 2009 年的重点集中在四川盆地和上扬子东部地区, 中石油和中国地质大学(北京)等有关单位也参与了该项目的研究。通过近一年的工作, 研究取得了积极进展, 但到目前为止, 我国还没有一口页岩气产气井。

我国页岩气研究目前主要集中在页岩气聚集条件和有利区评价方面, 其中大中型含油气盆地的研究程度较高^[3-6]。由于直接的页岩气井筒资料较少, 故目前的多数研究仍不得不借用常规油气勘探资料数据、煤层气和固体矿产勘探资料数据, 页岩样品也主要采自地表和近地表; 由于缺少第一手资料, 通过借鉴美国等国外资料开展类比研究的也较多^[7-8]。

在页岩气成藏条件研究方面, 对页岩本身特点(如厚度、矿物组成、孔隙度、渗透率、裂缝发育程度等)、页岩成烃能力(如有机质类型及含量、成熟度等)、页岩聚烃能力(如吸附能力及影响因素等)开展了实验和类比研究。

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在有利区优选方面,目前多数研究者主要依据页岩层厚度、埋深、总有机碳含量(TOC)和热演化程度(R_o)来优选的有利区,部分研究者获取了等温吸附能力参数,丰富了有利目标区优选参数,但含气量等直接参数尚不具备。从这一点看,我国页岩气有利区优选还处于富含有机质泥页岩优选阶段,优选出的主要是页岩气发育远景区,主体还没有进入页岩气富集有利区优选阶段。因此,充分利用以往地质资料,通过少量关键参数,优选具备形成页岩气富集条件的富含有机质泥页岩发育区作为页岩气勘探有利目标区,为进一步开展页岩气勘探提供依据,是我国开展页岩气勘探开发必定要经过的一个起步阶段。

2 我国富含有机质泥页岩发育特点

受复杂地质背景和多阶段演化过程的影响,我国含油气盆地类型多、盆地结构复杂。在早三叠世及古生代,我国发育有华北、扬子和华南、塔里木等大中型海相和海陆交互相克拉通和克拉通边缘盆地。经过中生代改造后,这些大中型盆地普遍遭到破坏,仅在四川、鄂尔多斯、塔里木等地保留下来一部分克拉通盆地。中生代以来,陆相盆地广泛发育。其中部分陆相盆地叠置在克拉通盆地之上,部分盆地发育在古生代褶皱带之上。盆地的不同演化规律直接控制着富含有机质泥页岩的发育与分布。依照形成环境,可将富含有机质泥页岩化分为海相厚层富含有机质泥页岩、海陆交互相及陆相煤系地层富含有机质泥页岩、陆相富含有机质泥页岩这 3 种类型。

2.1 海相厚层富含有机质泥页岩

我国海相富含有机质泥页岩主要发育于下古生界的下寒武统、下志留统一上奥陶统顶部,以扬子克拉通地区最为典型(图 1)。

下寒武统海相富含有机质泥页岩在中上扬子区发育较好,有机质类型为腐泥型—混合型。从区域沉积环境看,川东—鄂西、川南及湘黔(热水)3 个深水陆棚区下寒武统海相富含有机质泥页岩最发育, TOC 平均高达 8% 左右^[9]。从盆地看,四川盆地下寒武统泥页岩平均厚度为 139 m,总有机碳含量在 0.5%~4.0% 之间,多超过 1%,有机质类型为腐泥型, R_o 介于 2.0%~5.0%,盆地南部埋藏较浅。麻阳盆地、洞庭盆地泥页岩总有机碳含量多数大于 1%,有机质类型为腐泥型,凹陷区 R_o 多超过 3%,凸起区局部有热演化程度相对较低的地区($R_o < 1\%$)。下寒武统海相富含有机质泥页岩的热演化程度普遍

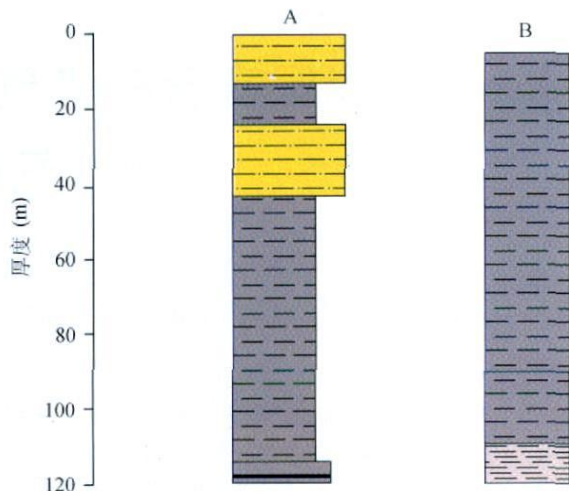


图 1 下古生界海相富含有机质泥页岩沉积特征图

注: A 为贵州牛蹄塘组厚层富含有机质泥页岩层剖面特征,下部厚层泥页岩中含石膏层,上部变为粉砂质泥岩; B 为渝东龙马溪—五峰组厚层富含有机质泥页岩

较高,仅在上扬子南部和北部、鄂西和下扬子中部地区 $R_o < 3.0\%$,其他地区下寒武统海相富含有机质泥页岩普遍 $R_o > 3.0\%$,页岩气的勘探前景不大。

下志留统海相富含有机质泥页岩主要分布在川东南、川东北、鄂西渝东、中扬子、下扬子等区,以硅质岩、页岩、碳质页岩为主,有机质类型为腐泥型, R_o 介于 2.0%~4.5%,厚度为 20~100 m。其中渝东鄂西地区热演化程度较低,是页岩气勘探较有利的地区之一。

我国南方地区下寒武统和下志留统富含有机质泥页岩在单层厚度和有机质含量上,总体均达到了形成页岩气藏的基本条件,而埋深和热演化程度则成为关乎其能否作为页岩气勘探靶区的主要因素。

2.2 海陆交互相及陆相煤系地层富含有机质泥页岩

晚古生代克拉通海陆交互相及陆相煤系地层富含有机质泥页岩在华北、华南地区和准噶尔盆地分布广泛。中生代陆相煤系地层富含有机质泥页岩主要在两类盆地发育:一是大型拗陷,如鄂尔多斯盆地和准噶尔盆地侏罗系、四川盆地上三叠统;二是断陷,如我国东北地区含煤盆地中的断陷。

华北地区海陆交互相富含有机质泥页岩单层厚度不大,多数与煤层交互出现。总有机碳含量受沉积相影响,变化较大,一般介于 0.5%~10%,其中沼泽相碳质页岩总有机碳含量普遍较高。这类泥页岩的有机质类型主要为混合型—腐殖型, R_o 多数介于 0.5%~2.5%,部分超过 3.0%。

华南地区海陆交互相富含有机质泥页岩有单独

发育以及煤层交互发育 2 种类型。滇黔桂地区上二叠统龙潭组深灰色页岩厚度一般为 20~60 m, 局部较厚。四川盆地上二叠统泥页岩厚度为 10~125 m, 在川中和川西南一带一般厚 80~110 m, 麻 1 井最厚, 达 125 m; 在四川盆地西北缘、北缘及东北缘较薄, 多小于 20 m; 暗色泥页岩总有机碳含量变化介于 0.5%~12.55%, 平均为 2.91%, 多分布在 3%~5%; 其中泸州地区及自贡—资阳一带总有机碳含量较低(小于 3%), 有机质类型以腐殖型为主, 但有机质相对富氢。

准噶尔盆地石炭系滴水泉组富含有机质泥页岩包括暗色泥岩和碳质泥岩, 累计厚度为 0~249 m, 前者有机碳含量平均为 1.45%; 后者有机碳含量平均为 15.53%, 有机质类型主要为偏腐殖混合型—腐殖型, R_o 介于 0.51%~1.75%, 平均为 1.15%^[10]。中生代断陷含煤盆地的暗色泥岩、煤和碳质泥岩互层分布的特点突出, 暗色泥岩总有机碳含量多数超过 1.0%, 碳质页岩多数超过 10.0%, 单层厚度普遍不大, 但累计厚度较大, R_o 多在 1.3% 以下^[11-12]。

总体上, 我国上古生界海陆交互相富含有机质泥页岩除上扬子及滇黔桂地区单层厚度较大且具有页岩气单独勘探开发的条件外, 多数地区发育的海陆交互相及陆相煤系地层富含有机质泥页岩单层厚度都不大, 不利于页岩气的单层独立开发。中生代陆相煤系富含有机质泥页岩一般单层厚度虽然也不大, 但其总有机碳含量较高、演化程度一般在过成熟早期以下, 有利于成气且泥页岩层多与煤层、致密砂岩层互层, 易形成页岩气、煤层气和致密砂岩气等多种类型性天然气近距离叠置成藏(图 2)。这是我国煤系地层普遍存在的天然气聚集特点。因此, 进一步深入研究页岩气、煤层气和致密砂岩气等多种类型天然气共生特点和叠置成藏规律, 开展多种共生天然气资源勘查, 探索其经济有效的多层合采开发技术, 是这类天然气资源有效开发利用的一个新课题。

2.3 湖相富含有机质泥页岩

我国准噶尔盆地等二叠纪断陷, 松辽、鄂尔多斯盆地等中生代断陷, 渤海湾盆地等新生代断陷, 都沉积了厚层富含有机质泥页岩。这些富含有机质泥页岩构成了上述盆地的主力烃源岩。

准噶尔盆地二叠系芦草沟组地层上段以灰黑色页岩、页岩油为主夹沥青质页岩, 累计厚度超过 200 m, 总有机碳含量为 4.85%~10.02%, 有机质类型为偏腐泥混合型, R_o 介于 0.54%~0.91%; 二叠系

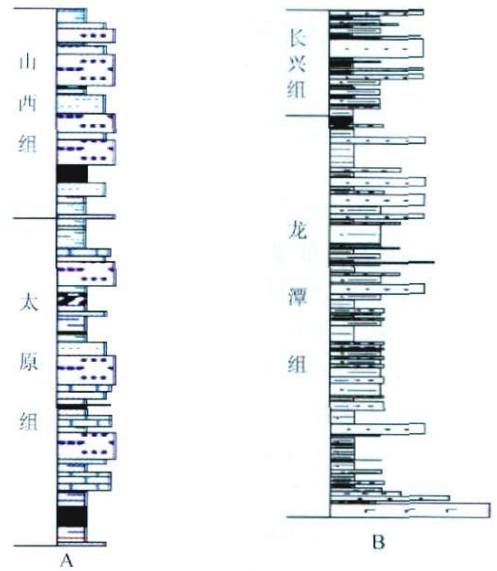


图 2 海陆交互相沉积剖面特征图

注: A 为华北地区上古生界海陆交互相沉积特征(沁水盆地); B. 为华南地区上古生界海陆交互相沉积特征(滇东地区)

红雁池组、平地泉组也发育有较好的富含有机质暗色泥页岩^[13]。

松辽盆地主要发育嫩江组和青山口组两套富含有机质泥页岩。其中, 嫩江组一段为一套黑色泥页岩, 全盆地稳定分布, 在中央拗陷区的厚度超过 100 m, 平均总有机碳含量高达 2.40%, 有机质以偏腐泥混合型和偏腐殖混合型为主。嫩二段暗色泥页岩分布范围比嫩一段更广, 发育更加稳定, 平均厚度在 150 m 左右, 平均总有机碳含量为 1.56%。青山口组一段在中央拗陷区几乎全部为暗色泥页岩, 厚度为 60~80 m, 平均总有机碳含量为 2.2%, 但有机质类型仍以腐泥型和混合型为主。嫩江组一段和青山口组一段的 R_o 在齐家古龙凹陷较高(分别达到 1.1% 和 2.0%), 在三肇凹陷次之(分别为 0.7% 和 1.3%), 在盆地的边部成熟度比较低。

鄂尔多斯盆地延长组长 4+5—长 8 段主要为湖相沉积, 富含有机质的暗色泥页岩发育。长 8、长 6 段暗色泥页岩有机质丰度在富县—葫芦河地区较高, 总有机碳含量分别为 3.5% 和 3.75%, 长 7 段暗色泥页岩有机质丰度以华池、吴旗地区为最高, 其中华池地区总有机碳含量达 5.81%; R_o 主要介于 0.73%~1.06%, 普遍达成熟阶段。

总体上, 湖相富含有机质泥页岩的热演化程度普遍不高, 多数还处于生油窗内, 部分泥页岩的岩石硬度小, 其中的黏土矿物遇水膨胀现象明显, 经常导致套损。这对于页岩气勘探开发较为不利。

3 我国页岩气勘探战略选区思考

战略选区是页岩气勘探开发前的基础性、前瞻性工作,面对的是新领域、第一手资料缺乏等困难。因此,优选页岩气远景区时,主要考虑以下几方面:页岩地质特征、页岩气资源前景和页岩气开发可行性。

3.1 从页岩地质特征来考虑

1) 海相厚层页岩的单层厚度大,有机质丰度高,有利于形成页岩气聚集,页岩的强度普遍较大,有利于井眼稳定;加之裂缝较发育,有利于页岩气开发。但部分页岩热演化程度高, R_o 已经超过 3.0%,生气高峰已过;部分页岩埋深较大,超过 3 000 m。这两方面的不利因素使其页岩气勘探有利区范围明显缩小。

2) 海陆交互相及陆相煤系富含有机质泥页岩有机质丰度高,热演化程度普遍不高, R_o 多在 3.0% 以下,多数处于生气高峰。但单层厚度普遍不大,单独开发的经济性存在疑问。由于其多与煤层和致密砂岩层互层产出,如果煤层中存在煤层气富集或致密砂岩层中普遍存在天然气富集,那么发展不同类型天然气资源多层合采技术也是海陆交互相及陆相煤系地层页岩气开发的一种可行方式。

3) 湖相富含有机质泥页岩中,高有机质丰度的中厚层泥页岩普遍发育,但多数成岩程度不高,并眼易于变形,不利于水平井开发技术的广泛应用。

3.2 从页岩气资源前景和页岩气开发可行性来考虑

考虑我国不同类型富含有机质泥页岩的具体特点,结合国外页岩气开发的成功经验,笔者认为:我国页岩气起步阶段首先要考虑海相厚层页岩中那些总有机碳含量大于 1.0%, R_o 介于 1.0%~2.5% 之间,埋深介于 200~3000 m 之间,厚度大于 30 m 的富含有机质页岩发育区;其次考虑海陆交互相富含有机质泥页岩与致密砂岩和煤层在层位上的紧密共生区,但同时要研发不同类型天然气资源多层合采技术;对于湖相富含有机质泥页岩,重点考虑硅质成分高、岩石强度大、有利于井眼稳定的层系。

按以上原则对页岩气远景区进行评价后认为:曾被广泛看好的四川盆地大部分地区的下寒武和下志留统海相厚层富含有机质泥页岩,由于其埋深较大且有机质热演化程度较高,并不利于页岩气的勘探开发,仅川南地区较为有利;渝东鄂西、滇黔桂和川北地区下寒武统、下志留统和上二叠统富含有机质泥页岩, R_o 普遍小于 3.0%,但由于构造改造,储层或部分出露地表或部分深埋,其中埋深介于 500~3 000 m 的条带状页岩储层为勘探有利区。

海陆交互相及陆相煤系地层的富含有机质泥页岩因单层厚度薄,多数不具备单独开发的条件。但我国海陆交互相及陆相煤系地层发育广泛,泥页岩层与煤层气特别是致密砂岩气叠置共生。因此,发展页岩气与致密砂岩气等多种类型天然气资源多层合采技术具有十分现实的意义。沁水盆地、鄂尔多斯盆地河东地区、滇东黔西等含煤盆地的中深部,特别是煤炭开采深度以下的煤系地层可以考虑作为发展多种类型天然气资源多层合采的研究试验区。

湖相富含有机质泥页岩发育区的页岩气有利区优选首先应考虑的是岩石强度指标。准噶尔盆地埋深在 3 000 m 以浅的二叠系芦草沟组、红雁池组和平地泉组厚层富含有机质泥页岩发育区是该类页岩气勘探的首选目标区。

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ABSTRACT: Through comparison analysis of shale gas accumulation conditions and the similarity of geological conditions in the U.S. A and China, this study concluded that both countries have similar geological conditions favorable for shale gas accumulation and have approximate shale gas resource reserves and development potentials. In general, the gas-bearing shale layers in China possess high TOC, high thermal maturity and a high degree of later reformation. Shale gas accumulations are characterized by terrestrial facies deposit, controlled by sedimentation region division, and various and complicated distribution. Shale gas accumulations can be classified into direct and indirect types, and also can be divided into three types as southern type, northern type and north-western type according to the regional geologic conditions in China. The southern type of shale gas, distributed around the Yangtze plate, is mostly accumulated in the Paleozoic marine shale which experienced intensive structural reformation, and is featured by a large thickness of a single layer, multiple developed layers, a wide distribution area, high thermal maturity, and a high degree of later reformation, etc. The northern type of shale gas, distributed in the north China plate, is mostly accumulated in the groups from Paleozoic via Mesozoic to Neozoic, and is characterized by sedimentary migration, a high frequency of thin interbedded layers, and an obvious division between sedimental facies. The north-western type of shale gas, distributed around the Tarim Plate, is accumulated in the groups from Paleozoic to Mesozoic, and has the characteristics of various types of sedimentation, high TOC, and relatively low thermal maturity. It is concluded that the recoverable shale gas resources is predicated to be about 26 tcm in China, close to 28 tcm of that in the U.S. A.

KEY WORDS: China, shale gas, resource evaluation, feature, accumulation pattern, development potential, North China platform, Yangtze platform, Tarim platform

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Development characteristics of organic rich shale and strategic selection of shale gas exploration area in China

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ABSTRACT: Shale gas, as a new type of unconventional natural gas resources, its exploration and development have got great success in the U.S. A., and fast progress in Canada, Australia and other countries. Shale gas exploration in China has just started and its study is still focused on shale gas reservoir conditions and favorable area evaluation. China's preferred shale gas favorable area is mainly related with organic-rich clay and shale, and the major optimization is a prospective area for shale gas. Complicated geological background and multi-stage evolution lead to many types of China's petroleum basins whose structures are complex. Different evolution history of each basin directly controls the development and distribution of organic-rich shale. By the different formation environment, organic-rich shale can be divided into marine thick layer organic-rich shale, continent-sea intercrossing organic-rich shale, coal-bearing strata organic-rich shale, and lacustrine organic-rich shale. Among them, the thick layer marine organic-rich shale is of first priority in China's near future shale gas exploration; continent-sea intercrossing organic-rich shale and coal-bearing strata organic-rich shale are thin in single-layer, but they have symbiotic conditions with tight sandstone gas and coal-bed gas, so the multi-layer co-mining technology of shale gas, tight sandstone gas and many other types of natural gas resources has great practical significance; the lacustrine organic-rich shale's diagenesis degree is generally low, and needs further optimization of a horizon with high-strength rock and the conditions of open hole completion for exploration and development.

KEY WORDS: China, shale gas, mud shale, play, marine facies, transitional facies, continental coal measure strata, lacustrine facies

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Application of Geo-anomaly Ore-prospecting Theory to shale gas exploration

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ABSTRACT: Based on the Geo-anomaly Ore-prospecting Theory and the characteristics and forming conditions of shale gas pools, the Geo-anomaly sequence of shale gas pools is divided into four levels, namely Background Geo-anomaly, Gas-accumulation Geo-anomaly, Gas-rich Integration Anomaly, and Profitable Geo-anomaly. The main indexes of Background Geo-anomaly are sedimentary basins and shale developed; the main indexes of Gas-accumulation Geo-anomaly are the thickness of shale and the total organic content (TOC); the main indexes of Gas-rich Integration Anomaly include gas content and gas reserves, as well as the associated temperature, pressure, porosity, thickness of shale, TOC, composition and humidity of clay, and geochemical and geophysical anomalies are the complementary indexes of Gas-accumulation Geo-anomaly; the main indexes of Profitable Geo-anomaly are gas production, gas productivity, as well as fracture density, brittleness of the shale. The above mentioned four levels of anomaly are the bases for identifying prospective areas, favorable plays, exploration targets, and commercial shale gas pools respectively. Prospective areas for shale gas exploration have been basically identified in China and the prediction of favorable plays is also fruitful. In contrast, the identification of exploration targets and commercial shale gas pools are still in the initial stage, thus they should be strengthened and speeded up.

KEY WORDS: Geo-anomaly Ore-prospecting Theory, shale gas, exploration, application, Background Geo-anomaly, Gas-accumulation Geo-anomaly, Gas-rich Integration Anomaly, Profitable Geo-anomaly

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Potentials of the Lower Palaeozoic shale gas resources in Chongqing and its adjacent areas

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ABSTRACT: Tectonic evolution of the Sichuan Basin can be divided into two stages: a stage of a cratonic basin from the Sinian to the Middle Triassic and a stage of a foreland basin stage from the Late Triassic to the Neogene. In the former stage, very thick marine deposits were accumulated. Two large-scale transgression events occurred in the Late Sinian and the Middle Ordovician, during which two sets of dark shale, one of which is the Lower Cambrian Qiongzhusi Formation and the other one is from the Upper Ordovician Wufeng Formation to the Lower Silurian Longmaxi Formation, were deposited respectively. As the tectonic events are complex in the process of basin evolution, the tectonic actions in Chongqing and its adjacent areas are characterized by high uplifting and strong compression. The Lower Paleozoic is shallow in burial depth, serious in deformation and strong in destruction. The present structure is presented by steep fold. The characteristics of tectonic evolution and geologic conditions in the study area are similar to those in the typical shale gas basins of the eastern U. S. A. The study area has the favorable conditions for shale gas accumulation, thus is an important frontier for shale gas exploration. Preliminary estimation with the volumetric method shows that the shale gas volume in the Qiongzhusi Formation is 7.5 tcm and that in the Wufeng-