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海底沉积物多边形断层及其对天然气水合物赋存的控制

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提要:多边形断层是一种非构造成因的小型层控伸展断层,多发育于细粒沉积物中,数量多且断距小,断层面在平面上呈不规则多边形排布,在剖面上呈倾向相近或相反的伸展断层。多边形断层的形成机制主要包括"密度反转"、"脱水收缩"和"剪切破裂",不同形成机制所主导的断层形态各有特点。"密度反转"的标志是波状地层接触面;"脱水收缩"的特征是犁状断层和生长层序,直接证据是海底沟纹和沉积物样品中的微裂缝;"剪切破裂"的特征是平直状断层和地堑−地垒式断层组合。多边形断层提高了细粒沉积层的渗透率,可作为烃类气、流体垂向运移的通道。脱水收缩形成的犁状断层流体输导性能可能弱于剪切破裂形成的平直状断层。天然气水合物作为浅表层烃类气、流体运移的产物,其赋存区域也可能会受到多边形断层的控制。分布较深的多边形断层可为天然气水合物提供气、流体运移通道,而分布较浅的多边形断层可为天然气水合物提供储集空间。

关　键　词:海底沉积物;多边形断层;形态特征;形成机制;流体输导性能;天然气水合物;油气勘查工程

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Polygonal fault in marine sediments and its impact on gas hydrate occurrence

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Abstract: Polygonal faults are non−tectonic small stratabound extensional faults generally developed in the fine−grained sediments with numerous fault planes and small offset. The fault planes are arranged in irregular polygonal shape in plan view, and occur as extensional faults with similar or opposite inclinations in profile view. The geometry of the polygonal faults is considered to be affected by formation mechanisms, such as density inversion, syneresis and shear failure. The prominent indicator of density

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inversion is the wave- like surface between horizons. The prominent indicators of syneresis are listric fault planes and growth sequences, and the furrows on the seafloor and the micro-fractures in the sediment samples make up the evidence. The occurrence of polygonal faults improves the permeability of fine-grained sediments, which can provide vertical pathways for gas and fluid migration. The conductivity of listric faults induced by syneresis is inferred to be better than that of straight faults. As a product of shallow gas and fluid migration, the occurrence area of gas hydrate is possibly dominated by polygonal faults. Deep polygonal faults provide pathways of gas and fluid migration for gas hydrate, and shallow polygonal faults provide reservoir spaces for gas hydrate.

Key words: marine sediments; polygonal faults; geometric characteristics; formation mechanism; fluid conductivity; gas hydrates; oil and gas exploration engineering

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1 引 言

天然气水合物通常与海底浅表层构造相关，多数浅表层构造可为烃类气、流体提供运移通道和储集空间，从而影响天然气水合物的形成与分布(Han et al., 2019)。在海洋环境中，细粒沉积物是良好的盖层，对流体运移起着重要的封盖作用(Seebeck et al., 2015)。细粒层中发育的多边形断层，不仅是层内释压通道，也是烃类流体向上运移的重要通道(Berndt et al., 2003; Cartwright et al., 2004; Möller et al., 2004; Berndt, 2005; Hustoft et al., 2007; Sun et al., 2010; Berndt et al., 2012; Laurent et al., 2012; Ostanin et al., 2012; Ho et al., 2016; Gay, 2017)。利用“多边形断层只存在于细粒层中”的特征，来识别深水砂岩储层(Jackson et al., 2014)，也是有据可循的储层预测方法。此外，向细粒层底部注入并埋存CO_2(Seebeck et al., 2015)和放射性废料(Buckley and Grant, 1985)的研究广受关注，而多边形断层的存在会破坏细粒层的封盖作用。

多边形断层的研究最早可追溯到20世纪80年代(Buckley and Grant, 1985)，Henriet（1991）也曾在北海南部古近纪黏土岩中识别出了该类断层。多边形断层在2D地震剖面上表现为层控伸展断层，因此在后来的研究中也曾被称作“块状断层、层控断层、小型伸展断层”。前人正式认识到这种断层始于1994年，英国学者Cartwright首次从北海地区丰富的3D地震资料中发现了多边形断层的平面形态，即多边形断层在平面上走向随机并呈不规则多边形排布(Cartwright, 1994b)。该断层在世界多个盆地均有发现(Dewhurst et al., 1999b; Berndt et al., 2003; Cartwright et al., 2003; Tewksbury et al., 2014; Morgan et al., 2015; Seebeck et al., 2015)，包括北海(Cartwright, 1994a; Cartwright, 1994b; Cartwright and Lonergan, 1996; Cartwright and Lonergan, 1997; Lonergan et al., 1998a; Clausen et al., 1999; Dewhurst et al., 1999b; Stewart, 2006; Hale and Groshong, 2014; Kumar et al., 2016)、澳大利亚伊罗曼加盆地(Watterson et al., 2000; Nicol et al., 2003; Kulikowski et al., 2018)、南中国海(Sun et al., 2010; Wang et al., 2010a; Wang et al., 2010b; Han et al., 2016; Jiang et al., 2017; Li Yufeng et al., 2017; Yang et al., 2017; Li et al., 2018)、下刚果盆地(Gay et al., 2004; Gay et al., 2006; Andresen and Huuse, 2011; Ho et al., 2012; Ho et al., 2016)等（图1）。多边形断层的概念提出后，迅速成为众多学者的研究焦点，该类断层的形成机制和形态特征也随之揭开。

2 断层特征

2.1 几何形态

多边形断层一般分布于被动大陆边缘的海底细粒沉积物中(Cartwright, 1994a; Cartwright, 1994b; Cartwright and Lonergan, 1996; Cartwright and Lonergan, 1997; Cartwright and Dewhurst, 1998; Dewhurst et al., 1999b; Goulty, 2001; Goulty, 2002; Berndt et al., 2003; Cartwright et al., 2003; Cartwright, 2011; Ostanin et al., 2012; Jackson et al.,

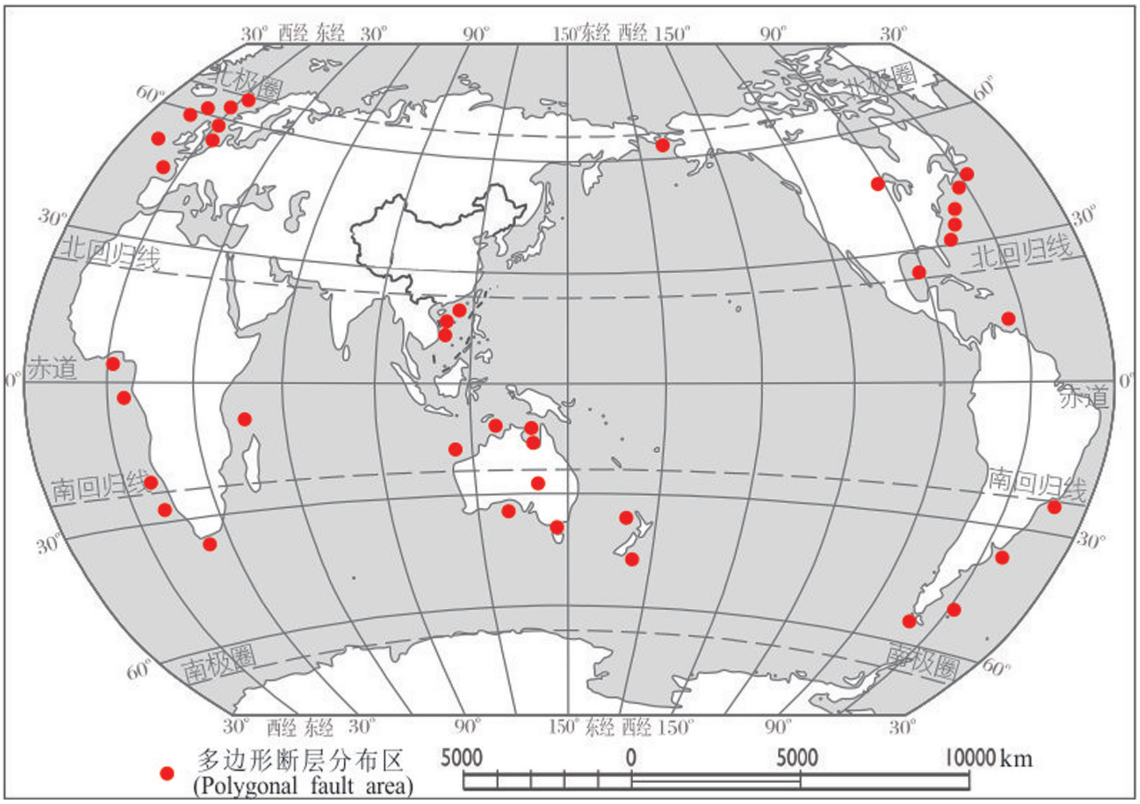

图1 海底多边形断层分布图（据Cartwright and Dewhurst, 1998; Cartwright et al., 2003修改）
Fig.1 The map of polygonal faults distribution (modified from Cartwright and Dewhurst, 1998; Cartwright et al., 2003)

2014; Tewksbury et al., 2014; Seebeck et al., 2015; Turrini et al., 2017)，位于海底以下0～1500 m的地层中(Cartwright and Dewhurst, 1998)。该断层具有层控的特征(Cartwright, 1994, 1994b, 2011; Cartwright and Lonergan, 1996; Cartwright and Dewhurst, 1998; Goulty, 2002; Gay, 2017; Jackson et al., 2014; Morgan et al., 2015; Seebeck et al., 2015; Kumar et al., 2016)，断距一般小于100 m，其在平面上呈多边形排列(Cartwright, 1994a; Cartwright, 1994b, 2011; Cartwright and Lonergan, 1996; Cartwright and Lonergan, 1997; Cartwright and Dewhurst, 1998；Lonergan et al., 1998a；Cartwright et al., 2003; Gay et al., 2004; Laurent et al., 2012; Jackson et al., 2014；Gay, 2017；Wrona et al., 2017)，走向随机；在剖面上普遍表现为伸展断层(Cartwright et al., 2003; Hale and Groshong, 2014; Seebeck et al., 2015)，倾向相近或相反（图2）。多边形断层将地层切割为多个不规则多面体，多面体大小不一，在部分大断块中还发育二阶多边形断层。

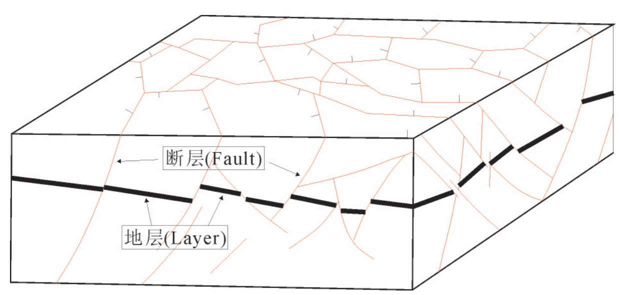

图2 多边形断层立体形态示意图（据Cartwright, 1994a修改）
Fig.2 3D geometry characteristics of polygonal faults (modified from Cartwright, 1994a)

二阶断层将大断块切割成小断块，形态类似“俄罗斯套娃”(Gay et al., 2004)。该类断层长度从几厘米至几千米不等，断距从几厘米至几十米不等，断层数量多且连续性较差，导致断层体密度难以统计。受限于目前的地震分辨率，厘米级的多边形断层在地震剖面上也难以识别，但在浅表层沉积物取心中已有报道(Wattrus et al., 2003)。

2.1.1 平面形态

地震属性提取和相干性时间切片通常被用来

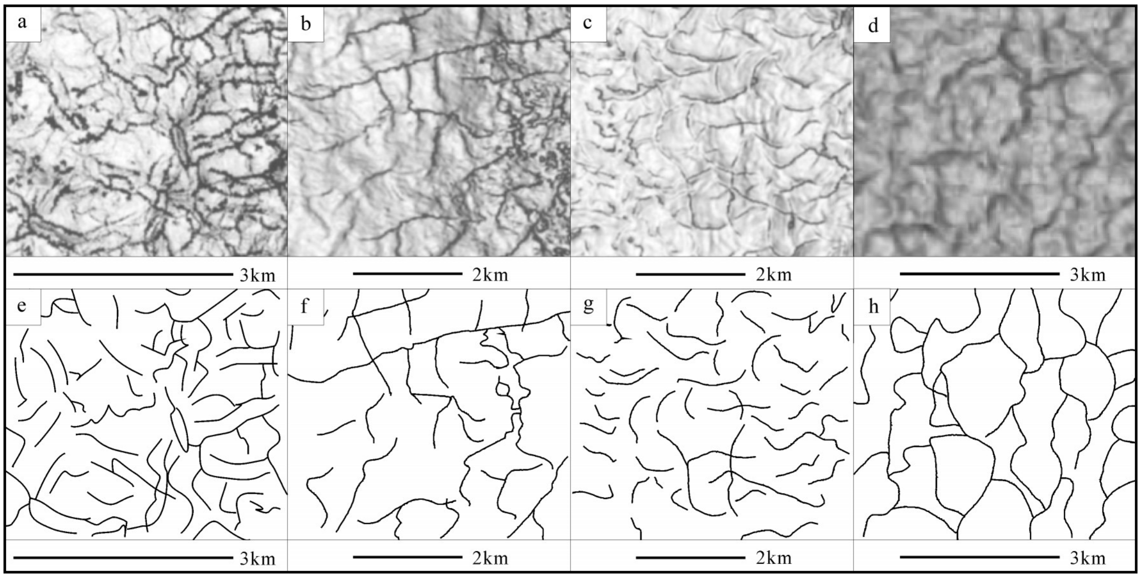

图3 多边形断层平面形态(据Watterson et al., 2000; Cartwright et al., 2003修改)
a、b、c、d—地震时间切片,e、f、g、h—平面形态示意图
Fig.3 The geometric map of polygonal faults. a-d are seismic time slices, e-h are hand-drawing schematics (modified from Watterson et al., 2000; Cartwright et al., 2003)

呈现多边形断层的平面形态(Sun et al., 2010; Wang et al., 2010a),多边形断层在平面上走向随机并呈不规则多边形排布。从不同地区来看,断层的平面形态可以分为交汇型(图3a、d)和孤立型(图3b、c),两者又各自包括线形(图3b)和弧形(图3c)两种形态(Cartwright and Lonergan, 1996; Lonergan et al., 1998a; Cartwright et al., 2003),其平面形态差异可能与赋存层位的岩性变化有关(Stuevold et al., 2003)。

多边形断层的平面形态容易受到构造应力的影响。在构造断层存在的地区,多边形断层几乎与构造断层走向一致(Ostanin et al., 2012)。盐层向上部地层底辟的过程中会产生上拱的环状应力,多边形断层趋向于沿圆环呈放射状分布。而在环状作用力区域外,多边形断层为随机走向(图4)(Stewart, 2006;Dan, 2012)。

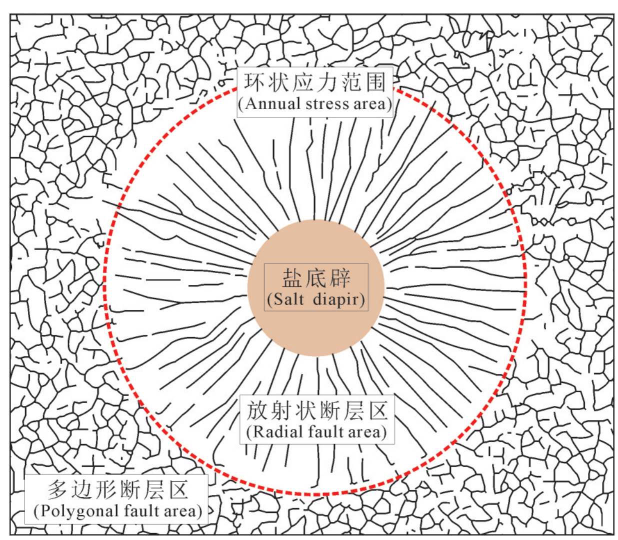

图4 受盐底辟影响的多边形断层平面形态(据Dan, 2012修改)
Fig. 4 The geometric map of polygonal faults influenced by salt diapir (modified from Dan, 2012)

2.1.2 剖面形态

多边形断层在地震剖面上一般呈犁状(图5a、c)或平直状(图5b、d)(Lonergan et al., 1998a)。离海底较近的多边形断层的断层面更加平直且倾角更高(50~80°),而埋藏较深的多边形断层的断层面更加弯曲且倾角更低(20~50°)(Cartwright, 2011),部分断层上部为平直状而下部逐渐过渡为犁状(Cartwright et al., 2003)。如果多边形断层层位底部存在流动地层单元,则断层也趋向于呈犁状(Stuevold et al., 2003)。

北海盆地存在典型的犁状多边形断层,乌拉圭陆缘存在典型的平直状多边形断层(图5)。北海盆地平均水深小于100 m,断层发育于海底以下500 m以深的地层中,多边形断层面短而弯曲,呈犁状

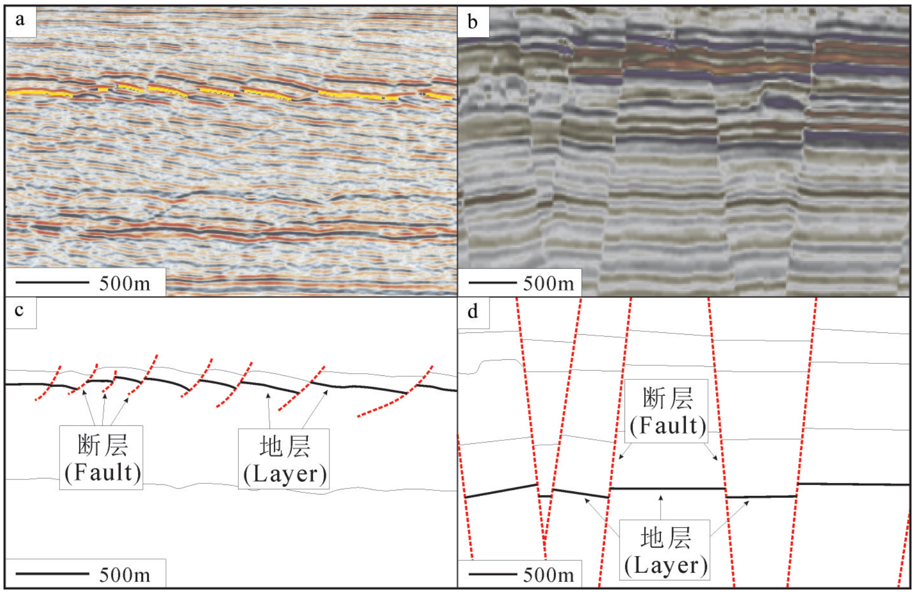

图5 多边形断层剖面形态（据Cartwright and Lonergan, 1996; Turrini et al., 2017修改）
c—地震剖面a的示意图，d—地震剖面b的示意图
Fig. 5 The geometric profile geometry of polygonal faults (modified from c−Schematic diagram of seismic section a; d−Schematic diagram of seismic section b Cartwright and Lonergan, 1996; Turrini et al., 2017)

(Cartwright and Lonergan, 1996)（图5a）；乌拉圭陆缘水深大于2000 m，断层发育于海底以下1000 m以深的地层中，断层面长而平直，呈地堑–地垒状断层组合(Turrini et al., 2017)（图5b）。两者由于水深、埋深等参数的不同，形成了不同形态的多边形断层。

此外，多边形断层的剖面形态会受到坡度影响。在几乎水平的地层中，相反倾向的多边形断层数量大致相当；而在倾斜地层中，向地层薄端倾斜的多边形断层占绝大多数（图6）。坡度会导致重力分布不均匀，影响压实力分布，造成差应力，使得断层更趋向于向上坡方向倾斜(Roberts, 2014)。前人研究提出，重力滑塌是多边形断层的形成机制(Higgs and Mcclay, 1993)，而本研究认为重力只是影响多边形断层形态的因素。因为在几乎水平的地层中，多边形断层也有发育(Cartwright and Lonergan, 1996)。

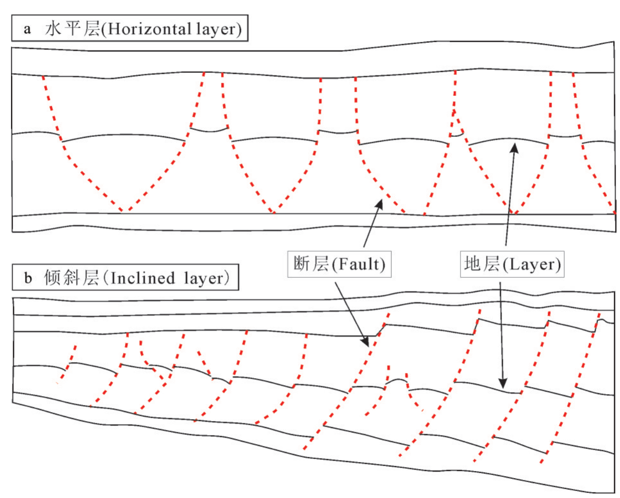

图6 受坡度影响的多边形断层剖面形态（据Roberts, 2014修改）
Fig. 6 The geometric profile of polygonal faults influenced by gradient (modified from Roberts, 2014)

2.2 赋存层位特征

前人对比了世界范围内的多边形断层赋存层位的地层特征，发现多边形断层仅存在于细粒沉积物中（表1）(Cartwright and Dewhurst, 1998; Cartwright et al., 2003)。在厚层细粒沉积物中的粗粒薄夹层也存在多边形断层，但在厚层粗粒层中未见多边形断层(Cartwright et al., 2003)。前人认为，多边形断层存在于泥岩或黏土岩中(Henriet et al., 1991; Cartwright, 1994a; Cartwright and Lonergan, 1996)，断层密度和长度通常随粒度变粗和地层变薄而减小(Hansen et al., 2004)。

沉积物的矿物组成对多边形断层的形态也有影响。前人研究了北海地区蒙脱石含量与多边形断层赋存层位的地层伸展量的关系，发现黏土矿物含

表1 多边形断层赋存层位的沉积物参数(据Cartwright and Dewhurst, 1998; Cartwright et al., 2003)

Table 1 The sediment parameters of polygonal fault in the layers (modified from Cartwright and Dewhurst, 1998; Cartwright et al., 2003)

地区	海底以下深度/m	岩性	主矿物
乔治亚湾	100~940	泥岩、黏土岩	蒙脱石
新泽西盆地	200~1500	泥岩、黏土岩	伊利石、高岭石
设得兰群岛西缘	113~413	软黏土、泥岩	伊利石-蒙脱石
卡奔塔利亚盆地	400~800	泥岩、粉砂岩	黏土矿物*
芒特艾萨盆地	400~1000	黏土-页岩	黏土矿物*
巴斯盆地	700~1100	泥岩、泥灰岩	黏土矿物*
纳米比亚	0~1000	黏土岩	黏土矿物*
奥兰治盆地	200~800	页岩、黏土岩	黏土矿物*
文彻盆地	400~600	泥岩	黏土矿物*
非洲东南缘	500~600	硬黏土	蒙脱石
伊罗曼加盆地	50~1500	泥岩、页岩	蒙脱石
北海盆地	500~1500	泥岩	蒙脱石
Voring盆地	100~1000	白陶土、泥岩	生源二氧化硅
Goban海脊	27~278	微化石白垩岩	碳酸钙、黏土
哈特勒斯盆地	590~950	生源黏土岩	碳酸钙、二氧化硅
新泽西	1000~1500	硅质白垩岩	碳酸钙、二氧化硅
查林杰高原	250~650	软泥、白垩岩	碳酸钙
罗克尔海槽	100~800	软泥、白垩岩	碳酸钙
哈顿—罗克尔盆地	70~700	软泥、白垩岩	碳酸钙
埃克斯茅斯高原	317~811	软泥、白垩岩	碳酸钙
查塔姆高地	200~500	软泥、白垩岩	碳酸钙
伊瓦兰盆地	208~530	白垩质白陶土	碳酸钙、蛋白石

注:*未定义矿物名称。

量高(高达95%)、蒙脱石含量高(高达70%)的层位对应的地层伸展量也最大(最大13%),该层位的平均粒径小于10 μm(Dewhurst et al., 1999b)。蒙脱石含量高的地层,脱水作用更强,地层体积收缩更显著,排出的孔隙流体更多,形成的多边形断层多而密集。

然而,多边形断层存在于细粒沉积物中是一种定性的概念,如果要对细粒沉积物进行定量研究,还应该确定沉积物粒径、矿物组成与层厚等参数。粒径大小可以影响层位渗透率,粒径越小,渗透率越低;矿物组成可以影响蒙脱石脱水收缩的程度,蒙脱石含量越高,脱水收缩作用越强烈;层厚可以影响压实力大小,层厚越大,压实力越大。以上不同层位参数组合会形成不同形态的多边形断层。此外,层位横向粒径变化分析也将有助于了解多边形断层的层内分布规律(Turrini et al., 2017),黏土颗粒和流体在早期埋藏中发生的变化有助于了解多边形断层形成时间、层位和机制等问题(Gay, 2017)。

3 断层形成机制

多边形断层的形成可能受多种机制控制。Henriet et al. (1991)用“密度反转”的机制解释了北海南部多边形断层的前身“块状断层”,之后研究人员对该类断层的形成机制展开了深入的研究和讨论。多边形断层是非构造成因的小型层控伸展断层,与沉积物固结成岩过程中发生的物理和化学变化密切相关。总结前人研究,本文认为多边形断层形成机制主要有3种,即密度反转、脱水收缩和剪切破裂。

3.1 密度反转

黏土层埋藏早期,上部与下部的孔隙水排出至邻近地层中并在黏土层的上部与下部形成不透水的封堵层(图7a)。随着压实作用的进行,孔隙水被封堵在孔隙中,中部黏土层处于欠压实状态。由于中部黏土层含有较多孔隙水,密度小于上覆地层,这种状态被称为密度反转。随沉积过程继续进行,被封堵的层位的孔隙水处于超压状态,超压层顶部产生水力裂缝和断层,超压随之释放(图7b)(Henriet et al., 1991; Cartwright and Lonergan, 1996; Watterson et al., 2000)。

波状地层接触界面可作为密度反转的地震反射标志,这种波状界面在多个地区的地震剖面上都有发现,包括挪威中部陆架(图8a)(Berndt et al., 2003),伊罗曼加盆地(图8b)(Watterson et al., 2000),法罗—设得兰盆地(图8c)(Davies, 2005)和荷兰北海地区(图8d)(Hale and Groshong, 2014)。密度反转形成的多边形断层面在平面图上呈“浅盘状”交汇(图9b),在剖面图上为切割波状界面的正断层(图9c)。

密度反转状态可受多种因素影响,包括岩性、沉积速率、流体热膨胀、黏土矿物转化、生烃作用、细菌甲烷化合作用(Yu and Lerche, 1996)。在较快的沉积速率下,密度反转的状态更容易形成(Victor and Moretti, 2006),快速沉积的黏土层易在层位中部形成超压,多边形断层形成以释放超压(Henriet et al., 1991);蒙脱石脱水向伊利石转化的过程也会导致孔隙水超压(Dewhurst et al., 1999b);异常高的

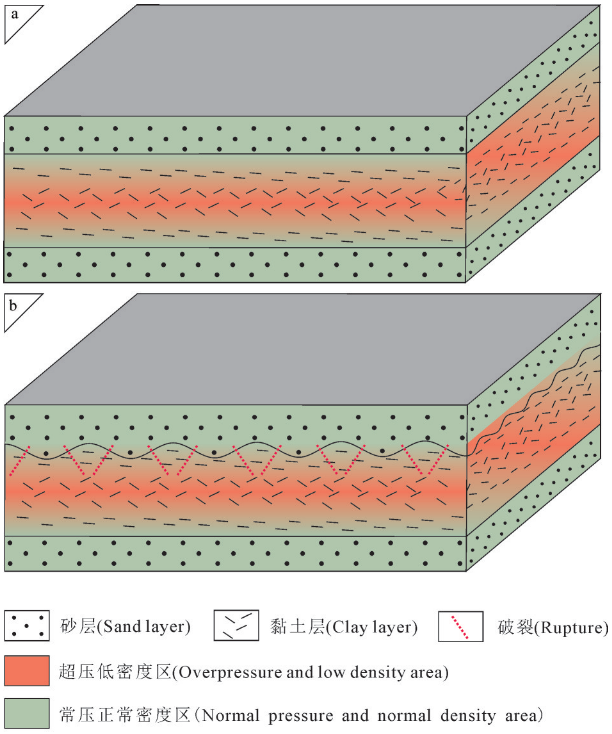

图7 密度反转机制示意图
a—黏土层中孔隙水排出受阻，超压形成；b—超压导致断层形成，超压释放
Fig.7 The schematic of density inversion
a−The pore water sealed in the clay layer, the overpressure formation.
b−The overpressure leading to fault formation, the overpressure releasing

古地温场导致流体增量明显超过岩石骨架体积增量，从而导致异常高压产生(Jiang et al., 2017)；地层中的有机质颗粒转化为油气也可导致超压(Yu and Lerche, 1996)。

3.2 脱水收缩

海底细粒沉积物沉积后，黏土颗粒在粒间吸引力（范德瓦尔斯力）作用下发生絮凝形成凝胶体，沉积物颗粒排列更紧密，在宏观上表现为沉积物体积收缩并排出孔隙水，这个过程被称为脱水收缩作用。凝胶体浅埋藏后，三维收缩在侧向上受到地层的限制，最终体积收缩被层位破裂和断层所调节（图10a）。凝胶体继续收缩，导致断层两侧发生滑动，表现为断层向上或向下生长（图10b）。

脱水收缩作用可能开始于沉积物−水界面上。Gay et al. (2004)在下刚果盆地海底表明发现了泥质沉积物脱水收缩缝，认为脱水收缩作用可能开始于沉积物−海水界面上。在苏必利尔湖湖底细粒沉积物活塞取心中，Wattrus et al. (2003)发现沉积物中存在肉眼可见的断裂和微小断层，认为它们是浅表层沉积物脱水收缩所致。前人在罐子中装入水饱和黏土并研究了其中的脱水收缩缝，实验表明该类裂缝可以在黏土自发脱水收缩的过程中形成，这些裂缝没有优势走向(White, 1961；Dewhurst et al., 1999a)。

犁状断层面和生长层序可作为脱水收缩作用的标志。前人在断层上盘发现生长层序，认为断层可能生长至沉积层表面并与沉积作用同期进行(Cartwright, 1994b; Cartwright and Lonergan, 1996; Lonergan et al., 1998b)。浅表层沉积物所处的水深较浅，上覆压实力较小，沉积物固结程度低、孔隙度高，整体较软，脱水收缩作用易于产生脱水收缩缝。沉积物脱水收缩产生的多边形断层通常短小而密集，平面上为高低不一的阶梯状，剖面上呈犁状。在断层面两侧，断块与断块之间相互邻接并存在一定旋转，断层上盘也作为邻接断层的下盘，在平面图上呈低缓的“阶梯状”（图11）。

3.3 剪切破裂

Cartwright and Lonergan (1996)用“莫尔−库伦定律”解释了海底细粒沉积物中的剪切破裂。沉积物浅埋藏时最大主应力(σ_1)是垂向的，由上覆层重力减去孔隙流体压力产生；最小主应力(σ_3)是横向的，由侧向地层压力产生。莫尔圆（左端点为最小主应力σ_3，右端点为最大主应力σ_1）与剪切破裂包络线相切时，沉积物会产生剪切破裂。有两种情况可以导致莫尔圆与破裂线相切：①随埋深进行，层内水平伸展力(F_1)增大，使最小主应力(σ_3)减小，莫尔圆向左半径增大并与破裂线相切，产生剪切破裂（图12a）；②孔隙流体压力(F_2)增大，使最大主应力(σ_1)和最小主应力(σ_3)减小，莫尔圆整体左移并与破裂线相切，产生剪切破裂（图12b）。

细粒沉积物的特殊力学性质导致其易于发生剪切破裂。细粒沉积物中存在极低的摩擦系数，在重力驱动的机械压实作用下极易产生剪切破裂和滑塌(Goulty, 2001,2002,2009)。细粒沉积物中存在较低的束缚力，成岩过程中一系列物理化学反应导致颗粒溶解，会改变颗粒尺度的物理参数，导致剪切破裂形成(Shin et al., 2008; Cartwright, 2011)。这些包括矿物溶解在内的成岩反应表现为颗粒尺度的沉积物体积减小，沉积物所受的侧向应力减小，

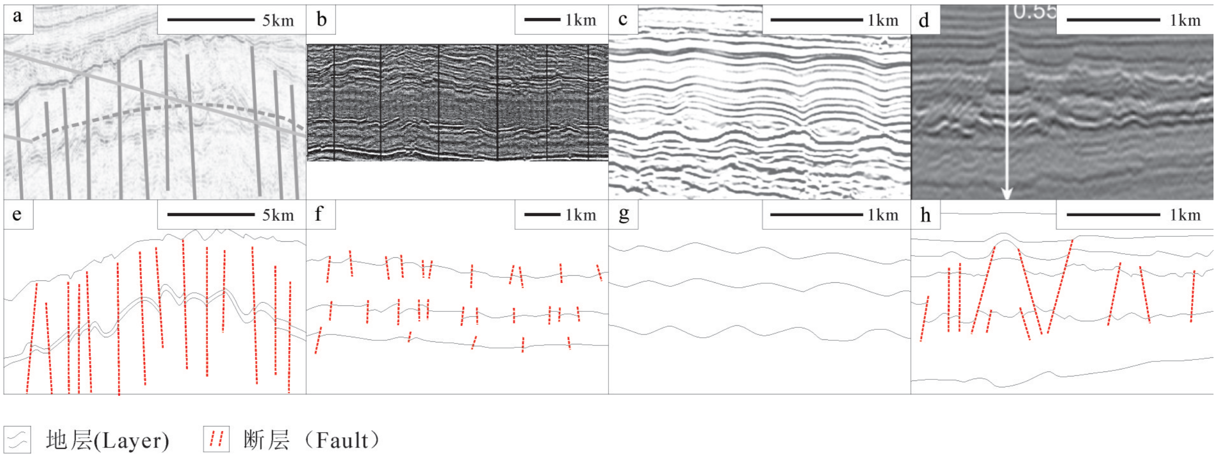

图8 波状地层接触面(据Watterson et al., 2000; Berndt et al., 2003; Davies, 2005; Hale and Groshong, 2014修改)
a~d—地震剖面图;e~h—手绘剖面示意图
Fig.8 Wave-like layer contact surface
(modified from Watterson et al., 2000; Berndt et al., 2003; Davies, 2005; Hale and Groshong, 2014)
a-d are seismic profiles. e-h are hand-drawing schematics

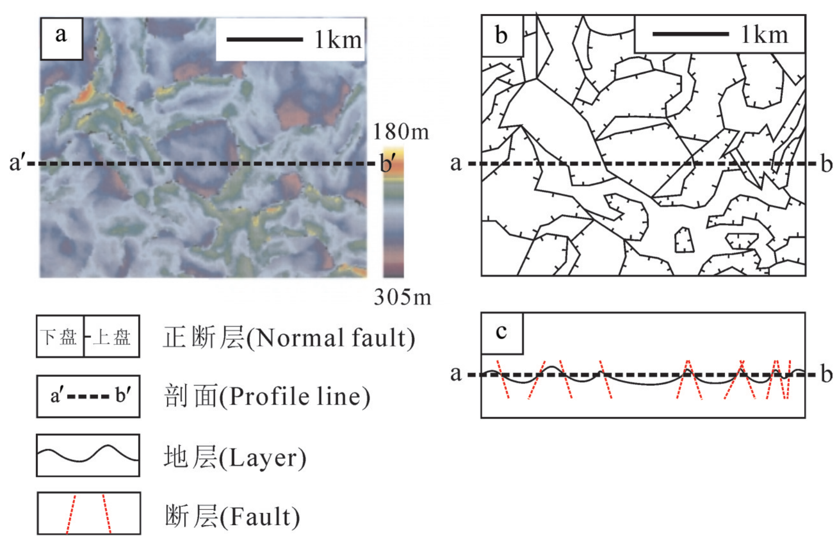

图9 浅盘状断层形态(据文献Watterson et al., 2000修改)
a—地震时间切片;b—图a的平面示意图;c—连线a'—b'的剖面示意图
Fig.9 Dish-like fault geometry (modified from Watterson et al., 2000)
a-Seismic time slice;b-Schematic of a;c- Profile schematic of line a'-b'

从而产生剪切破裂(Shin et al., 2008; Shin et al., 2010)。

平直状断层和地堑-地垒断层组合可作为剪切破裂的标志。对于埋藏较深的细粒沉积物,其固结程度较高,机械压实作用占主导,当沉积物内部流体排出困难时,易形成微小水力裂缝,沉积物易沿裂缝面滑动,形成剪切破裂。剪切破裂形成的多边形断层通常长而平直,断面两侧地层整齐,剖面呈现地堑-地垒形态,可见于乌拉圭陆缘(Turrini et al., 2017)。Roberts (2014)通过数值模拟方法研究了多边形断层的形成,发现剪切破裂形成的断层长而平直,与部分多边形断层的剖面形态一致。

4 流体输导性能

多边形断层因其独特的流体输导性能而广受关注。构造断层受控于构造应力,通常纵向切割较

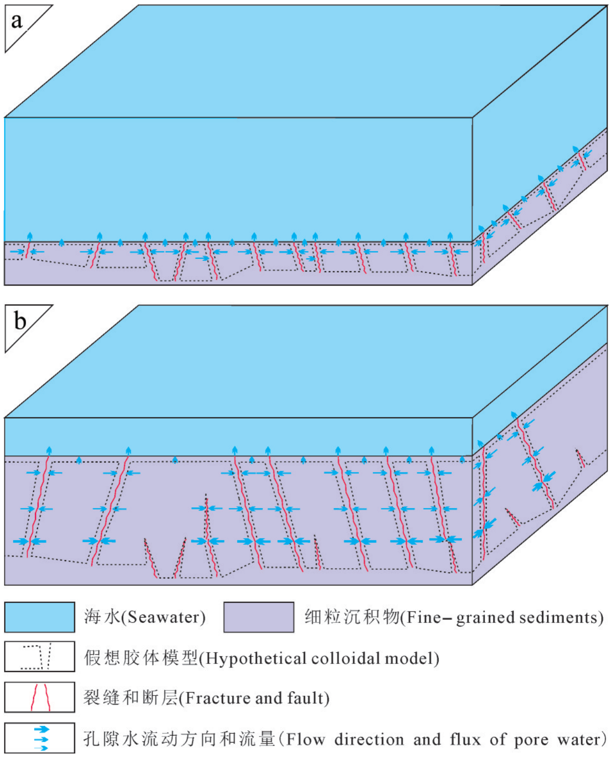

图10 脱水收缩机制示意图

Fig.10 Schematic diagram of syneresis mechanism

深，横向延伸较长，断层面可充当气、流体运移通道和储集空间。多边形断层是非构造成因的、层控性的、断层面短小且连续性较差，其对气、流体运移的影响并不十分清楚。

发育于海底细粒沉积物中的多边形断层改善了地层的渗透性能，为烃类气、流体的垂向运移提供了通道。Tewksbury et al. (2014)在埃及白垩纪地层中发现了多边形断层，并在断层面中发现了方解石脉，认为流体沿断层面流动时发生了矿化作用。Berndt (2005)发现埋藏于海底之下的多边形断层顶部末端存在管状构造，推测为流体沿断层面流动所形成。与气、流体运移相关的多边形断层连通海底时，流体沿断层从海底释放，会在海底形成麻坑(Gay et al., 2004; Wang et al., 2010a)。Laurent et al. (2012)认为这种连通至海底的断层可能仍处于活动状态。Ho et al. (2016)认为气体管道沿断面发育则指示断层是开启的，气体管道发育于断块之上则指示断层是封闭的。天然气水合物是浅层烃类气、流体运移的产物，分布较深的多边形断层可为其提供气体运移通道(Berndt, 2005; Hustoft et al., 2007)，分布较浅的多边形断层可为其提供储集空间(Gay et al., 2006)。但是，与多边形断层有关的流体活动过程通常是幕式的(Cartwright, 1994a; Roberts and Nunn, 1995)，这决定了多边形断层的流体输导性能有限。

断层形态是影响流体输导性能的重要因素。犁状断层面通常更短而弯曲。脱水收缩形成的犁状断层面在浅部为高角度，在深处渐变为低角度。低角度断层通常受上部地层的压实力更大，断层面闭合更紧实，流体输导能力较差。断层面短小、连

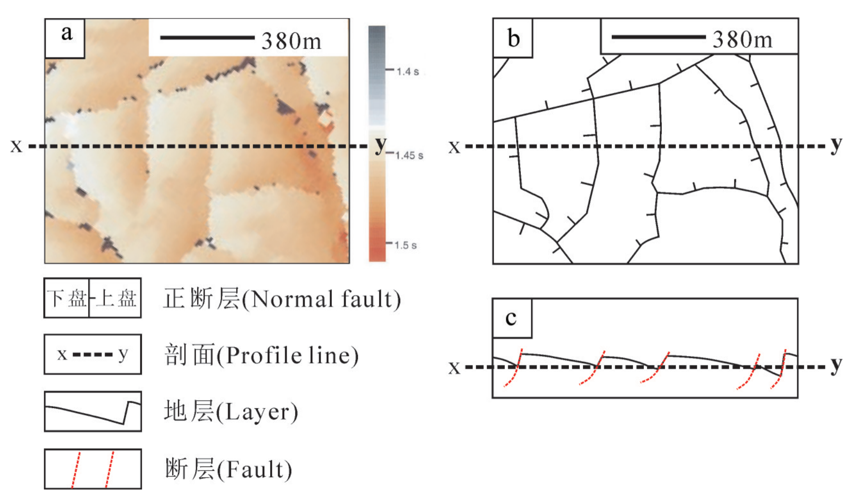

图11 阶梯状断层形态(Cartwright and Lonergan, 1996修改)

a—地震时间切片；b—图A的平面示意图；c—连线x-y的剖面示意图

Fig.11 Stair-stepping fault geometry (modified from Cartwright and Lonergan, 1996)

a-A seismic time slice; b-A schematic diagram of a; c-A profile schematic diagram of line x-y

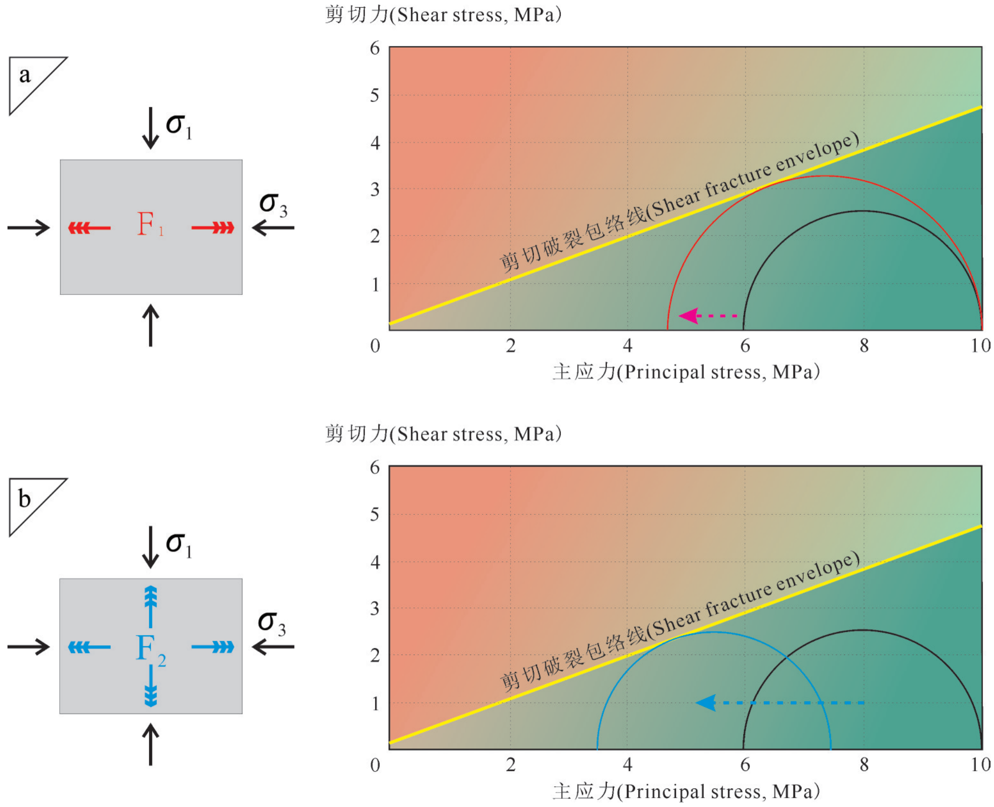

图12 剪切破裂机制示意图(据Cartwright and Lonergan, 1996修改)

F_1—伸展力,F_2—孔隙压力;σ_1—最大主应力,σ_3—最小主应力

Fig.12 The schematic diagram of shear rupture mechanism(modified from Cartwright and Lonergan, 1996)

F_1 −Extensional force; F_2 −Pore pressure; σ_1−Maximum principal stress; σ_3−Minimum principal stress

续性差,导致断层流体输导能力降低。断层面两侧的断盘存在一定角度的旋转,会加重泥岩涂抹的情况,使断面更封闭,流体输导能力降低。平直状断层面通常更长而平直。剪切破裂形成的平直状断层面规模更大,连续性更好,倾向相同和相近的断层数量相近,流体在断层中运移更容易。平直状断层通常断距更小,断面两侧的断盘无明显旋转,因此认为其流体输导能力相对更好。但目前尚无定性评价多边形断层输导性能的方法。

5 断层识别与描述

大尺度(米级以上)的多边形断层通常用高分辨率3D地震来呈现其形态,地震剖面可用于展现断层剖面形态,地震时间切片可用于展示断层平面形态。在多边形断层的概念提出前,研究人员在地震剖面上将多边形断层识别为块状断层、伸展断层、层控断层。直至Cartwright (1994a)通过北海盆地的三维地震时间切片展示了多边形断层的平面形态,多边形断层的立体形态才被呈现出来。在地震剖面上,同相轴分叉、变形和错断等特征可作为断层识别的标志。多边形断层断距较小,地震纵向分辨率越高越有利于识别小断层。地震相干体时间切片也常被用于显示多边形断层的平面形态、走向和分布规律等(Sun et al., 2009; Han et al., 2016)。

小尺度(米级以下)的多边形断层通常用实验模拟、沉积物取样等方法进行研究。为了研究黏土沉积物的脱水收缩作用,Dewhurst et al. (1999a)通过观察罐子中的水饱和黏土自发产生的收缩缝来研究多边形断层的形成机制。Cartwright et al. (2004)和Wattrus et al. (2003)在苏必利尔湖的湖底软沉积物取心中发现了肉眼可见的微裂缝和小断层,认为可能是沉积物脱水收缩或剪切破裂形成的多边形断层。细粒沉积物的脱水收缩作用发生在水饱和状态下,Tanner (1998)在野外观察了泥岩中的干燥缝,认为干燥导致的裂缝形态与脱水收缩导致的裂缝有很大区别。

高效的断层识别和统计方法是迫切需要的。多边形断层通常短而密集,数量巨大且走向随机,在地

震剖面上对其进行手动追踪是一项耗时耗力的工作。因此，对地震体属性通过方差体-蚂蚁体方法进行提取可以更加方便地呈现多边形断层的形态。在3D地震研究中通过等间隔统计剖面断层密度和平面断层密度，可作为研究其流体输导能力的依据。实验室尺度的沙箱模拟和数值模拟可进一步研究多边形断层的形态特征、形成机制和两者之间的关系。

6　结论与展望

（1）多边形断层多分布于海洋细粒沉积物中，具有层控、断距小、分布范围广等特征，其在平面上呈不规则多边形排列，在剖面上呈平直状和犁状。

（2）多边形断层的形成机制主要包括密度反转、脱水收缩和剪切破裂。波状地层界面可作为密度反转的标志；犁状断层和生长层序可作为脱水收缩的标志，海底沟纹和沉积物样品中的微断层可作为沉积物脱水收缩的证据；平直状断层和地堑-地垒式断层组合可作为剪切破裂的标志。

（3）多边形断层提高了细粒沉积层的渗透率，可作为烃类气、流体垂向运移的通道。脱水收缩形成的犁状断层流体输导性能可能弱于剪切破裂形成的平直状断层。天然气水合物是浅层烃类气、流体运移的产物，分布较深的多边形断层可为其提供气体运移通道，分布较浅的多边形断层可为其提供储集空间。

（4）多边形断层的定量描述是研究其流体输导性能的依据。高分辨率3D地震数据可以帮助识别多边形断层形态，并推测其形成机制。实验室尺度的沙箱模拟和数值模拟可以对所得认识加以验证。

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