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含体腔孔生物碎屑混积岩初始孔隙度恢复方法 ——以环渤中地区沙一二段混积岩储层为例

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摘要 【目的】环渤中地区古近系沙河街组一二段发育混积岩储层且富含大量油气资源,其中腹足类生物碎屑富集,其特有的生物体腔孔使得混积岩初始孔隙度不能以常规碎屑岩初始孔隙度恢复公式求取,目前国内外尚缺少混积岩初始孔隙度的恢复方法,而初始孔隙度的准确恢复是研究储层演化的关键内容。【方法】选用现代螺类样品,通过实验法和公式法分别求取螺类生物体腔孔体积,然后通过构造物理模拟实验模拟螺类生物体腔孔在真实沉积环境中的充填情况,最后以前人常用的储层初始孔隙度计算公式为基础,得到一种适用于混积岩储层的初始孔隙度计算公式。【结果】螺的种类是影响螺类生物体腔孔体积占比的最大因素。不同种类的螺,有效储集空间即体腔孔孔隙度的大小不同;影响同一种螺体腔孔孔隙度差异的原因主要为体腔孔开口的大小。以生物碎屑含量较高的QHD36-3-A井3 765.03 m混积岩样品为例,求得该深度混积岩的初始孔隙度约为51.68%。【结论】以前人公式为基础,结合物理模拟实验建立了一个新的求取混积岩初始孔隙度的计算方法,对于混积岩储层演化研究具有重要意义。

关键词 混积岩;腹足类生物;初始孔隙度;孔隙演化;体腔孔

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0 引言

孔隙度演化规律不仅是基础地质学研究的基本规律之一,也是石油地质应用领域中不可缺少的重要理论依据,在油气成藏过程中地层孔隙度是控制油气运移聚集的关键因素之一,因此掌握孔隙度在地史过程中的演化规律对于油气成藏机理的研究具有重要意义(刘震等,2007;潘高峰等,2011;杨宁等,2013;You *et al.*,2020)。初始孔隙度是孔隙演化的开始,不同岩性的初始孔隙度不尽相同(Wang *et al.*,2011;王琪等,2017;Zhao *et al.*,2022;Zhao *et al.*,2023),如细砂岩初始孔隙度平均值为29.58%,中砂

岩初始孔隙度平均值为30.47%,粗砂岩初始孔隙度平均值为31.65%。一般情况下,岩石的初始孔隙度不会高于40%,但这一规律并不适用于混积岩,混积岩的初始孔隙度通常较高,有的混积岩现今孔隙度就已达37.74%(庞小军等,2022),超过了已有的其他岩石类型的初始孔隙度。近年来,许多国内外学者研究认为混积岩储层也能够发育优质储层,可富含大量油气资源,具有较高油气潜力,混积岩储层已成为当前深层油气勘探的重点目标之一,掀起混积岩储层的研究热潮(Palermo *et al.*,2008;叶茂松等,2018;Gardner and Dorsey,2021;Li *et al.*,2021;Ye *et al.*,2021;Du *et al.*,2022;Hussain *et al.*,2022)。但目

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前国内对混积岩储层的研究主要集中于混积岩的分类命名、沉积模式以及优质储层主控因素等方面(解习农等,2018;叶茂松等,2018;王清斌,2020;庞小军等,2022;彭军等,2022;程俊阳等,2023),混积岩储层的成岩作用类型复杂,储层物性差异较大,非均质性较强(Li *et al.*, 2020; 庞小军等, 2020b),目前对混积岩储层孔隙演化特征方面的研究较为薄弱,需要深入研究。混积岩初始孔隙度的恢复是研究混积岩储层演化特征的关键,如何建立初始孔隙度计算公式是混积岩储层初始孔隙度恢复迫切需要解决的问题。目前对于孔隙度恢复方法的研究主要是以砂岩储层为例(王艳忠等,2013;王继伟等,2020;张玉晔等,2021;赵承锦等,2021),沿用Scherer(1987)提出的经验公式进行,但由于混积岩中含有较多生物碎屑成分,此公式并不适用于混积岩。本文以混积岩储层为例,将前人公式与物理模拟实验相结合,建立一种适用于混积岩初始孔隙度计算的公式,这对于混积岩储层的定量成岩演化过程研究,优质储层成因机理研究等方面均具有重要意义。

1 地质背景

环渤中地区位于渤海海域的中部,是渤海湾盆地的重要组成部分,它由渤中凹陷、石臼坨凸起、沙

垒田凸起、南堡凹陷东部等众多凹陷和凸起组成(图1a)(Walthe, 1894; 代黎明等, 2020; 刘丹丹等, 2020)。受新生代太平洋板块俯冲及欧亚板块强烈挤压的影响,研究区经历多期次构造运动改造,在沙三段沉积末期,渤海湾盆地多个凹陷内部发生构造反转,形成凹中隆构造,沉积中心向海域迁移(黄雷等,2012),之后的沙一二段沉积期进入相对稳定的沉降期(何仕斌等,2001),全球古气候逐渐转变为相对温暖的亚热带温热气候(朱伟林,2002;刘士磊等,2012),同时结合相对浅水的沉积湖盆环境(杜庆祥等,2016),偏咸的水介质条件(朱伟林,2002)以及盆内物源条件(叶茂松等,2025)等诸多有利因素的共同作用,为生物碎屑等类型的混积岩储层发育提供了良好条件。已经发现的混积岩储层中,以陆源碎屑为主的混积岩和以生物碎屑为主的混积岩是储集条件最好的两种储层(吴礼明等,2015;吕正祥等,2016;李欢等,2019)。研究区古近系主要发育孔店组、沙河街组及东营组,沙河街组主要发育沙四段、沙三段和沙一二段(图1b)。其中沙一二段为混积岩的主要发育层位,埋深普遍超过3 000 m,在优质混积岩储层中生物碎屑富集,生物碎屑体腔孔是其特色的储集空间(图2),储层平均孔隙度为30.88%,最高达40.12%。目前,环渤中地区已成为

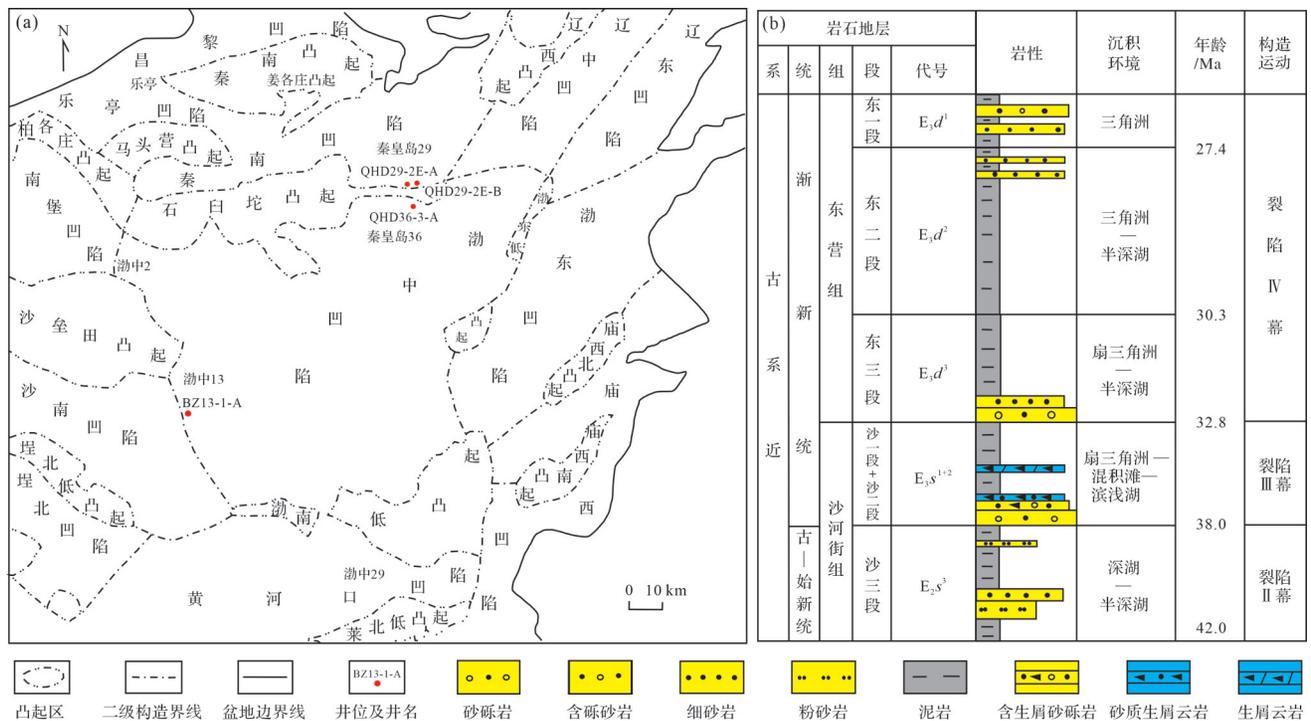


图1 研究区位置及地层综合柱状图(据庞小军等,2020a 修改)
 Fig.1 Location and stratigraphic histogram of the study area (modified from Pang *et al.*, 2020a)

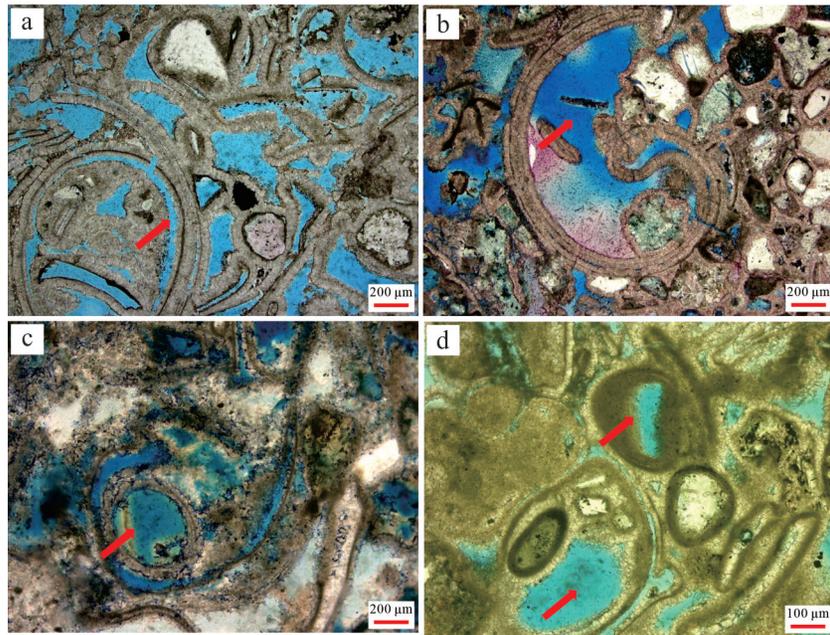


图2 生物碎屑为主的混积岩储层储集空间类型及特征

(a)BZ13-1-A井,4 095.90 m,螺类生物碎屑体腔充填大量泥晶白云石,沿壳体壁道溶蚀成优质孔喉通道,粒间原生孔隙大量发育;(b)QHD29-2E-A井,3 311.50 m,整体螺类生物体腔原生孔保存完好,粒间原生孔隙同样发育;(c)QHD29-2E-B井,3 358.00 m,整体螺类生物体腔孔保存较好,内部存在少量泥晶白云石充填,粒间原生孔隙同样发育;(d)QHD36-3-A井,3 778.10 m,整体螺类生物体腔孔保存较好,粒间方解石胶结,发育泥晶包壳

Fig.2 Types and characteristics of reservoir space of mixed rock reservoir dominated by bioclasts

(a) well BZ13-1-A, 4 095.90 m, the cavity of a snail bioclast is filled with a large amount of mud crystal dolomite, which is dissolved into high-quality pore throat channels along the wall channel of the shell, with a large number of intergranular primary pores developed; (b) well QHD29-2E-A, 3 311.50 m, overall, the body cavity pores of snail organisms are well preserved, and intergranular primary pores are developed; (c) well QHD29-2E-B, 3 358.00 m, overall, the body cavity pores of snail organisms are well preserved, with a small amount of mud-crystal dolomite infill and intergranular primary pores are developed; (d) well QHD36-3-A, 3 778.10 m, overall, the snail bioclasts have well-preserved cavity pores, intergranular calcite cementation, and mud crystal encrustations

渤海海域重点研究区域,并在石臼坨凸起东部秦皇岛29、秦皇岛36等构造区的混积岩储层中获得重大油气发现,测试日产油突破千立方(庞小军等,2020b)。

2 生物体腔孔计算方法

通过研究区QHD29-2E-A井、QHD29-2E-B井、QHD36-3-A井、BZ13-1-A井4口井取心段的岩心镜下观察发现,研究区沙一二段的主要生物类型为螺类和介形类,且螺类的含量远远大于介形类,尤以恒河螺属在数量上占有绝对优势(潘文静等,2020),出现频率高达90%。生物体腔孔的保存与生物体的大小、结构及成分有关,研究区螺类的长度为0.5~20.0 mm,钙质壳体抗压能力强,具有独特且复杂的包卷壳体结构,该结构能够减少其他沉积物充填;介形类一般个体微小,长度为0.4~2.0 mm,结构较简单,主要由两瓣外壳组成,死亡后双壳打开,体腔孔极易被充填。研究区只有螺类生物的体腔孔具有储

集作用,故而本研究借助实验法、公式法及构造物理模拟法,来研究螺类生物体腔孔的体积,进而求取体腔孔孔隙度。

2.1 实验法求取体腔孔体积

2.1.1 实验样品

为能够得到一种适合于计算螺类生物体腔孔体积的公式,提高精确度,挑选现代与恒河螺属生物体腔孔近似的18种螺类,共计180枚样品进行实验。这18种螺分别为绿螺、香螺、火炬螺、红号螺、红口螺、锥螺、刺螺、小葱螺、猫眼螺、白玉螺、花斑螺、花螺、灰扁螺、斑马螺、条纹斑螺、古文螺、田螺以及小田螺(图3)。

除了螺类样品之外,还选用了规格为100 mL、20 mL、50 mL及10 mL的量筒,规格为1 000 mL、500 mL的烧杯,规格为5 mL的注射器,规格为3 mL的胶头滴管(精度0.05 mL),以及输导软管、游标卡尺等实验器材。

2.1.2 实验流程及结果

实验过程中,首先使用5 mL注射器、注射软管、

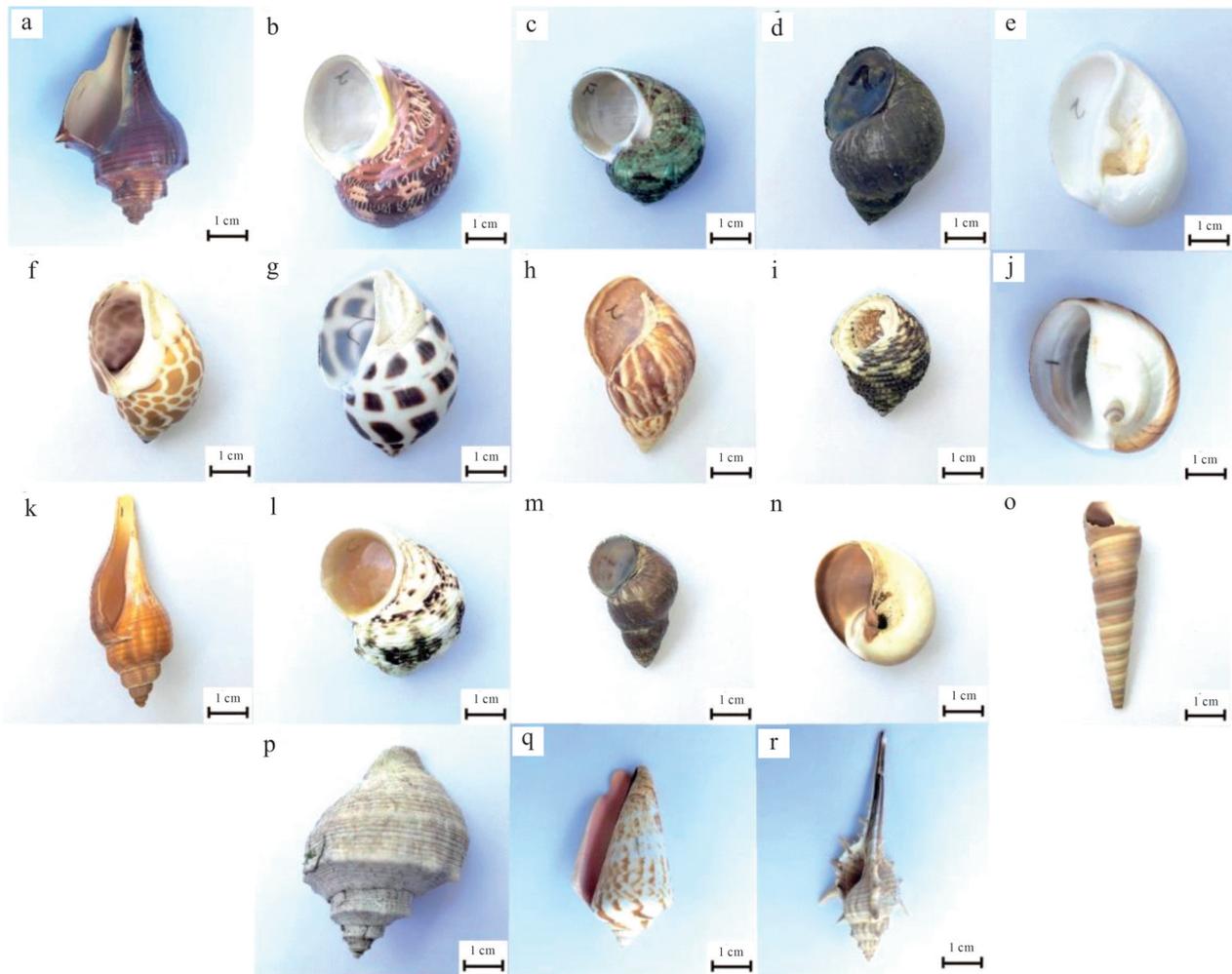


图3 18种与恒河螺属生物体腔孔近似的螺类样品

(a)红号螺;(b)古文螺;(c)绿螺;(d)田螺;(e)白玉螺;(f)花斑螺;(g)花螺;(h)斑马螺;(i)小葱螺;(j)灰扁螺;(k)火炬螺;(l)条纹斑螺;(m)小田螺;(n)猫眼螺;(o)锥螺;(p)香螺;(q)红口螺;(r)刺螺

Fig.3 Eighteen species of snail containing a biological cavity

(a) *Rapana bezona* Linnaeus; (b) turban snail; (c) green snail; (d) *Viviparus*; (e) *Polinices mammilla*; (f) *Nerita japonica*; (g) *Babylonia lutosus*; (h) Nerite snail; (i) green onion snail; (j) *Adeorbis plana*; (k) torch snail; (l) striped zebra snail; (m) small snails; (n) cat's-eye turban; (o) *Turritella terebra*; (p) *Neptunea cumingi* Crosse; (q) *Oliva miniacea*; (r) *Murex pecten*

3 mL胶头滴管相结合的方式向生物体腔中注水,记录注入水的体积即为生物体腔孔的体积;之后将该注满水的螺类样品放入装有50%左右水的量筒或烧杯中,记录其液面的变化,并将液面变化部分的水用5 mL注射器与3 mL胶头滴管慢慢取出,记录取出水的体积即为螺的总体积。用总体积减去生物体腔孔的体积即为该生物的外壳体积,生物体腔孔的体积与总体积的比值即为生物体腔孔的体积占比,实验数据见附表1^①。

以绿螺为例,研究同一螺类生物体腔孔体积的变化规律。通过实验数据可以看出,绿螺的生物体

腔孔体积占比介于57.39%~70.59%,平均为64.32%。当绿螺体积偏小时,测得的生物体腔孔的体积占比也就偏小,造成这种误差的原因可能与螺类生物体腔的体腔尾部大小有关,生物体腔孔体积与其总体积之间呈线性正相关(图4)。不同螺类的生物体腔孔体积占比差距明显,18种螺类体腔孔占比介于36.07%~88.89%,其中红口螺与小葱螺的生物体腔孔体积占比较小,平均值分别为36.32%和36.57%;田螺和斑马螺的生物体腔孔体积占比较大,平均值分别为83.0%和85.12%(图5),因此影响螺类生物体腔孔体积占比的最大因素是螺的种类。

①附加数据存储地址:<http://www.cjxb.ac.cn/cn/article/doi/10.14027/j.issn.1000-0550.2024.005>

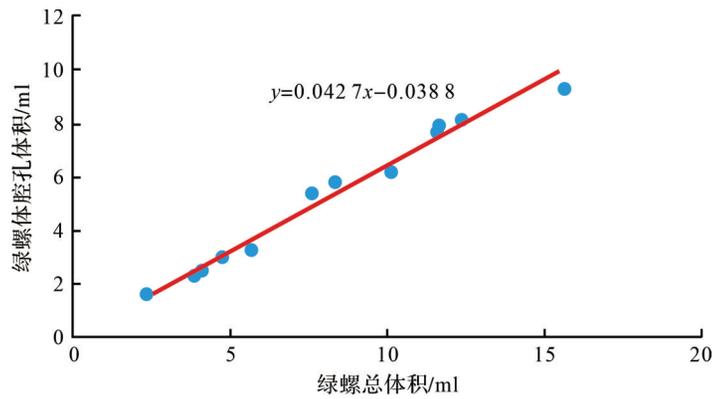


图4 绿螺体腔孔体积与其总体积的关系图

Fig.4 Relationship between cavity volume and total volume of green snail

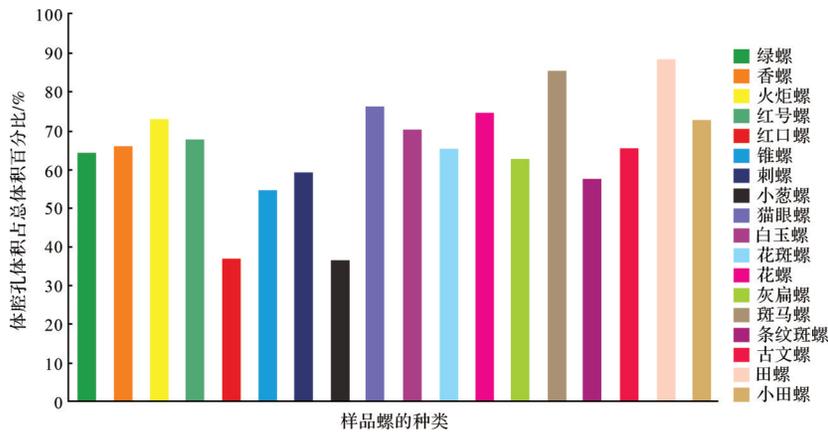


图5 实验法获取的不同螺类生物体腔孔体积占比柱状图

Fig.5 Histogram of proportions of body cavity pore volume of different snail organisms obtained by experiment

2.2 公式法计算体腔孔体积

依据螺类样品的螺纹曲线特征,选取对数螺线方程 $r=ae^{b\theta}$ 为平面上的求取方程(图6a),建立一个三维坐标,空间上任一点 m 在螺面上以角速度 w 绕 Z 轴旋转,同时又以线速度 v 沿平行于 Z 轴的正方向上升,则 m 点的轨迹就是一条螺旋线(图6b)。

设在时刻 $t=0$ 时, M 的坐标为 $(0,0,0)$,则在时刻 t 时, M 的坐标为 (X, Y, Z) ,其中 $X=vt \times \cos(wt)$, $Y=vt \times \sin(wt)$, $Z=vt$ 。令 $wt=\theta$,则螺旋线的参数方程为: $X=\cos\theta ae^{b\theta}$, $Y=\sin\theta ae^{b\theta}$, $Z=r=ae^{b\theta}$ 。微积分求长度,取一段微元 ds ,弧长公式如下:

$$ds = \sqrt{(dx)^2 + (dy)^2 + (dz)^2} \tag{1}$$

将 $X=\cos\theta ae^{b\theta}$, $Y=\sin\theta ae^{b\theta}$, $Z=r=ae^{b\theta}$ 代入公式得到弧线长度公式: $S = \int_0^\theta \sqrt{2} rd\theta$ 。

实验样品螺类体腔孔的横截面近似椭圆形(圆是特殊的椭圆),其椭圆公式如下:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{2}$$

设椭圆面积为 $\pi a_1 b_1$,圆的面积为 πr^2 ,有且仅有 $a_1=b_1$ 时为圆,因此螺口横截面底面积为 $\pi a_1 b_1$ 。由于所求弧线长均为最外弧线长,所求体积弧线长应为最外弧线长度的一半,实际弧线长公式如下:

$$S_{1/2} = \frac{\sqrt{2}}{2} \int_0^\theta rd\theta \tag{3}$$

通过公式(1)、(2)及(3)结合圆锥体体积等基本特征,求得螺类体腔孔的体积公式为:

$$V_{\text{体}} = \frac{1}{3} \pi a_1 b_1 \times S_{1/2} = \frac{\sqrt{2}}{6} \pi a_1 b_1 \int_0^\theta rd\theta \tag{4}$$

螺旋曲线 $r=ae^{b\theta}$ 确定 a, b 的值,当 $\theta=0$ 时, a 值就等于起点 r ,为提高 r 的精准度,借助游标卡尺进行量取,当 a 值确定后,任意取 θ 值, r 随之量取代入螺旋曲线公式即可确定 b 值,同一种螺类 a, b 值相同,螺旋曲线相同,不同螺类,螺旋曲线在 a, b 值上存在

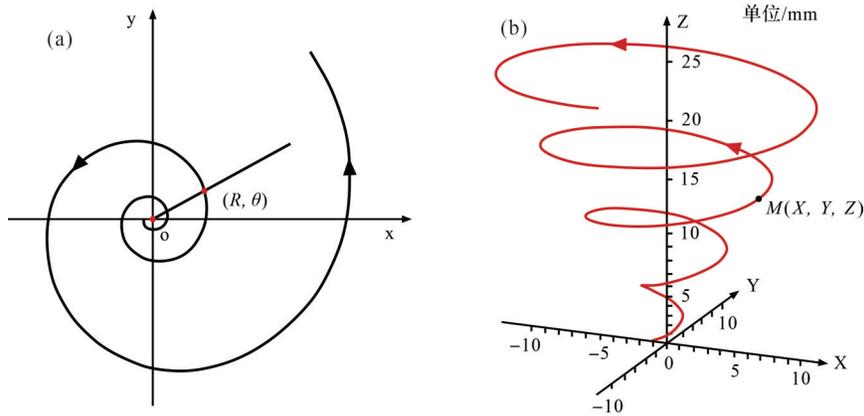


图6 对数螺线平面(a)及三维曲线图(b)

Fig.6 (a) Logarithmic spiral plane; (b) three-dimensional diagram

不同。如：绿螺的螺纹曲线 $r=0.1e^{0.1\theta}$ ，香螺椭圆的螺纹曲线则是 $r=0.12e^{0.12\theta}$ ，小田螺椭圆的螺纹曲线是 $r=0.1e^{0.07\theta}$ ， a_1, b_1 为腔孔半径值，前述实验中已经得到腔孔直径，取直径长度的一半并将数值代入公式(4)中，即可得到生物体腔孔体积，实验数据见附表2^①。

公式法与实验法得到的生物体腔孔体积误差较小，误差范围为1.32%~10.04%，以每种螺类1号样品为例对比2种方法的体腔孔体积(图7)发现，公式法与实验法求得生物体腔孔的体积大致相同，说明公式法具有很好的应用性和精准度。

2.3 残余体腔孔孔隙度求取

螺类生物体腔孔在沉积埋藏过程中，会有部分沉积物进入体腔孔中，剩余未被沉积物充填部分才

能作为有效储集空间，本研究利用“构造物理模拟实验设备”将细砂级、中砂级和粉砂级碎屑颗粒与螺类生物体在潮湿条件下混合，进行多次横向及纵向的构造挤压，以模拟波浪反复淘洗充填的过程，进而得到沉积物充填的生物体腔孔体积，剩余未被充填的体腔孔体积便是有效的储集空间，即螺体腔孔孔隙度为未被沉积物充填的体腔孔体积与该螺体腔孔体积的比值，具体数据见附表3^①。

不同种类的螺，其有效储集空间即体腔孔孔隙度的范围为46.27%~90.00%；同一种螺体腔孔孔隙度的差异主要体现在螺体腔孔体积大小上，体腔孔腔口大，相对易充填，体腔孔腔口小，相对不易充填，以花螺为例，其体腔孔体积与有效孔隙度之间呈负相关关系(图8)。

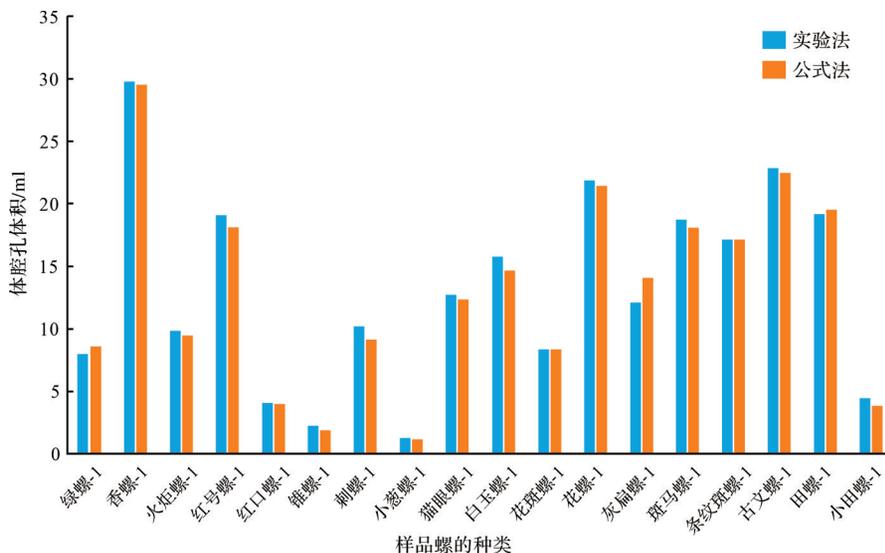


图7 实验法与公式法求得的体腔孔体积对比

Fig.7 Comparison of experimental method and formula method for body-cavity volume

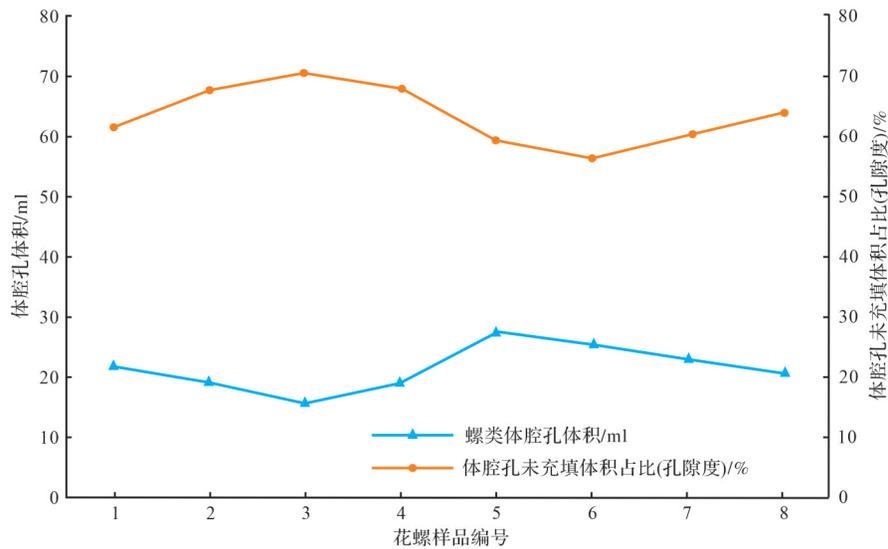


图8 花螺体腔孔体积与孔隙度相关性折线图

Fig.8 Relationship between cavity volume and porosity of Babylonia lutosa

3 混积岩初始孔隙度计算方法

混积岩是由陆源碎屑颗粒和生物碎屑颗粒组成的,其初始孔隙度可以近似认为是由陆源碎屑颗粒的初始孔隙度和生物体腔孔孔隙度相加得到。陆源碎屑颗粒的初始孔隙度仍沿用Scherer(1987)的经验公式 $\Phi_{\text{初始}} = 20.91 + 22.90/S_0$,生物体腔孔孔隙度用上述生物体腔孔孔隙度的计算方法,得到混积岩的初始孔隙度计算公式如下:

$$\Phi_{\text{初始}} = \Phi_{\text{混}} + \Phi_{\text{生物}} \quad (5)$$

$$\Phi_{\text{初始}} = 20.91 + 22.90/S_0 +$$

$$A_1 \left(\frac{\sqrt{2}}{6} \pi a_1 b_1 \int_0^\theta r d\theta / V_{\text{螺总}} \right) P_{\text{储集孔}} \quad (6)$$

式中: S_0 为Trask分选系数; A_1 为沉积物生物碎屑中螺类含量; a_1 、 b_1 为体腔孔腔口半径值; r 为对数螺线; θ 为旋转角度; $V_{\text{螺总}}$ 为螺的总体积; $P_{\text{储集孔}}$ 为体腔孔孔隙度(未被充填体腔孔体积/体腔孔体积)。

4 环渤中地区混积岩初始孔隙度恢复

以生物碎屑含量较高的QHD36-3-A井3765.03 m混积岩样品为例进行初始孔隙度的恢复。根据研究区螺类的种类及特征,认为现代田螺在结构上与研究区恒河螺属最接近,可以作为恒河螺属生物体腔孔孔隙度计算的替代对象。据上述物理模拟实验数据结果,田螺的体腔孔孔隙度介于57.86%~62.51%,平均值为60.18%。

综上所述,混积岩初始孔隙度计算公式(公式6)中的各项参数的具体赋值如下:

由 $S_0 = P_{25}/P_{75}$,借助图像粒度分析软件获得粒度累积曲线上 P_{25} 和 P_{75} 的粒度值,得到分选系数 $S_0 = 2.22546$; $P_{\text{储集孔}}$ 为体腔孔孔隙度,本次用田螺的体腔孔孔隙度替代,得到 $P_{\text{储集孔}} = 60.18\%$; a_1 、 b_1 及 θ 值分别选取田螺已测数据的平均值;镜下统计的生物碎屑中螺类含量 A_1 为41%。最终计算得到该深度处陆源碎屑部分的初始孔隙度为31.20%;田螺生物体腔孔孔隙度为49.95%,结合生物碎屑含量可得该深度生物碎屑体腔孔孔隙度为20.48%;则该深度混积岩的初始孔隙度约为51.68%。

初始孔隙度是孔隙演化定量分析的首要基础数据,其决定着压实损失孔隙度与胶结损失孔隙度的计算误差,进而控制了最终孔隙度预测的质量(张创等,2014)。此次已得到QHD36-3-A井3765.03 m混积岩样品的初始孔隙度约为51.68%,以此为基础,便可定量求取单因素影响下的关键成岩作用期不同成岩作用类型的孔隙度变化值,进而恢复各成岩阶段的孔隙度(陈修等,2016),明确储层孔隙演化特征。

5 结论

(1) 以前人公式为基础,同时结合构造物理模拟实验,建立了一种新的求取混积岩初始孔隙度的计算方法。

(2) 选用现代螺类样品通过实验法和公式法分别求取螺类生物体腔孔体积,研究发现螺的种类是影响螺类生物体腔孔体积占比的最大因素;不同种类的螺,有效储集空间即体腔孔孔隙度的大小不同,影响同一种螺体腔孔孔隙度差异的原因主要为体腔孔腔口的大小。

(3) 以生物碎屑含量较高的 QHD36-3-A 井 3 765.03 m 混积岩样品为例,通过物理模拟实验得出田螺的生物体腔孔孔隙度平均值为 60.18%,代入混积岩初始孔隙度计算公式求得该深度混积岩的初始孔隙度约为 51.68%。

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Method for Restoring the Initial Porosity of Bioclastic Mixed Rocks with Body Cavities: A case study of mixed rock reservoirs in the Es₁₂ Formation around Bozhong Sag, Bohai Bay Basin

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Abstract: [Objective] The Paleogene Shahejie Formation around the Bozhong Sag, Bohai Bay Basin, contains mixed-rock reservoirs with abundant oil and gas resources. The unique biomass cavity pores (lumens) in mixed-rock reservoirs are such that their initial porosity cannot be obtained by conventional formulas. No methods are known in China or elsewhere for recovering the initial porosity for mixed rocks, although accurate recovery is a key element in determining the evolution of the reservoir. [Methods] Experimental and numerical methods were used to determine the volume of the body cavity in modern snail samples. A physical simulation experiment was then conducted to simulate the cavity infill conditions in an actual depositional environment. Finally, a formula for calculating the initial porosity of mixed-rock reservoirs was derived based on commonly used formulas. [Results] Studies have shown that differences in the snail species have the greatest effect on the percentage of body cavity pore volume (i.e., body cavity porosity). Within the same species, the main reason for the difference in body cavity porosity is the size of the body cavity. For example, the mixed-rock sample from well QHD36-3-A at a depth of 3 765.03 m, with a high content of fragmented bioclasts, has an initial porosity of 51.68%. [Conclusions] A new calculation method for finding the initial porosity of mixed rocks is proposed based on previous formulas combined with physical simulation experiments. This is highly significant in the study of mixed-rock reservoir evolution.

Key words: mixed rock; gastropoda; initial porosity; porosity evolution; body cavity pore