

南大西洋被动陆缘盆地盐岩对油气成藏的影响

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摘要:南大西洋两岸被动陆缘盆地经历了相似的构造演化历史, 在早白垩世阿普特期发育了区域性分布的盐岩。在对南大西洋中段两岸 6 个主要含盐盆地的区域构造、沉积演化及油气成藏综合研究的基础上, 通过各盆地盐构造样式的地震剖面解析, 将盐盆划分为伸展区、过渡区和挤压区 3 个盐构造带。巴西大陆边缘盆地发育的盐下烃源岩现今仍处于生油窗内, 而西非盐上烃源岩的成熟速率高于盐下烃源岩, 主要由于盐岩具有较高的热导率, 能抑制盐下烃源岩的生烃, 促进盐上烃源岩热成熟。盐流动产生多种样式的盐构造, 为盐上油气聚集提供了构造圈闭条件。盐相关圈闭是盐上重要的圈闭类型, 富集的油气储量占南大西洋被动陆缘盆地盐上油气总可采储量的 84.8%。伸展区发育的盐窗作为输导通道, 控制油气主要于盐上层系成藏。同时盐岩作为厚层的区域盖层控制了过渡区到挤压区的盐下油气成藏。

关键词:盐岩; 油气成藏; 构造带; 被动陆缘; 南大西洋

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Impact of salt on hydrocarbon accumulation in South Atlantic passive margin basins

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Abstract: South Atlantic passive margin basins experienced a similar tectonic evolution and regionally distributed salt was deposited during the Aptian. Based on a comprehensive study of regional tectonics, depositional environment and hydrocarbon accumulation, integrated with the study of salt-related structural styles determined by analyzing regional seismic sections, three tectonic belts, which include extensional domain, transitional domain and compressional domain, were recognized in the 6 main salt basins. The pre-salt source rocks in the Brazil salt basins are still in the oil window. In West Africa, the post-salt source rocks experienced a higher maturation rate than the pre-salt source rocks. The salt has a relatively higher thermal conductivity and can restrain the hydrocarbon generation of the pre-salt source rocks but accelerate that of the post-salt source rocks. The salt flow resulted in several kinds of salt-related structural traps for hydrocarbon accumulation in the post-salt sequences. Reserves in the post-salt related structural traps account for 84.8% of the total post-salt reserves. The salt windows developed in the extensional domain served as hydrocarbon migration pathways and controlled hydrocarbon accumulations in the post-salt sequence. The thick salt provided a regional cap rock, which controlled the pre-salt hydrocarbon accumulations in the transitional-compressional domain.

Key words: salt; hydrocarbon accumulation; tectonic belt; passive continental margin; South Atlantic

随着陆上油气勘探的成熟度越来越高、勘探技术的进步和勘探理论的发展, 油气勘探逐渐走向深水, 特别是深海油气勘探已成为油气勘探的主战场之一。近年来, 在南大西洋两岸的巴西东部和非洲

西部被动大陆边缘深水盐盆相继发现一系列大型油气田, 如巴西桑托斯盆地 2006 年发现了石油可采储量超过 10×10^8 t 的 Lula (原 Tupi) 油田; 西非安哥拉宽扎盆地 2013 年发现可采储量超 1×10^8 t

油当量的 Lontra 1 油气田等。这些大型油气田的发现使得南大西洋两岸的盐盆成为了全球油气勘探的热点地区和油气新增储量的重要地区。受区域地质背景的控制,南大西洋含盐盆地油气的形成和分布具有一定的相似性,但不同盆地盐下和盐上油气资源富集程度有所不同。盐岩在油气成藏过程中起了关键作用。目前,国内外学者对南大西洋被动陆缘盐盆的构造演化特征、沉积特征、盐构造样式、石油地质条件进行了较为详尽的探讨^[1-9]。本文依据南大西洋含盐盆地最新油气勘探进展,通过分析盐岩对油气成藏要素的影响,旨在深化与盐相关油气富集规律的认识,为我国海外油气勘探提供参考。

1 区域地质特征

南大西洋被动陆缘盐盆位于南大西洋中段,在古地理位置上是共轭的,包括巴西从塞尔西培—阿拉戈斯盆地向南至桑托斯盆地的一系列盆地,西非为自北而南的加蓬盆地、下刚果盆地和宽扎盆地(图 1)。盐盆的形成与演化受冈瓦纳大陆的裂解和南大西洋开启的控制^[2-4],属于中生代被动大陆边缘沉积盆地。总体上,盆地构造演化可划分晚侏罗世之前的裂前内克拉通阶段、贝利阿斯—早阿普特期同裂谷阶段、晚阿普特—阿尔比早期过渡阶段和阿尔比—新生代被动大陆边缘阶段(图 1)。

裂前阶段,南大西洋被动陆缘盐盆处于西冈瓦纳大陆的中部地带,构造活动相对稳定,大部分地区主要受隆升剥蚀作用,仅在局部地区出现拗陷沉

降^[5]。晚侏罗世—早白垩世岩石圈开始扩张,软流圈抬升,标志着南美洲和非洲开始拉张分裂,进入同裂谷演化阶段。早白垩世巴列姆期,南大西洋中段的大陆边缘处于拗陷的局限湖盆内,繁盛的生物以及底部缺氧环境下,湖盆内沉积了暗色湖相页岩(图 1),是南大西洋盆地盐下重要的烃源岩。

过渡演化早期,在区域准平原化基础上沉积了湖相碳酸盐岩和碎屑岩。早白垩世阿普特中晚期,由于受南大西洋中部的 Walvis 海岭的阻隔,使得南大西洋中部盆地处于半封闭浅水环境^[6],在构造沉降相对稳定、气候温暖干燥和蒸发作用强的环境下,发育了盐岩沉积(图 1)。

阿尔比期,南美板块和非洲板块分别向西南和向北漂移,洋壳持续的拉张和冷却引起了区域性的大幅度热沉降,南大西洋盆地开始了被动大陆边缘发育阶段。由于构造运动逐渐远离南美与非洲板块间的洋中脊区,引起了岩石圈的冷缩,导致盆地向海方向热沉降幅度增大,盆地发生向海一侧的轻微倾斜。盆地的倾斜和差异压实作用诱发盐岩流动,形成盐构造。晚白垩世和整个新生代期间,被动陆缘近陆地一侧发育了河流—三角洲相砂岩,远离陆地一侧发育深水浊积砂岩和泥页岩(图 1)。河流—三角洲体系及相关浊积岩是被动陆缘盆地盐上层系的重要油气储集层。

2 盐岩发育特征

被动陆缘盆地盐岩沿着大陆架向海延伸分布,分布范围具有从南向北逐渐变小的特征,盐岩厚度

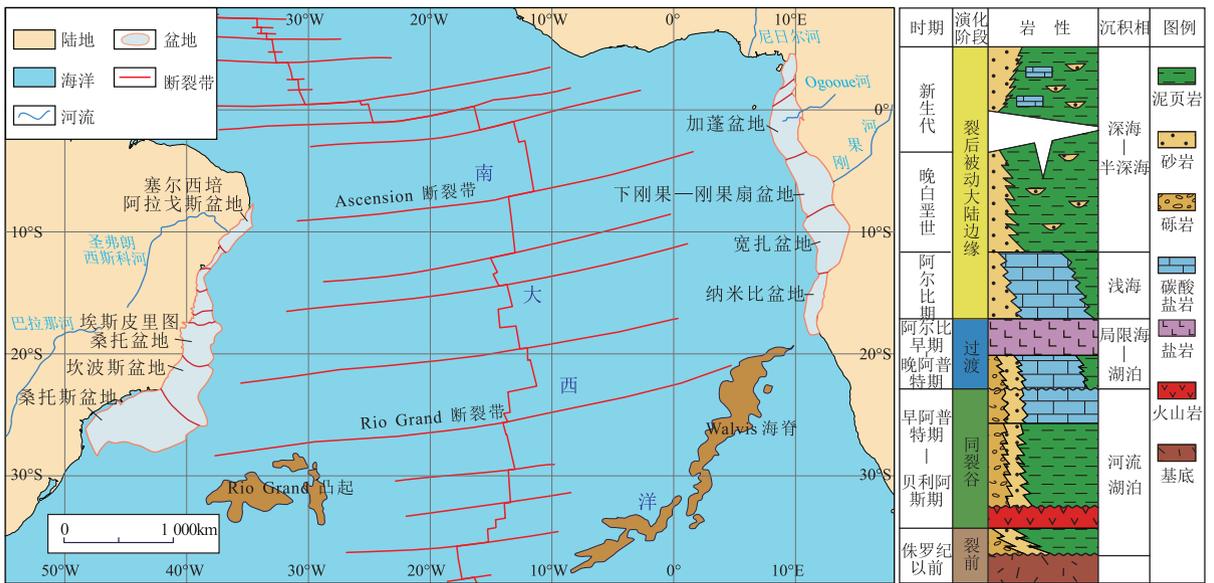


图 1 南大西洋含盐盆地分布位置(a)与盐盆地层柱状图(b)

Fig.1 Location (a) and stratigraphic column (b) for the South Atlantic salt basins

具有自南向北和自洋陆壳分界线向两侧变薄的特征^[7]。盐岩的现今厚度不仅与原始沉积厚度有关,也受后期盐构造运动的影响,盐岩的向下滑脱和挤压会造成盆地深水地区盐岩厚度的增大。桑托斯盆地深水区的 Ariri 组蒸发岩厚度最大,可达 2 500 m。

根据盐构造的形成机制,可对南大西洋盐盆进行构造带划分^[10-13]。本文以前人研究成果为基础,将南大西洋盐盆从陆地向海方向划分为伸展区、过渡区和挤压区 3 个构造带(图 2)。各构造带内以发育不同的盐构造样式为特征,并且盐构造的成熟度表现为向海逐渐增加的趋势。

伸展区以拉张应力为主,盐岩主要发生向坡下的滑脱运动,发育非刺穿型的低成熟度盐构造。伸展区靠近陆地一侧盐层薄,扩张开始时脆韧性耦合强烈,形成一系列向海倾的同生长铲式正断层,以发育盐筏、小型的滚动构造和掀斜断块为特征(图 3)。向海一侧,盐层原始沉积厚度增加,发育盐枕、盐丘、盐背斜和大型盐滚构造。过渡区位于大

陆斜坡的底部,盐层受拉张应力和挤压应力相互作用的影响,盐岩主要发生底辟变形,以发育大型的盐底辟为特征。拉张应力在盐上脆性地层形成铲式共轭断层,塑性盐岩在挤压应力下向盐上垂向流动,形成大型的盐底辟。挤压区位于盐盆外侧,压缩是主要的构造应力。在挤压应力作用下,盐层可发生挤压底辟、褶皱和逆冲推覆 3 种构造变形。

巴西大陆边缘坎波斯盆地的坡度要大于相邻的桑托斯盆地,而且新生代河流向盆地注入大量的碎屑沉积物,因此,盆地内盐岩向下滑脱范围较大、距离较远,坎波斯盆地发育的伸展区比相邻的桑托斯盆地和埃斯皮里图桑托盆地范围大。裂后被动陆缘期西非陆地隆升,同时盆地发生大幅度的向海倾斜,引起了盐岩向海的大幅度滑脱,因此,西非盐盆的伸展区总体都比较宽。

3 盐岩对油气成藏影响

3.1 烃源岩

桑托斯盆地发育了盐上 Itajai-Acu 组和盐下 Guaratiba 群 2 套烃源岩。盐下 Guaratiba 群烃源岩在位于近海向陆一侧地区成熟度高,达到成熟 ($R_o = 0.7\% \sim 1.2\%$) 与高成熟 ($R_o > 2.0\%$) 阶段^[14],而在远离陆地一侧成熟度逐渐降低至低成熟 ($R_o < 0.7\%$) (图 4)。在盐岩厚度较薄的伸展区,盐岩对盐下烃源岩的影响作用较小,烃源岩进入了高成熟演化阶段,盐下油气以天然气为主,天然气可采储量占伸展区盐下油气总可采储量的 72.3%,凝析油占 12.5%,其余的 15.2% 则为石油。在盐岩连续、沉积厚度较大的过渡区和挤压区,厚层的盐岩抑制了盐下烃源岩的成熟,烃源岩处于生油窗阶段,过渡

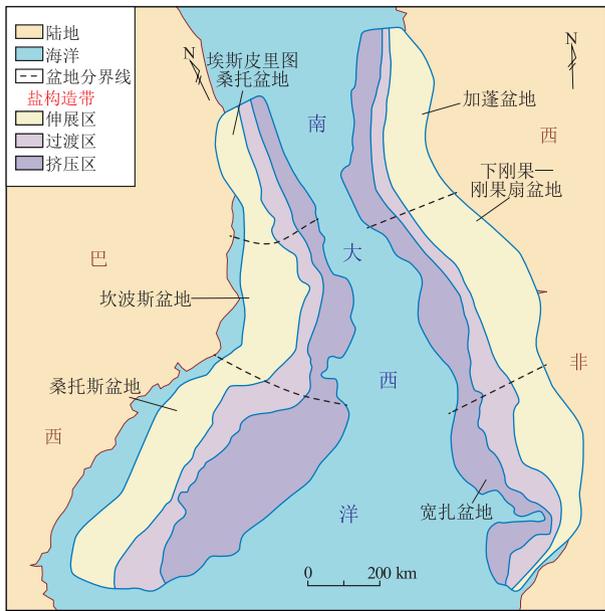


图 2 南大西洋含盐盆地盐构造带分布

Fig.2 Distribution of salt tectonic domains in the South Atlantic salt basins

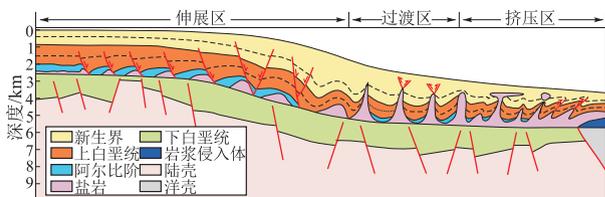


图 3 南大西洋被动陆缘盆地盐构造带分区剖面模式

Fig.3 A schematic profile showing the distribution pattern of salt tectonic domains in the South Atlantic passive basins

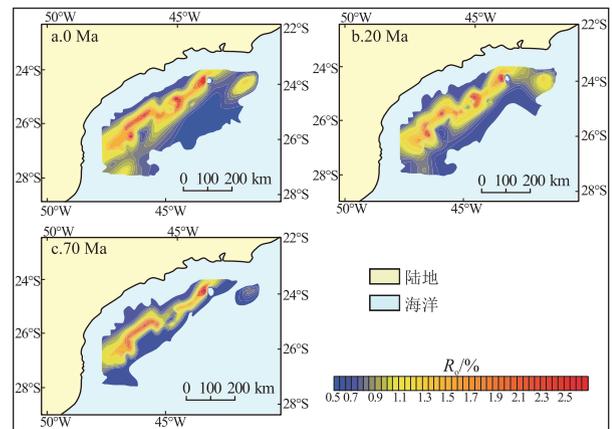


图 4 桑托斯盆地盐下 Guaratiba 群源岩成熟度平面图
据文献^[14],有修改。

Fig.4 Regional variation of source rock maturation of the pre-salt Guaratiba Group in the Santos Basin

区和挤压区盐下油气以石油为主,石油储量分别占到了各构造区内油气总可采储量的 84.7% 和 81.1%。

下刚果—刚果扇盆地发育了盐下 Bucomazi 组和盐上 Iabe 组烃源岩。本研究统计分析了这 2 套烃源岩成熟度指标 T_{max} , 结果表明盐下烃源岩 T_{max} 趋势线的斜率大于盐上烃源岩 T_{max} 趋势线的斜率, 即在达到同样的成熟度 T_{max} 下, 盐上烃源岩需要的埋藏深度比盐下烃源岩的埋藏深度要小(图 5), 这反映了盐岩对其上下地层中烃源岩的有机质成熟度产生了影响。

盐岩具有较高的热导率, 造成盐岩及周围地层产生热异常^[15]。盐岩造成盐下地层热负异常, 抑制了盐下烃源岩的成熟生烃, 盐岩造成盐上地层热正异常, 促进盐上烃源岩成熟生烃。随着盐岩厚度的增大, 盐岩对烃源岩热成熟的控制作用表现越加明显。

3.2 盐上圈闭

盐岩具有易流动的特性, 被动大陆边缘盆地倾斜、拉张构造应力和上覆地层的差异负载作用造成盐岩流动并带动盐上地层发生构造变形, 形成了大量的盐构造及相关断层。盐构造不仅影响了盐上层系的构造形态和沉积特征, 也控制了盐上圈闭的

形成^[12,16-19]。

伸展区发育滚动背斜、穹窿背斜、断层遮挡和断层—岩性复合等圈闭(图 6)。过渡区内盐底辟及相关的共轭断层为油气圈闭的形成提供了构造条件。在盐底辟侧面可发育岩性尖灭圈闭和盐底辟遮挡圈闭, 并可在盐底辟顶部形成穹窿型背斜圈闭、断层遮挡型圈闭和构造—岩性复合圈闭。挤压区发育大型的盐刺穿构造, 盐岩及周围地层构造变形强烈, 在盐顶、盐间和盐侧可形成以盐岩自身作为遮挡条件的盐刺穿遮挡型圈闭。

盐上最重要的储集层类型为浊积岩, 这类储集层常与盐构造复合组成构造—地层岩性复合圈闭, 这也是南大西洋盐上油气藏最重要的圈闭类型。南大西洋被动陆缘盐盆在盐相关的构造和构造—地层复合圈闭中已发现石油可采储量约 69×10^8 t, 天然气可采储量约 1.8×10^{12} m³, 占盐上油气总可采储量的 84.8%(表 1)。

3.3 油气运移聚集

盐岩具有各向同性的应力状态、易流动可塑性和非常低的孔渗性^[1-21], 不仅能够抵抗水力压裂,

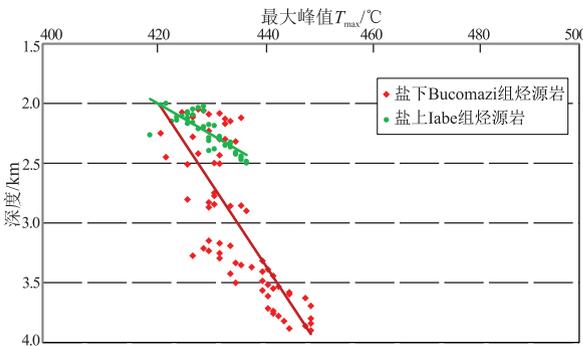


图 5 下刚果—刚果扇盆地烃源岩 T_{max} 统计

Fig.5 Cross plots of source rock T_{max} vs. depth in the Lower Congo-Congo Fan basins

表 1 南大西洋盐盆盐上盐相关圈闭与其他圈闭油气可采储量特征

Table 1 Characteristics of reserves in post-salt salt-related traps and the other traps in the South Atlantic salt basins

盆地	圈闭类型	石油/ 10^6 t	天然气/ 10^8 m ³
加蓬盆地	盐构造	329.5	551.9
	其他	6.8	8.2
下刚果—刚果扇盆地	盐构造	3 722.3	9 248.7
	其他	25.2	10.5
宽扎盆地	盐构造	19.6	33.6
	其他	0.0	0.0
埃斯皮里图桑托盆地	盐构造	50.6	358.4
	其他	351.4	868.7
坎波斯盆地	盐构造	2 298.1	2 565.5
	其他	851.1	779.9
桑托斯盆地	盐构造	488.9	5 257.0
	其他	106.4	275.9

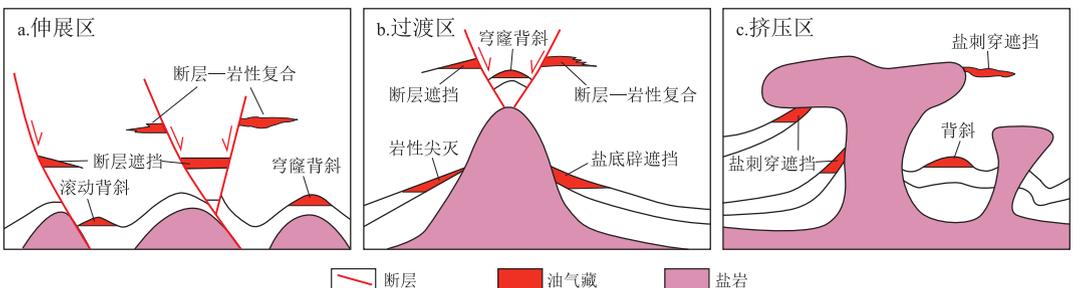


图 6 盐构造带内盐相关圈闭类型

Fig.6 Salt related trap types in different salt domains

也不易被断层切穿,能有效封盖下伏油气藏。区域性分布的阿普特阶盐岩是盐下与盐上层系之间有效的阻挡层,对盐下和盐上油气的运移聚集产生了重要影响。受盐岩滑脱作用影响,伸展区内的盐岩厚度薄、盐窗非常发育、盐岩连续性差。伸展区内大量的盐窗构成了盐下油气向盐上层系运移的通道,油气主要在盐上聚集成藏。南大西洋盐盆伸展区内盐上层系的油气储量占伸展区油气总储量的 78.3%。过渡和挤压区盐岩的原始沉积厚度大,而且受伸展区盐滑脱以及盐底辟挤压作用影响,发育的盐岩厚度较大、盐窗数量少、盐窗规模小。在过渡和挤压区,区域性连续分布的盐岩构成了盐下油气的优质区域盖层,有效阻隔了盐下油气向盐上运移,这决定了盐下烃源岩生成的油气主要在盐下聚集成藏。深水盐下发育的地垒带是油气运移聚集的有利场所^[22]。虽然过渡—挤压区盐下发现的油气藏数量少,但在南大西洋被动陆缘盐盆中占有重要的地位。桑托斯盆地过渡—挤压区盐岩封盖的盐下油气可采储量约占南大西洋被动陆缘盐下油气总可采储量的 68.2%。

4 结论

(1) 自陆而海,南大西洋盐盆划分为伸展区、过渡区和挤压区 3 个构造带,盐构造的成熟度表现为逐渐增加的趋势。

(2) 盐岩具有较高的热导率,造成盐下和盐上层系分别产生热负异常和热正异常,结果抑制盐下烃源岩生烃,促进盐上烃源岩热成熟。巴西大陆边缘盆地发育的厚层盐下烃源岩现今仍处于生油窗内,西非盐上烃源岩的成熟速率高于盐下烃源岩。

(3) 盐岩流动变形在盐上形成大量的盐构造,为盐上油气聚集提供了圈闭条件。盐构造与浊积岩组成的构造—地层岩性复合圈闭是盐上重要的圈闭类型。已发现盐相关油气藏的油气储量约占南大西洋被动陆缘盆地盐上油气总可采储量的 84.8%。

(4) 伸展区发育的盐窗为盐下油气向盐上运移提供了运移通道,油气主要在盐上层系聚集成藏;过渡区和挤压区厚层连续的盐岩作为盖层控制了盐下油气聚集成藏。

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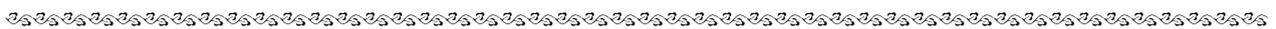
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