

莫桑比克南部陆缘沉积基底反射波层析成像

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摘要 为探讨复杂沉积背景下的沉积层速度结构及其成因机制, 有必要充分挖掘海底地震仪(OBS)广角折射人工地震数据记录中的浅部沉积层信息, 反演成像出沉积层速度结构; 可靠的沉积层结构还可为构建全地壳初始模型提供支持. 本研究基于非洲莫桑比克南部陆缘OBS广角折射人工地震数据, 通过拾取沉积基底折射/反射震相(Ps/PsP)和结晶地壳折射震相(Pg), 利用层析成像反演方法(JIVE3D软件), 获得了沉积层精细速度结构和剧烈变化的沉积基底埋深. 结果表明: (1) 沉积基底埋深与多道地震深度剖面具有很好的一致性; (2) 与海盆区域相比, 陆缘区域的沉积层存在高速异常. 结合构造演化背景, 通过与周边地震测线对比分析, 得出陆缘区域的高速异常可能与岩浆-构造作用有关的初步认识. 本研究还为缺乏多道地震深度剖面约束的区域提供了一种新的沉积层建模思路, 有助于获得更可靠的沉积层及地壳结构.

关键词 海底地震仪, 地震层析成像, 沉积层速度结构, 莫桑比克南部陆缘

主动源海底地震仪(Ocean-Bottom Seismometer, OBS)广角折射/反射地震探测可用于揭示地壳及上地幔的深部结构^[1]. 多道反射地震探测(Multi-Channel Seismic, MCS)数据可用于获取沉积层界面^[2,3], 这非常有助于开展地壳-上地幔深部结构建模和微地震定位等研究^[4]. 因为在构造演化复杂的海域, 沉积层结构通常具有横向变化, 而且相对基岩, 沉积层速度较低速, 所以如不能充分考虑沉积层的厚度和速度变化, 会导致射线路径和走时误差的累积, 进而影响壳/幔深部结构成像的精度和微地震震源位置的可靠性^[5]. 但是对缺少MCS数据的区域, 如何获得较准确的沉积层速度和界面信息, 目前仍然较为困难^[6].

OBS广角折射/反射地震数据中记录的沉积层震相(如沉积层折射震相Ps和反射震相PsP)为解决上述问题

提供了可能性, 尤其是当沉积层较厚时, 因与直达水波有较大的走时差, 从而使Ps和PsP震相更易于识别和分析. 本研究基于自然资源部第二海洋研究所于2021年在非洲东部莫桑比克南部陆缘采集的OBS人工源数据和沿同一剖面的MCS数据^[7], 对沉积层进行了二维层析成像, 该调查区是特殊的岩浆富集型转换大陆边缘, 有可能存在受岩浆和构造共同控制的巨厚沉积层^[8], 可以识别出十分清晰的Ps/PsP震相. 具体做法是, 使用OBS记录中的Ps/PsP震相进行沉积层基底埋深和速度结构反演, 与MCS深度剖面进行对比分析, 进而探讨OBS数据在沉积层结构成像中的优势和不足.

本研究的意义在于为缺少MCS数据区域约束沉积层结构的海域壳/幔结构建模提供新的思路, 其特殊意义可为我国在极地海域开展的壳/幔地震层析成像研究

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提供新的思路,例如,北冰洋加克洋中脊等密集冰区无法同时开展OBS与MCS探测^[9],缺少沉积层信息,使得壳/幔深部结构模型可能存在一定误差。

1 数据和方法

1.1 数据

自然资源部第二海洋研究所于2021年在莫桑比克南部陆缘开展了中国-莫桑比克国际合作地球物理调查航次(中-莫航次,图1)。本研究采用的Dz04测线长523 km,沿测线共布放25台OBS,成功回收23台(其中20台数据有效),设计台站间距为20 km。沿测线共激发2615炮,炮间距约为200 m。使用的OBS有两种型号,频带宽度分别是0.0167~50 Hz和2~200 Hz,两种OBS的采样率均为100 Hz。震源系统由四支 Bolt Model 1500LL LongLife™气枪组成,采用2×2的气枪阵列,单个气枪容量为2000 in³,震源总容量为8000 in³(约131 L),激发时压力为2000 psi。

OBS数据处理工作主要包括数据格式转换、滤波、时钟和位置校正以及震相拾取。格式转换和数据预处理均使用了Seismic Unix (SU)软件^[15]。根据Bolt空气枪主频为4~8 Hz^[16,17]和OBS最低采样率为50 Hz等信息,使用最小相位带通滤波方法去除噪声,选取的最佳滤波频带范围为4~25 Hz。由于沉积层的反射震相出现在小偏移距区域,通常在直达水波包络线内,我们采用预测反褶积对直达水波进行了压制,以便能够较好地地区分出沉积层的反射震相^[18~20]。OBS在海底工作时不能实时校正时钟,其内置晶振时钟容易受工作环境的温度和压力等影响,发生时钟漂移,通过记录OBS启动采集时和浮出水面后两次对钟的时间差,基于时钟漂移近似呈线性变化的假设,把时钟漂移量校正到OBS连续波形中。在滤波和时钟校正处理后,使用直达水波到时进行OBS位置校正,选取OBS水听器分量中偏移距小于2 km的直达水波到时(精确到毫秒),结合OBS站位水深完成OBS二维测线的位置校正^[21,22]。最后是震相拾取,本研究拾取了20个OBS站位沉积层基底的Ps、

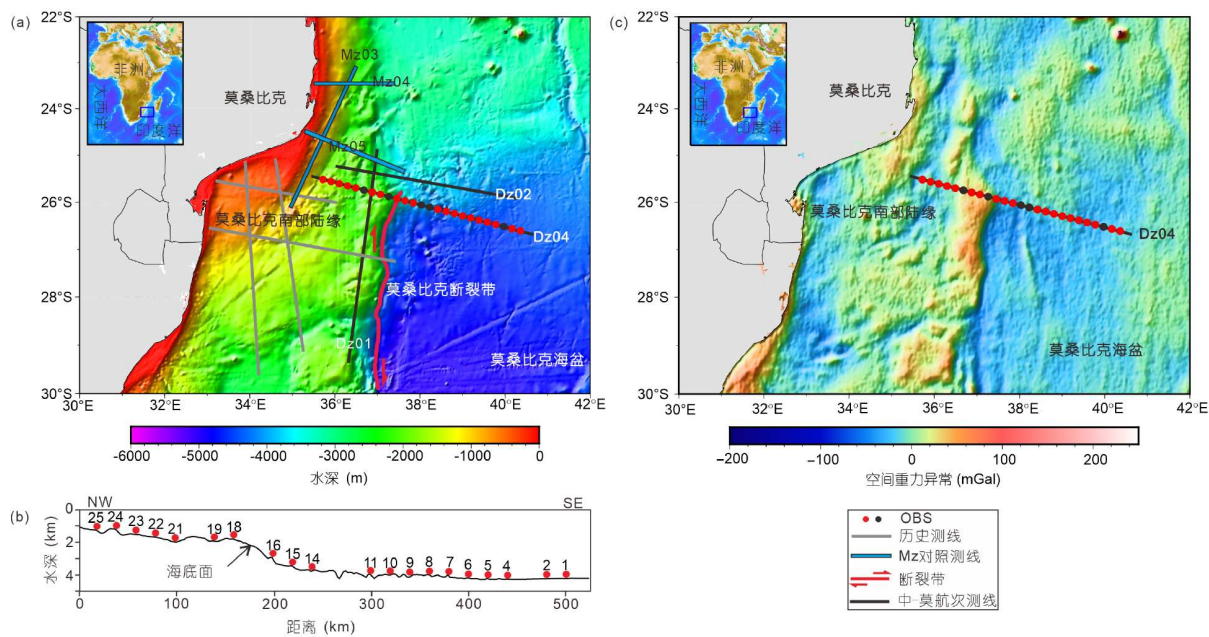


图 1 研究区水深图和空间重力异常图。(a) 研究区水深图,其左上角插图研究区位置图,灰色和蓝色实线为2016年主动源OBS测线^[10],黑色实线为2021年中-莫航次主动源OBS测线,红色圆圈为本研究使用的OBS台站,黑色圆圈为未成功回收和没有可用数据的OBS台站,红色曲线为莫桑比克断裂带所处的位置^[11];(b) 本研究使用的20个OBS台站位置剖面图及水深剖面图;(c) 研究区空间重力异常图,海底地形数据和空间重力异常数据来自GMT^[12~14]内置的卫星数据

Figure 1 Bathymetric map and free-air gravity anomaly map of the study area. (a) Bathymetric map of the study area. The inset in the upper left corner shows the location of the study area, the gray and blue solid lines represents the 2016 active-source OBS survey line^[10], the black solid line represents the 2021 mid-Mozambique cruise active-source OBS survey line, the red circles represent the OBS stations used in this study, the black symbols represent the OBS stations that were not successfully recovered or for which no usable data are available, and the red curve shows the location of the Mozambique Fracture Zone^[11]. (b) Profile map showing the locations of the 20 OBS stations used in this study and the bathymetric profile. (c) Free-air gravity anomaly map of the study area; seafloor topography and gravity anomaly data are included in GMT^[12~14]

PsP震相, 同时为了增加沉积层底部射线密度, 也拾取了结晶地壳折射震相(Pg). 参考研究区附近沉积层的平均速度^[23], 以2.5 km/s作为初始折合速度开展震相识别, 并对每一OBS通过调整折合速度, 确保每台OBS震相清晰可识别(图2). 由于Ps、PsP、Pg震相为后续震相, 受直达水波和沉积层折射波的影响, 其拾取时间误差

相对较大, 根据经验设定为60 ms^[24]. 为保证所拾取震相的可靠性, 我们只拾取了偏移距在 ± 20 km以内的震相. 除OBS18、19站位外, 其余台站的震相左右2支波形连续, 可识别明显的反射震相特征.

与Dz04测线共线的MCS剖面数据同样来源于2021年中-莫航次^[25]. 使用弯曲射线叠前时间偏移技术生成

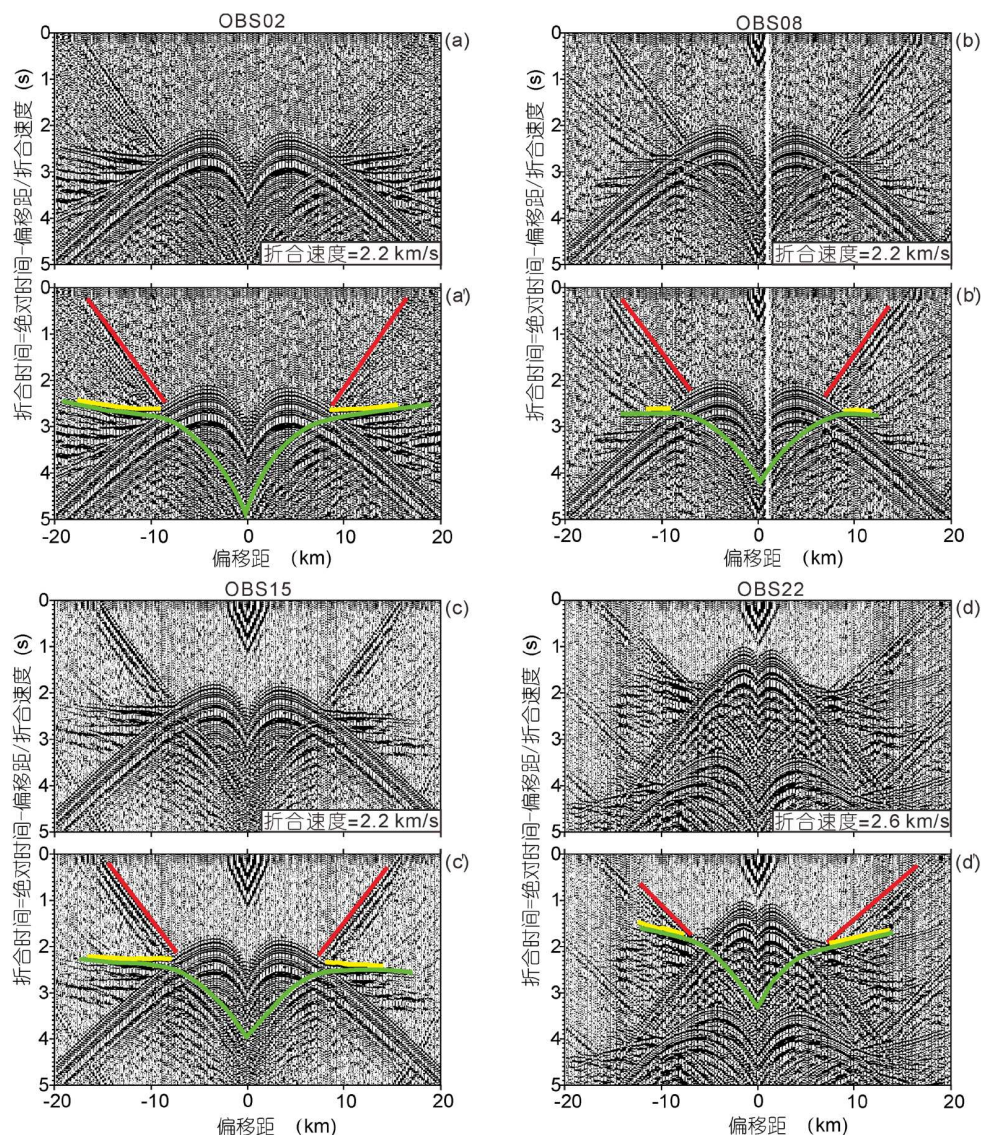


图 2 OBS02, OBS08, OBS15和OBS22的折合时间地震剖面. (a) OBS02台站地震剖面, (a') OBS02台站震相的拾取位置; (b) OBS08台站地震剖面, (b') OBS08台站震相的拾取位置; (c) OBS15台站地震剖面, (c') OBS15台站震相的拾取位置; (d) OBS22台站地震剖面, (d') OBS22台站震相的拾取位置. (a)~(d)的右下角标有该台站的震相折合速度, (a')~(d')则标注出了本研究拾取的Ps震相位置(黄点)、PsP震相位置(绿点)和Pg震相位置(红点)

Figure 2 The time-corrected seismic profiles for OBS02, OBS08, OBS15, and OBS22. (a) Seismic profile of station OBS02; (a') location of phase picks for station OBS02. (b) Seismic profile of station OBS08; (b') location of phase picks for station OBS08. (c) Seismic profile of station OBS15; (c') location of phase picks for station OBS15. (d) Seismic profile of station OBS22; (d') location of phase picks for station OBS22. The upper panels for each station display the seismic records, with the corresponding velocity reduction indicated in the lower right corner of figures (a)~(d). The lower panels (a')~(d') mark the locations of the seismic phases identified in this study, including Ps phases (yellow dots), PsP phases (green dots), and Pg phases (red dots)

CRP道集, 通过迭代速度分析和剩余速度校正, 将均方根速度转换为层速度模型, 使其更接近真实地层速度。随后, 以该层速度模型为基础, 对前序处理数据进行叠前深度偏移成像, 最终获得沿剖面的沉积基底深度。

1.2 方法

为减少因人为经验对自动反演获得的深部结构的可靠性的影响, 本研究的二维层析成像反演采用的软件是JIVE3D [26,27]。其主要特点是采用线性迭代正则化算法, 结合最小二乘迭代反演, 在无阻尼的情况下可以有效减少对初始模型的依赖。反演过程大致分为以下几个步骤[28]: 首先, 通过平滑因子约束对初始模型进行调整, 使模型初步符合数据的宏观特征, 包括平均地震波速度、层内速度梯度和平均反射深度。这种平滑约

束模型捕捉了数据中大尺度的构造信息[29]。接下来, 逐步降低平滑约束的强度, 使模型能够揭示小尺度的构造特征, 反映数据中包含的更多细节, 从而得到高分辨率的速度结构。

反演则通过最小化目标函数 Ψ 实现, 其定义如下:

$$\Psi(\delta m) = \delta t_l^T C_D^{-1} \delta t_l + \lambda_m m^T C_M^{-1} m, \quad (1)$$

其中, m 为模型参数矩阵, δm 为模型的扰动量, $\delta t_l = r - A\delta m$ 为Frechet 残差矩阵, C_D^{-1} 为描述走时不确定性的数据协方差矩阵, C_M^{-1} 为衡量模型平滑度的权重矩阵, λ_m 为正则化参数, 控制模型平滑度。

初始模型包括海水层、沉积层和结晶地壳层(图3(a))。采用三维建模、二维反演的方法设定了模型的尺度, 模型长0~523 km(x)、宽0~1 km(y)、深0~10 km(z), 模

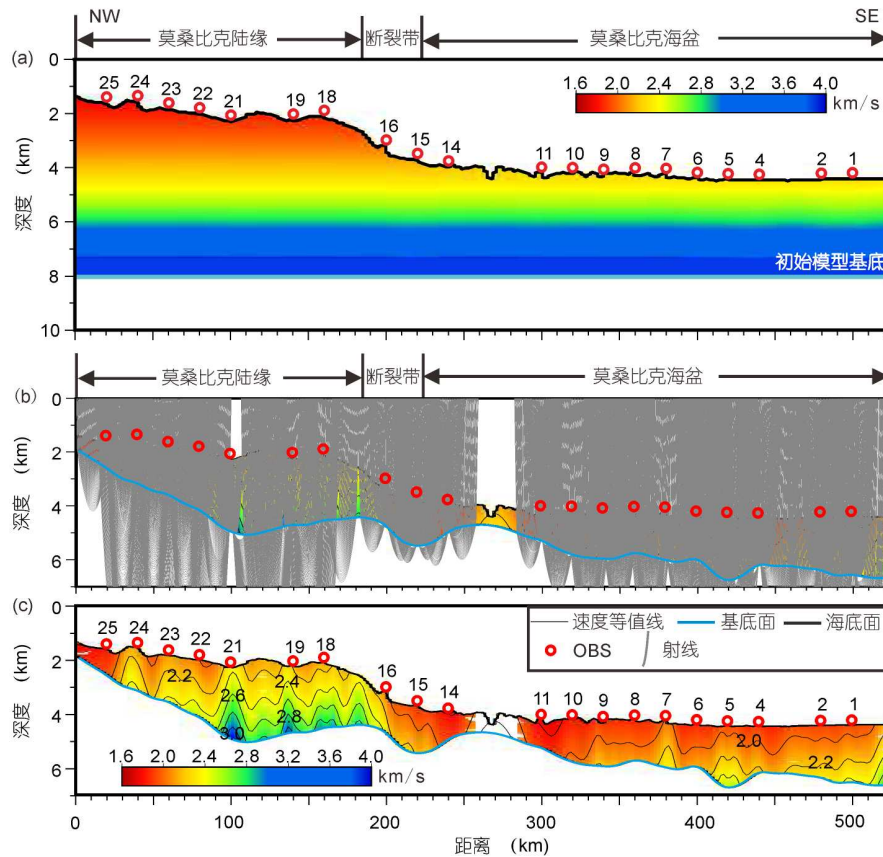


图 3 初始模型、射线追踪和最终反演结果。初始模型(a)、射线追踪(b)和反演最优模型(c)。(c)展示了较好的射线覆盖区域获得的最优模型。红色的圆圈和上面的数字分别代表OBS位置和编号, 蓝色实线为模型的基底界面, 黑色粗线为海底面, 黑色细线为速度等值线(间隔0.2 km/s)。(b)中灰色曲线为射线。为了更好地显示沉积层速度变化, (b, c)使用了与(a)相同的色标, 见(c)左下角

Figure 3 Initial model, ray tracing, and final inversion results. (a) The initial model, (b) the ray tracing, and (c) the optimal model obtained from the inversion. (c) Displays the optimal model derived from the region with good ray coverage. The red circles and the numbers above represent the positions and IDs of the OBS stations, the blue solid line indicates the basement interface, the black thick line represents the seafloor surface, the black thin lines are the velocity contour lines (with a 0.2 km/s interval). In panel (b), the grey curve represents the ray paths. To better highlight the sedimentary velocity variations, panels (b) and (c) use the same color scale as panel (a), as shown in the lower left corner of (c)

型网格为规则立方体(1 km×1 km×1 km). 仅反演水平(x)和深度(z)两个方向的网格, 另一个水平方向(y)方向仅有1个节点, 不扰动, 通常输出y=0.5 km处的模型. 海水层速度设定为1.5 km/s, 沉积层的速度范围设定在1.5~4.0 km/s之间, 结晶地壳层的速度范围设定在5.0~7.0 km/s^[30]. 反演时仅扰动沉积层的速度和基底界面, 其他层的速度和界面均不改变. 为得到最优模型, 反演开始时 λ_m 取最大值(0.0); 之后, 逐步减小 λ_m 的值, 直至达到-8.0. 优化率也从一开始的30%逐步减小, 一直减至0.01%, 使模型精细化. 每一步反演使目标函数在其线性区域内达到最小值, 从而获得最优模型.

2 二维层析成像反演结果

OBS剖面的速度结构模型如图3所示, 它较好地展示了剧烈变化的莫桑比克南部陆缘区沉积层基底埋深和速度结构. 根据转换大陆边缘的地质特征, 参考地形变化和前人研究^[10], 我们把剖面分为三个构造单元, 剖面0~182 km为莫桑比克陆缘, 182~222 km为断裂带, 222~523 km为莫桑比克海盆. 不同构造单元海底面深度变化剧烈, 莫桑比克陆缘整体较浅, 约1.4 km, 断裂带是一个陡坡, 水深从2.2 km增加到3.9 km, 莫桑比克海盆整体偏深, 约4.2 km. 沉积层厚度和速度结构也与不同构造单元和海底面水深变化有一定的相关性, 沉积层厚度总体呈现由西侧陆缘向东侧海盆减薄的趋势, 而速度结构也表现为西侧陆缘速度较高, 东侧海盆速度较低. 莫桑比克陆缘沉积层厚度变化范围为0.9~2.9 km, 平均厚度为2.2 km, 表层速度变化范围为2.0~2.5 km/s, 基底速度变化范围为2.4~3.2 km/s, 层平均速度为2.7 km/s; 断裂带沉积层厚度变化范围1.9~2.5 km, 平均厚度为2.3 km, 表层速度变化范围为1.8~2.0 km/s, 基底速度变化范围为1.9~2.2 km/s, 层平均速度为1.9 km/s; 莫桑比克海盆厚度变化范围为0.5~2.3 km, 平均厚度为1.6 km, 需要指出的是, 0.5 km较薄的沉积层出现在海盆中央的裂谷, 由于缺少精确的OBS数据约束, 本文不再讨论, 表层速度变化范围为1.8~2.0 km/s, 基底速度变化范围为2.1~2.4 km/s, 层平均速度为2.1 km/s.

3 模型评价

模型反演共使用了6615个沉积基底折射/反射走时数据和上地壳折射走时数据, 在误差范围内拟合到6031个(图4(b)), 拟合率为91%. 卡方统计误差值 χ^2 从

263.984降低到1.418, 表明模型拟合残差与拾取误差相当, 模型较接近真实结构.

卡方统计误差值 χ^2 的计算方法为

$$\chi^2 = \frac{1}{n-1} \sum_{i=1}^n \left(\frac{T_{oi} - T_{ci}}{u_i} \right)^2, \quad (2)$$

其中, n 为拾取的走时数, T_{oi} , T_{ci} 和 u_i 分别代表观测走时、理论走时和设定的拾取误差. 对于某一走时数据, 如果 χ^2 等于1, 说明该走时在误差范围内达到了最佳拟合; 如果 χ^2 小于1, 表明可能存在过拟合; 如果 χ^2 大于1, 则说明拟合残差较大^[31]. 最优模型的 χ^2 为1.418, 表明模型可以较好的反映出真实沉积层结构^[27].

拟合残差的分布见图4(a), 黑色横线为误差范围, 红色圆点为最优模型残差分布. 结果表明, 最优模型拟合残差的63%位于±0.06 s误差范围内, 79%位于±0.1 s误差范围内, 有21%偏离. 最优模型所有台站射线实际走时与理论走时的拟合较好(图4(b)), 91%的走时数据位于设定的拾取误差范围内^[32].

使用检测板测试的方法对最优模型进行了分辨率测试(图5). 由于是二维反演, 只扰动水平方向和深度方向, 测试的网格尺度长30 km、深1.5 km(图5(a)). 图5(a)测试了网格大小为30 km×1.5 km的理论模型, 扰动量为该节点速度值的±10%, 图5(b)为图5(a)的恢复模型, 可以看出, 在水平方向恢复较好, 表明水平方向分辨率可达约30 km; 深度方向在陆缘区域由于沉积层厚度较大, 在一定程度上可以恢复, 而在沉积层厚度较薄的海盆区域恢复相对较差.

4 讨论

为了验证模型的可靠性, 以及评估无沉积层约束而对深部结构反演产生的影响, 本研究将获得的OBS沉积层速度结构与共线的MCS沉积层深度剖面进行了对比分析, 同时对沉积层内速度异常结构及其成因开展了初步分析(图6~8).

4.1 MCS结果与OBS反演结果对比

通过对比MCS沉积基底(图6(b)红线)和OBS反演得到的沉积基底(图6(b)蓝线)的埋深及沉积层厚度(图6(c, d)), 可以发现两种方法获得的基底埋深基本一致, OBS反演获得沉积基底埋深整体较光滑, 结果更为平均, MCS结果展现出更多细节和小尺度变化, 最大的差异位于断裂带向陆缘转换区域附近(模型中150~

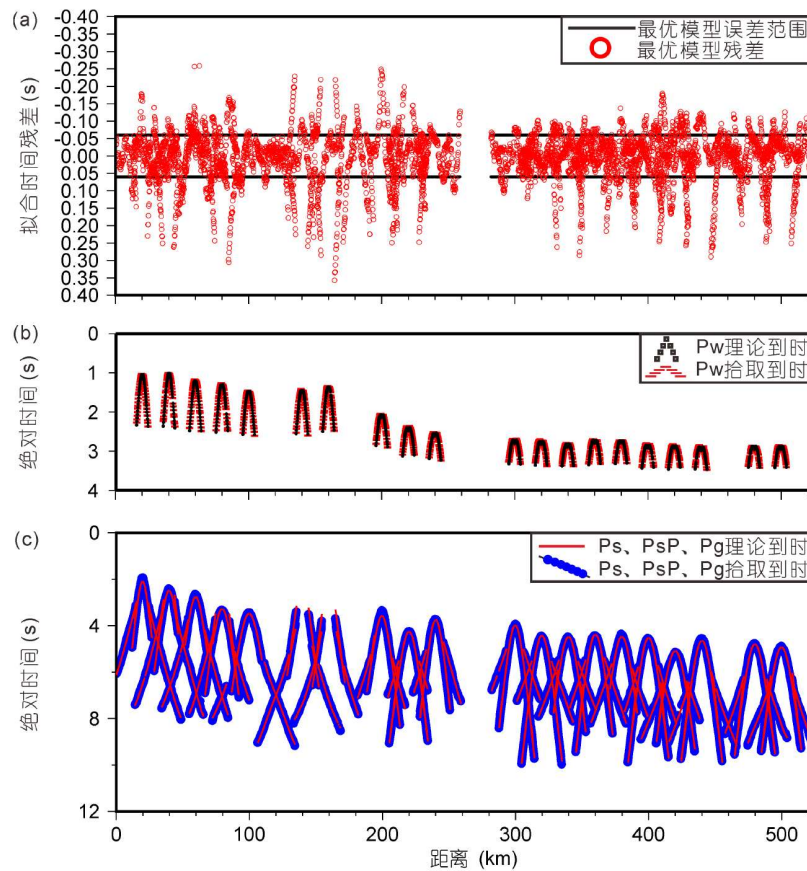


图4 拟合残差分布图。(a) 最优模型(红圆圈)的射线拟合残差分布, 其可接受的误差范围 ± 0.06 s用黑色虚线表示; (b) Pw波拾取到时和理论到时对比图, 其中红色短线为Pw拾取到时, 黑色方块为Pw理论到时, 可接受误差范围 ± 0.025 s; (c) 拾取震相到时和反演拟合到时对比图, 其中红色实线表示理论到时, 蓝色圆圈表示拾取的到时, 拟合率为91%

Figure 4 Distribution of fitting residuals. (a) The residual distribution of ray fits for the optimal model (red circles). The acceptable error range of ± 0.06 s is represented by the black dashed line. (b) A comparison between the observed and theoretical arrival times for Pw waves, where the red short lines represent the observed arrival times of Pw waves, and the black squares represent the theoretical arrival times of Pw waves. The acceptable error range is ± 0.025 s. (c) The comparison between the observed and inverted fitting arrival times, where the red solid line represents the theoretical arrival times, the blue circles represent the observed arrival times, and the fitting rate is 91%

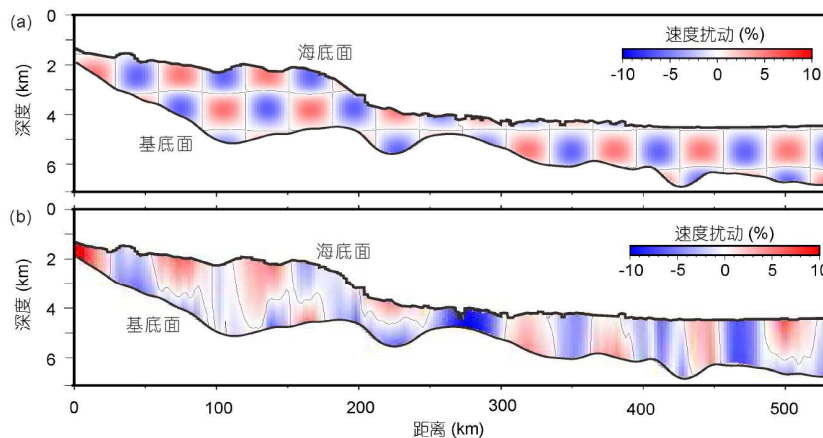


图5 最优模型检测板分辨率测试。(a) 理论模型, (b) 恢复模型, 扰动半波长为 $30 \text{ km} \times 1.5 \text{ km}$, 速度扰动为 $\pm 10\%$

Figure 5 Optimal model checkerboard resolution test. (a) Synthetic model, (b) recovered model with perturbation half-wavelength of $30 \text{ km} \times 1.5 \text{ km}$ and $\pm 10\%$ velocity perturbation

250 km), 由于OBS台站缺失, 可靠性可能受影响, 但OBS反演揭示出沉积基底明显隆升与海底地形的突然隆升有一定的一致性, 空间重力异常也揭示出模型中150~250 km处存在明显的正异常^[28], 表明可能在断裂带向陆一侧存在岩浆入侵等高密度体。

OBS反演获得的沉积层结构另一个重要特征就是不同构造单元下方速度结构差异较大, 莫桑比克陆缘的沉积层平均速度明显比断裂带和海盆区域分别高0.6

和0.5 km/s, 表明沿整个剖面沉积层的层速度不相同, 当缺少沉积层信息时, 通常的做法是参考MCS提供的界面信息, 设定相同的层速度, 但当剖面跨越不同构造单元时, 这将会带来较大的误差。所以有必要使用Ps、PsP和Pg震相反演沉积层速度结构。

4.2 莫桑比克陆缘沉积层高速异常区成因初步分析

沉积层速度结构的一个重要特征是在莫桑比克陆

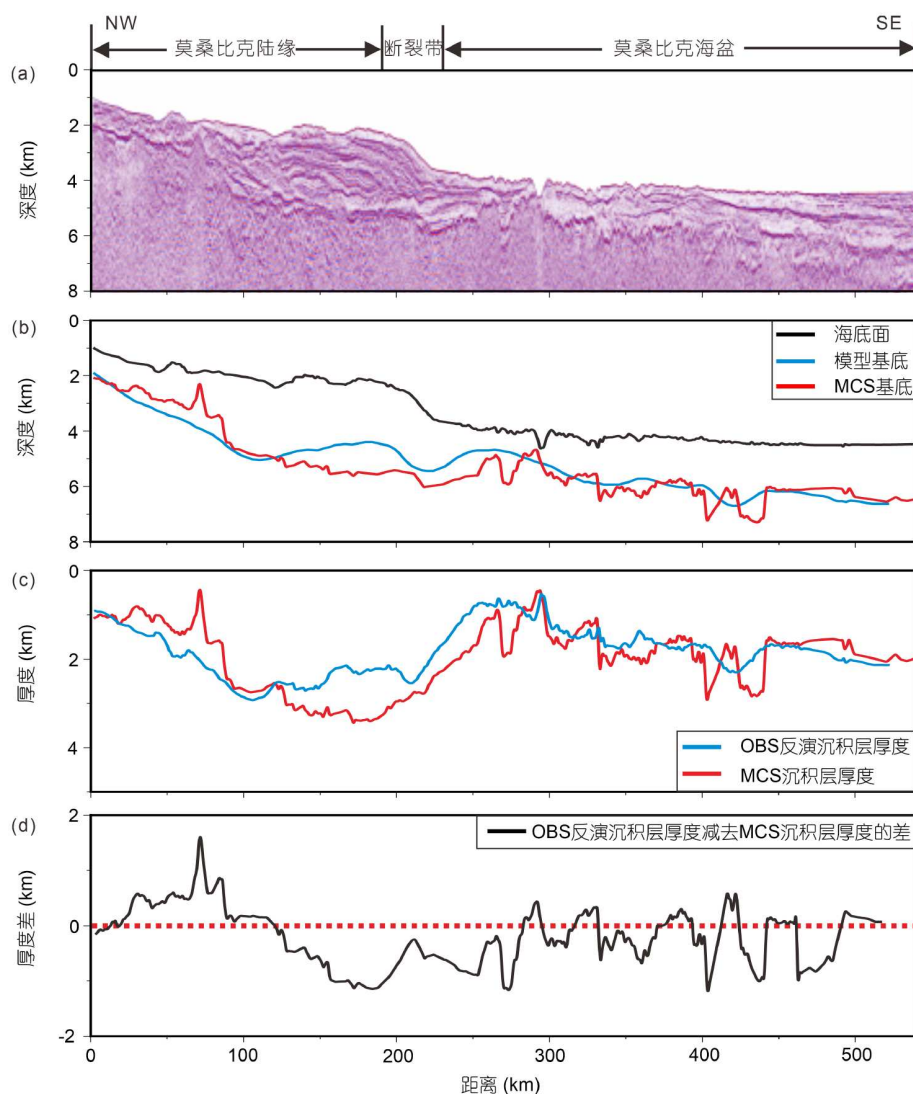


图6 OBS反演结果与多道地震(MCS)沉积层深度剖面对比。(a) 多道地震剖面图^[32];(b) MCS沉积层基底与OBS反演结果对比图, 黑色实线为海底面, 蓝色实线为OBS反演的沉积层基底界面, 红色实线为MCS基底界面;(c) 沉积层厚度对比图, 蓝线为OBS反演沉积层厚度, 红线为MCS沉积层厚度;(d) 沉积层厚度差异图, 黑色实线为厚度差值线, 红色虚线为0 km基准线

Figure 6 Comparison of OBS Inversion Results with MCS Sedimentary Layer Depth Profiles. (a) Multi-channel seismic section^[32]. (b) Comparison between the MCS sedimentary layer basement and OBS inversion results: the black solid line represents the seafloor, the blue solid line shows the sedimentary layer basement derived from OBS inversion, and the red solid line indicates the MCS basement interface. (c) Comparison of sedimentary layer thickness, with the blue line corresponding to the OBS inversion and the red line to the MCS measurements. (d) Sedimentary layer thickness difference map, where the black solid line denotes the thickness difference and the red dashed line represents the 0 km reference line

缘区存在大范围的相对高速异常(图7), 主要位于模型100~200 km处(OBS16-21台站下方). 前人研究表明, 大约在140±5百万年前, 岩浆活动引发了陆缘区域的大规模岩浆入侵, 形成了大火成岩省^[33]. 岩浆入侵可能导致局部沉积层的P波速度显著升高. 同时, 该区域的沉积层厚度明显增厚, 空间重力异常也揭示出该区域存在正的重力异常^[28](图1(b)), 这可能与岩浆活动引发的海底火山喷发有关. 大量岩浆和火山灰的堆积使得沉积层变厚, 然而, 这种厚沉积层的快速堆积, 其成分可能包含火山灰、熔岩流以及火山碎屑岩等, 这些成分会导致沉积层的孔隙度增大, 从而使P波速度降低, 这与模型结果不符. 同时, 在图6(a)的多道地震深度剖面中,

同一地区也未显示出明显的岩浆入侵特征.

与前人在临近区域的研究结果进行对比分析(图8), 发现陆缘OBS 21台站下方P波速度, 其浅部速度明显高于临近区域的背景P波速度范围, 初步解释是该台站下方岩性有可能不同于周围岩性, 可能存在岩浆入侵作用^[34]. 因此导致增厚高速体形成的原因可能是由于岩浆活动导致的海底火山喷发使得沉积层快速堆积, 之后岩浆侵入沉积层改变其岩性和孔隙度, 导致局部P波速度升高, 表现沉积岩形成过程受到了岩浆-构造共同控制作用^[23,35]. 而多道地震深度剖面没有明显岩浆入侵特征的原因可能是当存在大量火成岩时多道地震成像效果较差导致.

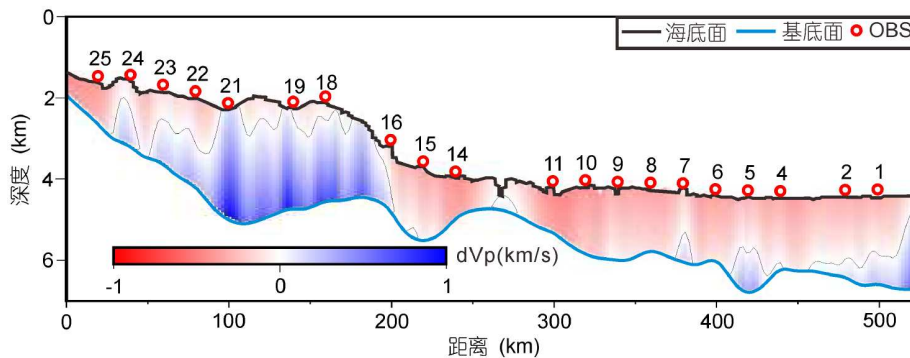


图7 速度异常(dV_p)图. 使用最优速度模型减去最优模型沉积层P波平均速度2.223 km/s, 得到速度异常结构

Figure 7 Velocity anomaly (dV_p) map. The velocity anomaly structure is shown by subtracting the optimal average P-wave velocity of the sedimentary layer (2.223 km/s) from the optimal velocity model

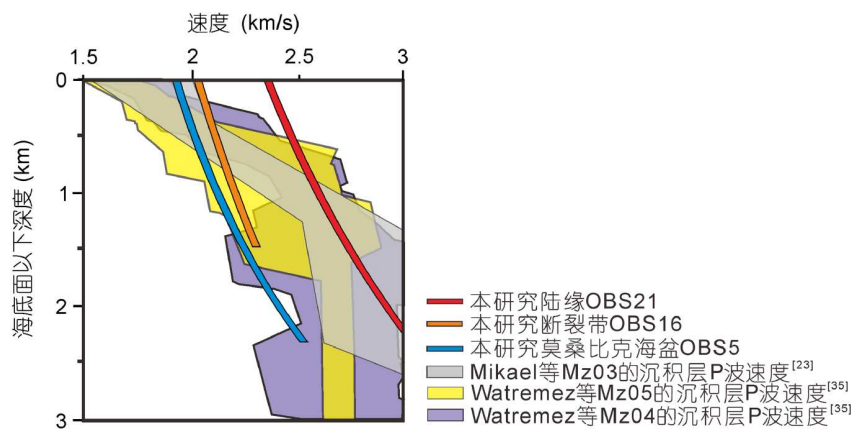


图8 沉积层P波速度分布图. 红线是位于莫桑比克南部陆缘OBS21下方的沉积层P波速度, 橙线是位于莫桑比克断裂带OBS16下方的沉积层P波速度, 蓝线是位于莫桑比克海盆OBS5下方的沉积层P波速度. 灰色区域为Mz03测线在海底面以下的P波速度范围; 黄色区域为Mz05测线在海底面以下的P波速度范围; 紫色区域为Mz04测线在海底面以下的P波速度范围

Figure 8 P-wave velocity distribution map of sediment layers. The red line indicates the P-wave velocity in the sedimentary layers beneath OBS21 at the southern continental margin of Mozambique; the orange line shows the velocity beneath OBS16 in the Mozambique Fault Zone; and the blue line represents the velocity beneath OBS5 in the Mozambique Basin. The gray, purple, and yellow areas correspond to the P-wave velocity ranges below the seafloor along profiles Mz03, Mz04, and Mz05, respectively

5 结论

本研究选取沿同一剖面开展MCS探测和OBS人工源地震探测的研究区, 基于莫桑比克南部陆缘的20台OBS人工广角反射地震数据, 通过识别沉积基底折射/反射震相Ps/PsP和结晶地壳折射震相Pg, 使用JIVE3D三维层析成像反演软件^[18], 沿剖面开展二维反演, 主要有如下认识:

获得了较稳定沉积层速度结构和沉积基底埋深, 通过与MCS深度剖面对比, 结果表明OBS反演获得的沉积层厚度与MCS结果较一致, 验证了本研究方法的可行性, 在缺少沉积层信息的研究区, 使用本方法获得沉积层结构, 可以有效降低深部结构的误差。

发现了莫桑比克陆缘沉积层存在高速异常区, 初步分析其成因可能受到了岩浆-构造作用的共同控制。

致谢 “大洋号”科考船和中国-莫桑比克国际地球物理联合航次的科考队员和船员为本研究的数据采集提供了支持。感谢中国科学院地质与地球物理研究所王元博士向本研究提供graw2sac软件和技术指导。在数据处理期间感谢自然资源部第二海洋研究所卫小冬研究员、张洁副研究员、刘张聚博士、虞嘉辉和魏焱的帮助。感谢自然资源部第二海洋研究所谭平川副研究员和王春阳副研究员对速度模型分析提供的宝贵建议。感谢浙江大学Bryan Riel副教授和自然资源部第二海洋研究所赵阳慧副研究员对英文摘要提出的重要修改建议。部分图件使用GMT^[12-14]绘制。

参考文献

- Ruan A G, Li J B, Feng Z Y, et al. Ocean bottom seismometer and its development in the world (in Chinese). *Donghai Mar Sci*, 2004, 22: 19–27 [阮爱国, 李家彪, 冯占英, 等. 海底地震仪及其国内外发展现状. *东海海洋*, 2004, 22: 19–27]
- Ding W W, Li J B. Seismic stratigraphy, tectonic structure and extension factors across the southern margin of the South China Sea: evidence from two regional multi-channel seismic profiles (in Chinese). *Chin J Geophysics*, 2011, 54: 3038–3056 [丁巍伟, 李家彪. 南海南部陆缘构造变形特征及伸展作用: 来自两条973多道地震测线的证据. *地球物理学报*, 2011, 54: 3038–3056]
- Wang W, Xu H Y, Sun B, et al. Application of high resolution multichannel seismic survey technique to the investigation of natural gas hydrate resources in the South China Sea (in Chinese). *Mar Geol Front*, 2019, 35: 19–24 [王威, 徐华源, 孙波, 等. 高分辨率多道地震勘探技术在南海天然气水合物调查中的应用. *海洋地质前沿*, 2019, 35: 19–24]
- Grevemeyer I. Upper mantle structure beneath the mid-atlantic ridge from regional waveform modeling. *Bull Seismological Soc Am*, 2020, 110: 18–25
- Niu X W, Li J B, Ruan A G. Evidence of serpentinized mantle beneath a non-transform discontinuity at an ultra-slow spreading ridge from wide-angle ocean bottom seismometer data (in Chinese). *Chin Sci Bull*, 2015, 60: 952–961 [牛雄伟, 李家彪, 阮爱国, 等. 超慢速扩张洋中脊NTD的蛇纹石化地幔: 海底广角地震探测. *科学通报*, 2015, 60: 952–961]
- Ma F, Huang H B, Qiu X L, et al. Influence of shallow structure uncertainty on wide-angle seismic traveltimes forward modeling——A case study using OBS2011-1 on the Xisha Block (in Chinese). *Chin J Geophys*, 2021, 64: 3669–3684 [马飞, 黄海波, 丘学林, 等. 浅层结构不确定性对广角地震走时正演模拟结果的影响——以西沙地块OBS2011-1测线为例. *地球物理学报*, 2021, 64: 3669–3684]
- Wang W, Singh S, Wang Z, et al. Crustal structure of continental margin and oceanic basin at the southern mozambique margin. Vienna: Copernicus Meetings, 2024
- Roche V, Leroy S, Guillocheau F, et al. The limpopo magma-rich transform margin, South Mozambique-2: implications for the Gondwana Breakup. *Tectonics*, 2021, 40: e2021TC006914
- Zhang T, Li J, Niu X, et al. Highly variable magmatic accretion at the ultraslow-spreading Gakkel Ridge. *Nature*, 2024, 633: 109–113
- Schnürle P, Leprière A, Evain M, et al. Crustal structure and stratigraphy of the south mozambique margin to south mozambique ridge from combined wide-angle and reflection seismic and drill hole data. *Earth Space Sci*, 2023, 10: e2021EA001902
- Li H, Tang Y, Moulin M, et al. Seismic evidence for crustal architecture and stratigraphy of the Limpopo Corridor: new insights into the evolution of the sheared margin offshore southern Mozambique. *Mar Geol*, 2021, 435: 106468
- Wessel P, Smith W H F. The generic mapping tools (GMT). Version 3. Technical Reference and Cookbook, 1995
- Sandwell D T, Harper H, Tozer B, et al. Gravity field recovery from geodetic altimeter missions. *Adv Space Res*, 2021, 68: 1059–1072
- Pavlis N K, Holmes S A, Kenyon S C, et al. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *J Geophys Res*, 2012, 117: 2011JB008916
- Cohen J K, Stockwell J W. The SU User's Manual. Colorado School of Mines, 1995. 40
- Zhao M H, Qiu X L, Wang P, et al. Large volume air-gun sources and its seismic waveform characters (in Chinese). *Chin J Geophys*, 2008, 51:

- 400–408 [赵明辉, 丘学林, 夏少红, 等. 大容量气枪震源及其波形特征. 地球物理学报, 2008, 51: 558–565]
- 17 Liu C C, Hao T Y, Qiu X L, et al. A study on the deep structure of the northern part of southwest sub-basin from ocean bottom seismic data, South China Sea (in Chinese). *Chin J Geophys*, 2011, 54: 3129–3138 [吕川川, 郝天珢, 丘学林, 等. 南海西南次海盆北缘海底地震仪测线深部地壳结构研究. 地球物理学报, 2011, 54: 3129–3138]
- 18 Niu X W, Ruan A G, Wu Z L, et al. 2014b. Progress on practical skills of Ocean Bottom Seismometer (OBS) experiment (in Chinese). *Progr Geophys*, 2014, 29: 1418–1425 [牛雄伟, 阮爱国, 吴振利, 等. 海底地震仪实用技术探讨. 地球物理学进展, 2014, 29: 1418–1425]
- 19 Xia S H, Ao W, Zhao M H, et al. Corrections and analysis of wide angle seismic data from the sea (in Chinese). *Mar Sci Bull*, 2011, 30: 487–491 [夏少红, 敖威, 赵明辉, 等. 海洋广角地震数据校正方法探讨. 海洋通报, 2011, 30: 487–491]
- 20 Wang Y L, Yan P, Zheng H B, et al. Timing and positioning corrections of ocean bottom seismograph data (in Chinese). *J Trop Oceanogr*, 2007, 26: 40–46 [王彦林, 阎贫, 郑红波, 等. OBS记录的时间和定位误差校正. 热带海洋学报, 2007, 26: 40–46]
- 21 Xue B, Ruan A G, Li X Y, et al. The seismic data corrections of short period auto-floating ocean bottom seismometer (in Chinese). *J Mar Sci*, 2008, 26: 98–102 [薛彬, 阮爱国, 李湘云, 等. SEDIS IV型短周期自浮式海底地震仪数据校正方法. 海洋学研究, 2008, 26: 98–102]
- 22 Ao W, Zhao M H, Qiu X L, et al. The correction of shot and OBS position in the 3D seismic experiment of the SW Indian Ocean Ridge (in Chinese). *Chin J Geophys*, 2010, 53: 2982–2991 [敖威, 赵明辉, 丘学林, 等. 西南印度洋中脊三维地震探测实验中炮点与海底地震仪的位置校正. 地球物理学报, 2010, 53: 2982–2991]
- 23 Zhuang Y, Lv X H, et al. Crustal structure of the East African Limpopo margin, a strike-slip rifted corridor along the continental Mozambique Coastal Plain and North Natal Valley. *Solid Earth*, 2021, 12: 1865–1897
- 24 Zelt C A, Smith R B. Seismic traveltimes inversion for 2-D crustal velocity structure. *Geophys J Int*, 1992, 108: 16–34
- 25 Zhuang B J, Tang Y, Lv X H, et al. Method for determining the foot point of continental slope in complex geological background: take the southern continental margin of Mozambique as an example (in Chinese). *J Mar Sci*, 2024, 42: 13–22 [庄宝江, 唐勇, 吕孝辉, 等. 复杂地质背景下大陆坡脚点的确定方法: 以莫桑比克南部陆缘为例. 海洋学研究, 2024, 42: 13–22]
- 26 Niu X W, Wei X D, Ruan A G, et al. 2014. Comparison of inversion method of wide angle Ocean Bottom Seismometer profile: a case study of profile OBS973-2 across Liyue bank in the South China Sea (in Chinese). *Chin J Geophys*, 2014, 57: 2701–2712 [牛雄伟, 卫小冬, 阮爱国, 等. 海底广角地震剖面反演方法对比——以南海礼乐滩OBS剖面为例. 地球物理学报, 2014, 57: 2701–2712]
- 27 Hobro J W D, Singh S C, Minshull T A. Three-dimensional tomographic inversion of combined reflection and refraction seismic traveltimes data. *Geophys J Int*, 2003, 152: 79–93
- 28 Hobro J. Three-dimensional tomographic inversion of combined reflection and refraction seismic traveltimes data. Doctor Dissertation. Cambridge: University of Cambridge, 1999
- 29 Niu X W. Wide angle seismic tomography (2D/3D) of Southwest Indian Ridge (in Chinese). Doctor Dissertation. Hangzhou: Zhejiang University, 2014 [牛雄伟. 西南印度洋中脊2D/3D广角地震层析成像. 博士学位论文. 杭州: 浙江大学, 2014]
- 30 Scott C L, Shillington D J, Minshull T A, et al. Wide-angle seismic data reveal extensive overpressures in the Eastern Black Sea Basin. *Geophys J Int*, 2009, 178: 1145–1163
- 31 Zelt C A, Forsyth D A. Modeling wide-angle seismic data for crustal structure: southeastern Grenville Province. *J Geophys Res*, 1994, 99: 11687–11704
- 32 Paulatto M, Minshull T A, Baptie B, et al. Upper crustal structure of an active volcano from refraction/reflection tomography, Montserrat, Lesser Antilles. *Geophys J Int*, 2010, 180: 685–696
- 33 Mueller C O, Jokat W. Geophysical evidence for the crustal variation and distribution of magmatism along the central coast of Mozambique. *Tectonophysics*, 2017, 712–713: 684–703
- 34 Ouyang Q, Wu Z L, Wei X D, et al. Comparison of crustal structures in the fossil spreading center of South China Sea basins and the tectonic significance (in Chinese). *Chin Sci Bull*, 2017, 62: 2380–2391 [欧阳青, 吴振利, 卫小冬, 等. 南海海盆残留扩张中心地壳速度结构对比及构造意义. 科学通报, 2017, 62: 2380–2391]
- 35 Watremez L, Leroy S, d'Acremont E, et al. The limpopo magma-rich transform margin, south Mozambique: 1. insights from deep-structure seismic imaging. *Tectonics*, 2021, 40: e2021TC006915

Summary for “莫桑比克南部陆缘沉积基底反射波层析成像”

Tomographic imaging of sedimentary basement reflection waves in the southern Mozambique continental margin

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This study examines the velocity structure and formation mechanisms of sedimentary layers in tectonically complex environments, focusing on the inversion of shallow sedimentary velocity structures using wide-angle refraction seismic data obtained from Ocean-Bottom Seismometers (OBS) with active sources. Accurate sedimentary velocity models are crucial for developing initial crustal models and providing vital constraints for geological and tectonic analyses, especially in regions where multi-channel seismic (MCS) data is lacking. These models are fundamental for understanding the composition and structural heterogeneity of the Earth's crust, particularly in continental margin areas where data is scarce.

The research uses OBS data collected from the southern Mozambique margin, an area known for its dynamic geological setting, shaped by complex tectonic and magmatic activity. These factors produce sedimentary layers with intricate and highly variable velocity structures, making interpretation more challenging. The methodology employed involves three key steps: (1) identifying sedimentary basement refracted and reflected phases (Ps/PsP) and crystalline crust refracted phases (Pg); (2) performing high-resolution tomographic inversion using JIVE3D software to generate sedimentary velocity models; and (3) validating the inversion results by comparing them to existing MCS depth profiles. The inversion reveals significant variations in sedimentary basement depths and uncovers distinct high-velocity anomalies within the sedimentary sequences, pointing to the impact of geological processes on the subsurface structure.

The study offers several important findings. First, the sedimentary basement depths derived from the OBS inversion show strong consistency with MCS depth profiles, validating the inversion approach and demonstrating the effectiveness of OBS data for sedimentary modeling in regions with sparse or absent MCS data. This method provides an alternative for subsurface characterization where conventional techniques are not applicable. Second, the sedimentary layers of the Mozambique margin show pronounced high-velocity anomalies, interpreted as indicators of unique geological processes linked to tectonic-magmatic interactions. These anomalies suggest the presence of subsurface features such as magmatic intrusions, volcanic activity, or crustal deformation, all of which play a significant role in shaping the sedimentary architecture of the region.

By integrating regional tectonic evolution and comparing seismic data from surrounding areas, the study suggests that these high-velocity anomalies are likely the result of combined magmatic and tectonic processes. These include syn-depositional magmatic activity, such as intrusions and volcanic events, along with tectonic processes like crustal thinning or differential subsidence. These findings offer a new perspective on the geological history of the region, highlighting the role of both magmatic and tectonic forces in shaping sedimentary structures.

The OBS-based inversion method presented in this study offers two key advantages, particularly in areas lacking MCS data: (1) independent modeling, which removes the need for MCS data constraints and enables sedimentary velocity analysis in data-limited regions, and (2) enhanced imaging, which improves the accuracy of deep crustal imaging by refining velocity models. This method is especially effective for studying thick or laterally heterogeneous sedimentary sequences, which are typical in tectonically complex regions. By generating reliable velocity models, this approach aids in more accurate structural analysis of both the crust and upper mantle, advancing our understanding of continental margin evolution. Additionally, this methodology has broad applications in other regions with limited access to MCS data, providing a practical solution for geophysical research in challenging exploration environments.

ocean-bottom seismometer, seismic tomography, sedimentary layer velocity structure, southern Mozambique continental margin

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