海底地震仪(OBS)广角地震记录中二次震相的识别及应用

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摘要 在海底地震仪(OBS)记录的广角地震剖面中, 经常可识别出能量强, 连续性好的多次波震相. 在常规OBS数据处理过程中, 多次波被作为无效信号剔除, 但是作为地下界面的真实反射, 多次波同样蕴含着地下构造的重要信息. 通过对南海海盆OBS2013-ZN测线地震数据的多次波震相进行处理分析, 对多个台站Pg, PmP和Pn震相的二次震相进行识别. 以OBS06和OBS07台站为例, 详细阐述了二次震相的辨别和确认过程, 准确拾取了二次Pg, PmP和Pn震相的走时数据. 并通过射线追踪模拟, 确定其传播路径. 最后, 在原有P波速度模型基础上, 利用走时反演方法将初至震相和二次震相进行联合成像获得新的局部速度结构. 结果显示, 与初至震相结果相比, 浅部沉积层和中深部的壳幔速度结构都有一定程度的变化. 该研究有助于充分利用OBS数据, 挖掘多次波震相特征, 提高地壳结构的成像精细度.

关键词 海底地震仪, 多次波层析成像, 二次震相, 地壳结构

海底地震仪(ocean bottom seismographs, OBS)人工源探测, 主要是通过广角反射/折射方式进行, 数据处理多以射线追踪和走时正、反演技术来建模^[1,2], 模拟和迭代拟合的震相大都是容易识别的初至波, 主要包括直达水波(Pw)、地壳内折射波(Pg)、地幔顶部的折射波(Pn), 以及莫霍(Moho)面反射波(PmP)^[3~5]. 在这些震相的约束下, 海底以下介质主要的速度间断面会被揭示, 从而使我们获得较大尺度的海底深部速度结构^[6~8]. 但在实际的数据处理中, 我们发现几个问题值得进一步研究: 就浅部而言, OBS资料中浅层沉积层反射震相(PsP)极少, 这意味着利用近浅层反射划分沉积基底会受到限制^[9], 所获模型沉积层速度结构粗糙. 而对于深部的地壳结构, 火山型边缘海由于岩浆的底侵作用而产生下地壳高速层(7.2~7.4

km/s)^[10], 但大多在OBS地震记录剖面上很难识别, 只是通过反演获得, 而没有直接的证据. 另外, 有时候地震剖面中Moho面的反射震相并不清楚, 主要是依赖于折射的Pn震相来确定, 误差较大. 同时, 在OBS广角地震探测中, 经常可以见到能量很强、连续性很好的多次波震相. 多次波是指地震波在某些地层中经过多次反射再出射, 有些情况下其振幅强于一次波. 多次波在地下的传播路径比一次波更长, 含有丰富的地下构造信息, 它们与一次波或它们之间的时差可以反映层界面之间的厚度和速度^[11]. 显然, 我们可以利用多次波来解决上面提到的问题, 即沉积层的细分层、Moho面的约束、下地壳高速层的识别等^[12~14].

关于多次波前人已经做过一些尝试性研究. 利

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用叠前克希霍夫深度偏移的方法对OBS数据中的初至波和深水多次波进行联合成像,结果显示模型浅部沉积层的成像精度有了一定的改善^[14]. 提取出多次波,然后利用含一次波和多次波的记录代替震源子波,将多次波作为接收记录,再用常规的方法对多次波成像^[15,16]. 还有人提出了基于双程弹性波动方程的叠前深度偏移方法对一次波和多次波进行成像,但该方法需要精确的速度场,且对硬件的要求较高^[17]. 也有人提出了基于最小二乘联合成像的方法对一次波和多次波联合成像,但该方法在复杂地质环境下的应用受到了限制^[18-20]. 部分研究者先利用表层相关多次波衰减(surface-related multiple elimination, SRME)预测出表层相关多次波,然后将其转化为一次波,并用常规方法对其进行成像^[21-23]. Malcolm等人^[13]利用层间多次波解决了初至波浅层沉积层照明度差的问题. 郭书娟等人^[24]提出了基于广义炮偏移的方法,实现了地表多次波和一次波的联合成像.

以上研究为多次波的有效利用提供了很大的帮助,然而在复杂海底地质环境下的OBS广角地震数据成像上,多次波的研究开展较少, Dash等人^[12]提出了镜像偏移,并将该方法应用于实测OBS数据,结果显示浅层沉积层的成像精细度得到了提升. 万奎元等人^[25]对OBS广角探测地震数据中二次Pg的震相特征和其在地壳结构成像中的应用作出了探讨. 本文拟使用南海OBS2013-ZN测线的地震数据,以OBS06和OBS07两个台站记录的地震剖面为例,分析其二

次震相的走时和波形特征,并通过模拟计算确定其传播路径,然后利用射线追踪方法对初至震相和二次震相进行走时拟合^[6],分析多次波震相在OBS地震数据反演成像中的应用.

1 海底地震仪数据及二次震相特征

1.1 数据

OBS2013-ZN测线完成于2013年4月,位于南海中央海盆,呈东西走向,横跨“中南礼乐断裂”(图1). 共投放OBS 15台,回收15台. 测线长度203 km,台站间距10 km,震源由4支24580 cm³的BOLT枪阵列组成,工作压力120 kg/cm²以上. 放炮间隔时间为120 s,航速4~5节. OBS数据的采样率统一设定为 250 Hz(即采样时间间隔4 ms)^[26].

1.2 二次震相特征分析

(i) 二次震相走时特征. OBS06台站位于南海中央海盆中部,水深4.253 km,记录剖面清晰显示了该OBS台站记录到的初至及多次波震相(图2). 在综合地震剖面右半支,偏移距7.8 km处,折合时间4 s处开始出现清晰的初至Pg震相,在初至Pg下方,走时迟滞约1.5 s处出现了多次波震相,两者走势一致,视速度相近,该震相与初至Pg相比振幅更为突出,清晰连续,可追踪至偏移距27 km处,认为其为二次Pg. 地震剖面左半支,在偏移距-16 km折合走时约

图1 OBS2013-ZN测线位置图. 图中黄色虚线表示Ruan等人^[26]确定的中南礼乐断裂

Figure 1 Location of the profile OBS2013-ZN. The yellow dotted lines represent the Zhongnan fracture zone determined by Ruan et al.^[26]

图2 测线OBS06号台站垂直分量地震记录, 折合速度8 km/s. 红色实线为后文中抽取的单道地震波形位置, 分别对应第457, 331和296道
Figure 2 Vertical component of station OBS06 in the profile OBS2013-ZN. The reduced velocity is 8 km/s. The solid red lines indicate the location of the extracted single-channel seismic (trace Nos. 457, 331, 296) waveforms in subsequent part

5 s处, PmP震相开始出现, 在下方迟滞约1.6 s处出现了相同走势的多次波震相, 清晰连续, 可追踪至偏移距-23.6 km处. 该震相与初至PmP视速度相当, 振幅相近, 认为其为二次PmP. 同样, 左半支Pn下方也出现了形态相似的多次波震相, 其振幅较初至Pn更大,

认为其为二次Pn.

(ii) 二次震相波形特征. 从以上分析获得的初至震相和二次震相的形态和走时特征上, 我们对二次震相有了一定的认识. 为进一步对二次震相作量化识别, 分别绘制了OBS06台站接收的第457(偏移距19.1 km), 331(偏移距-21.3 km)和296(偏移距-36.7 km)道地震波形, 与地震剖面显示结果相同, 波形图中二次震相的振幅比初至震相振幅还要强烈, 两者走时差在1.5~1.6 s(图3). 对比截取时窗内的初至震相和二次震相, 两者具有相似的波形特征(图4(a1), (b1)和(c1)); 从初至震相和二次震相的相关性分析中可以看到, 两者在0延迟附近的相关性达到最大, 说明在这个时窗内两者相位具有高度对应性(图4(a2), (b2)和(c2)). 计算了截取时窗内初至和二次Pg, PmP和Pn的相关系数, 分别为0.8499, 0.7975和0.8298, 接近于1(相关系数等于1时, 表明两者最大相关).

2 二次震相传播路径及其应用

OBS06及OBS07记录的地震剖面中, 不仅初至

图3 OBS06 台站记录的地震波形及拾取的初至震相和二次震相到时. (a) 第457道波形数据, 偏移距为19.1 km; (b) 第331道波形数据, 偏移距为-21.3 km; (c) 第296道波形数据, 偏移距为-36.7 km. 与图2中红色实线相对应

Figure 3 Single-channel seismic waveforms recorded as well as arrival times of first arrivals and secondary seismic phases picked up at the OBS06 station. (a) The waveform data of trace No. 457 (offset of 19.1 km); (b) the waveform data of trace No. 331 (offset of -21.3 km); and (c) the waveform data of trace No. 296 (offset of -36.7 km). Corresponding to the red solid lines in Figure 2

图4 OBS06号台站记录的初至震相和二次震相波形对比图和相关性分析图。(a1), (b1), (c1)分别是初至和二次Pg, PmP, Pn的波形对比图, 对应图2中红色实线表示的第457, 331, 296道波形数据, 其中紫色为初至震相波形, 截取时窗分别为6.296~7.296, 7.280~8.280和8.2~9.2 s, 蓝色为二次震相波形, 截取时窗分别为7.832~8.832, 8.896~9.896和9.8~10.8 s。(a2), (b2), (c2)为初至和二次Pg, PmP, Pn的相关性分析图

Figure 4 Waveform comparison and correlation analysis of first arrivals and secondary seismic phases recorded by OBS06 station. (a1), (b1), and (c1) are comparisons of the waveforms of first arrival and secondary Pg, PmP, and Pn, respectively, which correspond to waveform data of trace No. 457, No. 331, and No. 296 (solid red lines in Figure 2). Waveforms of first arrival phases (purple lines) and the time windows intercepted are 6.296~7.296, 7.280~8.280, and 8.2~9.2 s. Waveforms of secondary seismic phase (blue lines), and the time windows intercepted are 7.832~8.832, 8.896~9.896, and 9.8~10.8 s. (a2), (b2), and (c2) show the correlation analysis of first arrivals and secondary Pg, PmP, and Pn, respectively

震相清晰连续, 二次震相也可追踪至较远偏移距。为进一步验证初至震相和其对应的二次震相, 在OBS06和OBS07台站的地震剖面上拾取了初至和二次震相的精确到时。在二次震相的拾取过程中, 先根据炮点时间, 偏移距以及震相的折合时间计算出理论走时, 然后以地震剖面上震相的大致走势为基础, 在实际地震波形上找到对应的位置并对比前后地震波形特征以保证拾取的精度。经过反复的分析辨别, 设置拾取误差为80~150 ms, OBS06台站拾取二次震相151个, OBS07台站拾取二次震相110个(表1), 由于噪音影响, 未对OBS2013-ZN 06号台站右半支和

OBS2013-ZN 07号台站左半支的二次PmP和二次Pn进行拾取。另外, 从这些台站中也拾取了初至震相, 拾取误差为80 ms。

2.1 二次震相传播路径分析

OBS广角地震中二次震相是先经过层间反射再经过折射或界面反射到达接收点^[25,27]。由于海水与空气、海底与海水、沉积层与上地壳沉积基底之间的分界面均是强波阻抗差界面, 易发生二次反射, 形成多次波, 二次震相的二次反射界面难以分辨, 为确定OBS06和OBS07台站地震剖面中所拾取的二次震相

表 1 OBS06 和OBS07 台站二次震相拾取及拟合结果

Table 1 Picking-up and fitting results of secondary seismic phases at stations OBS06 and OBS07

站名	水深(km)	震相	拾取误差(ms)	拾取震相走时个数	走时残差(ms)	卡方值
OBS06	4.253	Multiple Pg	150	69	201	1.814
		Multiple PmP	80	29	80	1.043
		Multiple Pn	100	53	104	1.109
OBS07	4.225	Multiple Pg	100	62	96	0.935
		Multiple PmP	100	15	108	1.030
		Multiple Pn	80	33	80	1.043

对应的二次反射界面, 我们利用射线追踪方法对其传播路径进行分析^[6].

Rayinvr射线追踪中, 我们不断修改模型, 拟合模型计算的理论走时与观测走时, 使得RMS值(实际观测走时与理论计算走时的差异)和 χ^2 值(实际观测走时与理论计算走时的拟合程度, 越接近1即为拟合越好)较小, 并在拟合的过程中评估二次震相射线路径的准确性. 在对OBS06台站数据二次震相的射线路径进行拟合分析时, 分别设置以下3种射线路径: (1) 以海表面和海底面作为反射界面发生上下发射, 反射层为海水层(图5(a)); (2) 以海表面和沉积基底面作为反射界面发生上下反射, 反射层为海水层和沉积层(图5(b)); (3) 以海底面和沉积基底面为反射界面发生上下反射, 反射层为单一的沉积层(图5(c)).

从图5中可以看到, 二次震相传播过程中二次反

射发生界面的不同, 使得二次震相与初至震相的走时差具有明显的差异, 且不同传播路径下拟合出的理论二次震相的走势有明显的变化, 与初至震相的走势呈现局部不同, 说明二次震相在传播过程中受双程旅行时的影响, 在界面起伏的情况下, 走时变化较一次波剧烈. 拟合结果显示, 只有二次反射反射层为单一的沉积层时, 二次震相的理论走时和实际走时具有较高的一致性, 其他两种路径的假设下, 拟合出的二次震相理论走时与实际震相的走时有较大的偏差, χ^2 值也较大, 因此可以认定, 以上二次Pg, PmP和Pn震相的二次反射发生在海底面和沉积基底面之间.

2.2 二次震相在地壳结构成像中的应用

为进一步探讨二次震相在OBS数据成像中的作

图 5 初至震相和二次震相射线追踪及走时拟合图, 折合速度为 8 km/s. (a1), (b1), (c1)分别为将海水层、海水层和沉积层, 沉积层设为反射层的射线追踪图. (a2), (b2), (c2)为对应的走时拟合结果. 其中橙色为二次Pg震相, 紫色为二次PmP震相, 红色为二次Pn震相.

Figure 5 Ray tracing and travel time fitting of secondary seismic phases as well as first arrivals, with the reduced velocity of 8 km/s. (a1), (b1), and (c1) present the results of ray tracing with seawater, seawater-sediment interface, and sediments as the second reflecting layer. (a2), (b2), (c2) are the travel time fitting results which correspond to (a1), (b1), (c1). The secondary Pg phase (orange), secondary PmP phase (purple), and secondary Pn phase (red) are shown

用,利用OBS06和OBS07号台站中拾取的初至震相和二次震相走时数据,以原来的P波速度模型^[26]为初始模型,采用试错法对两个台站下方的速度结构进行拟合,得到了新的速度结构(图6(a)).表1为上述加入二次震相的两个台站的详细拟合结果,除OBS06号台站的右半支二次Pg走时残差较大外,其他较小,二次震相拟合结果的 χ^2 值都接近标准值1.0,说明拟合结果较好,表明上述讨论中确定的二次震相的传播路径是可信的.与只有初至震相的射线密度相比(图6(b)),加入二次震相后,OBS06和OBS07台站附

近,浅部沉积层、地壳甚至壳幔边界处的射线密度都有了较大的提升(分别由20提升至60,50提升至80)(图6(c)),这为获得更高精细度的模型打下了基础.

2.3 合成地震记录验证

为验证上述成像方法的可靠性,基于所获台站下方速度结构,计算出OBS06和OBS07台站正下方的平均一维速度,利用反射率正演方法合成OBS06台站单道地震波形^[28,29],与实际地震资料中的单道波形(第457,331和296道)对比(图7),结果显示合成

图6 初至震相与二次震相的走时拟合结果以及射线覆盖密度. (a) 初至震相与二次震相联合约束走时拟合结果,红色实线表示抽取的一维速度; (b) 初至震相约束下的射线覆盖密度; (c) 加入二次震相之后的射线覆盖密度

Figure 6 Travel time fitting results and the ray density distribution of first arrivals and secondary phases. (a) Travel time fitting results under the combined constraint of first arrivals and secondary seismic phases. The red solid lines indicate the 1D velocity. (b) The ray density distribution of first arrivals. (c) The ray density distribution after the addition of secondary phases

图7 合成地震波形及实测地震波形对比图, 其中黑色为合成地震波形, 红色为抽取的实测地震波形. (a)~(c)中实际地震波形分别为抽取自OBS06 台站记录地震剖面的第457, 331 和296 道波形数据, 对应图2 中红色实线

Figure 7 Comparison of synthetic and observed seismic waveforms. The black lines indicate the synthetic waveforms and the red lines represent observed waveforms. (a), (b), (c) The observed waveforms are extracted from section of station OBS06, represent traces No. 457, No. 331, and No. 296, respectively (traces correspond to the red solid lines in Figure 2)

地震波形与实际地震波形的初至震相的走时及形态均有较高的一致性, 深部二次震相形态一致, 走时差在50 ms内, 说明拾取二次震相正确, 也验证了上文探讨的二次震相传播路径的可靠性, 反过来也说明所获速度结构可信.

3 讨论与结论

OBS海上人工地震探测人力物力耗费巨大, 数据获取十分昂贵, 因此如何提高地震资料的利用率, 充分挖掘地震数据信息极其重要. 多次波震相由于其本身的传播路径更长, 射线覆盖的区域更广, 且反射角度要比初至震相角度小, 往往蕴含了初至震相没有的信息, 多次波震相与初至震相进行联合反演成像可以获得更精细的地壳结构, 本文基于实际地震资料就二次震相的识别特征、传播路径和实际应用进行了分析和探讨:

通过对OBS2013-ZN OBS06和OBS07两个台站实测数据进行处理分析, 在初至Pg, PmP和Pn后方识别出二次Pg, PmP和Pn, 两者走时差在1.53~1.62 s之间, 对其波形特征进行分析, 发现二次震相的波形振幅较为突出, 甚至有时比初至震相的振幅还大, 两者波形特征极为相似, 多次波震相整体形态也与初至形态大致相同, 相关性系数达到0.8左右. 从本文中拾取的二次震相可以看到, 沉积层的厚度变化使得

多次波震相的形态有一定的变化, 另外地壳的复杂程度也会影响二次震相的走势, 因此对不同地震剖面中二次震相的走时特征和波形特征进行分析, 可以积累更为丰富的二次震相识别信息, 能够帮助我们更为精确地拾取二次震相到时数据进行研究, 这提醒我们今后在多次波震相的识别过程中需要根据不同的地质条件和实际情况来进行相应的分析和讨论.

从走时拟合结果(图6)来看, 二次震相多次穿过沉积层, 提高模型中的射线覆盖密度, 可以为走时反演提供更多的约束, 改善沉积层和地壳的成像精细度. 为进一步分析加入二次震相后地壳结构成像的结果, 我们提取台站下方新老速度结构局部一维速度进行比较(图8), 可以看到两者总体趋势相似, 但加入二次震相约束后, 浅部的沉积层和中深部的地壳在速度结构上有一定的变化, 在100(图8(a))和130 km(图8(d))处的一维速度中发现浅部沉积层速度一致, 厚度变大, 110(图8(b))和120 km(图8(c))处中深部的地壳界面深度一致, 速度变大, 另外局部区域莫霍面埋深也略有抬升(图8(b)), 这对应于Ruan等人^[26]揭示的中南礼乐断裂的位置.

基于以上讨论, 我们得出如下结论:

(1) 通过对OBS2013-ZN测线中两个台站的数据进行处理, 分析了二次震相的走时特征及波形特征,

图8 一维速度对比. (a) 模型 100 km处; (b) 模型 110 km处; (c) 模型 120 km处; (d) 模型 130 km处. 对应图 6(a)中的红色实线, 红色为本文拟合结果、黑色为前人结果^[22]

Figure 8 Comparison of 1D velocities. (a) 100 km, (b) 110 km, (c) 120 km, and (d) 130 km (red solid lines in Figure 6(a)). The red lines are the time fitting results from this study, and the black lines indicate previously published results

识别并精确拾取了二次Pg, PmP和Pn;

(2) 利用射线追踪模拟计算, 确认了二次震相的二次反射界面; 结合初至震相和二次震相, 拟合了两个台站下方的速度结构, 与初至震相处理结果相比, 浅部沉积层及深部的壳幔边界附近射线覆盖密度均有提升, 在反演中提供了更多的约束, 为提高沉积层成像精细度, 改善中深部地壳及地幔成像打下了基础.

(3) 计算所得速度结构中平均一维速度, 合成地震波形, 并与实际地震波形对比, 验证了二次震相的拾取、反射界面的确定和所获速度结构的可靠性.

OBS2013-ZN是目前南海记录多次震相信息较多的剖面, 共在9个OBS记录中识别出二次震相, 这为下一步开展更高精细度的南海地壳结构研究提供了数据基础, 将提高人们对南海深部结构的认识.

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Summary for “海底地震仪(OBS)广角地震记录中二次震相的识别及应用”

The identification and application of multiple phases recorded by ocean bottom seismometer

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In recent years, data obtained from ocean bottom seismographs (OBS) have played a major role in studies of the oceanic crust and mantle structure, thus greatly facilitating improved understanding of deep structures in the Earth. In addition to primary, first arrival phases, multiple seismic phases can often be detected in OBS data sections. These phases tend to have high energy and good continuity, but are often rejected as invalid signals in conventional OBS data processing. However, multiple phases can be real reflections of subsurface interfaces, and contain a large amount of important information about subsurface structures. For example, in shallow sediments with poor resolution of first arrival phases, an inversion using multiple phases can improve the resolution of the sediments. Similarly, deep multiple phases can also reflect the media characteristics near the Moho, and improve the imaging precision of crustal structures. By analyzing the measured data from seismic line OBS2013-ZN at stations OBS06 and OBS07, the secondary Pg, PmP and Pn phases are identified behind the first arrival Pg, PmP, and Pn phases, with travel time differences in the 1.53–1.62 s range. Analysis of waveform characteristics reveals that the amplitude of the secondary phases is more prominent, and greater than that of the first arrival phases in some cases. The waveform characteristics of these two phases are very similar in terms of apparent velocity. The overall form of the multiple phases is also approximately the same as that of the first arrivals, with a correlation coefficient of ~0.8. According to the recognition characteristics described, accurate arrival times of the first arrival and secondary phases are detected in the seismic sections of stations OBS06 and OBS07. The theoretical travel time is first calculated from the secondary phases based on the fire time, offset, and reduced time of seismic phases. After repeated analysis and identification, the uncertainty in detection is set to 80–150 ms. A total of 151 secondary phases are detected at OBS06 and 110 at OBS07, and first arrival phases are detected from these stations with an uncertainty of 80–110 ms. To determine the secondary reflecting interface corresponding to the secondary seismic phases detected at OBS06 and OBS07, their propagation paths are analyzed by ray tracing. A new local velocity structure is obtained using travel time inversion based on the original P-wave velocity model by combining the first arrival and secondary phases. The results show that the velocity structure changes in both shallow sediments and mid to deep crust-mantle depths compared with previous results of processing first arrival phases. The fitting results of travel time shows that the secondary phases traversed sedimentary intervals several times and increased the ray-coverage density in the model, providing more constraints on travel-time inversion and improved imaging precision of the sediments and crust. To validate the reliability of the imaging method, the average one-dimensional velocity is calculated for the region directly below OBS06 and OBS07 based on the velocity structure obtained. Next, the single-channel seismic waveforms of OBS06 are synthesized by forward modeling of reflectivity and these are compared with the single-channel waveforms in the actual seismic data. The results show that the first arrival phases of synthetic and actual seismic waveforms are highly consistent in terms of both travel time and form. These findings demonstrate the reliability of the secondary seismic phases detected, and also validate the reliability of the propagation paths of secondary seismic phases. This in turn shows that the velocity structure obtained is credible. This study provides a reference for making full use of wide-angle OBS data and future studies of multiple phases, and has implications for investigating fine details of crustal structures, particularly in terms of improving imaging precision.

ocean bottom seismometer, multiple waves tomography, secondary phases, crustal structure

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