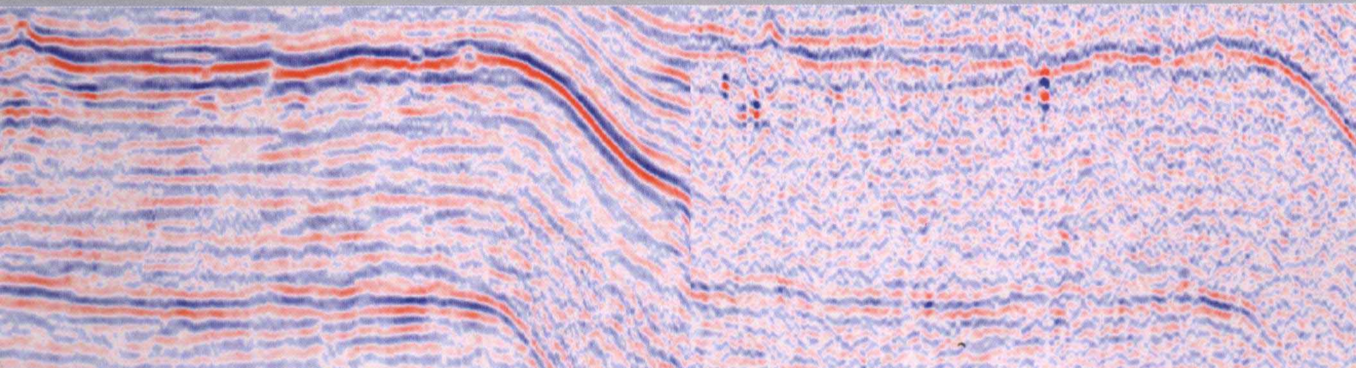
地震资料的相对保真处理方法与应用

王西文　王宇超　王小卫　刘文卿　苏 勤　吕 彬　田彦灿　等著



Methods and Application for Relative Fidelity Processing of Seismic Data

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内 容 提 要

本书在对地震资料的相对保真处理方法进行研究的基础上，详细介绍了基于射线理论的Kirchhoff积分偏移方法和基于波场延拓的单程波偏移及波动方程逆时偏移的方法原理，并介绍了保幅偏移算法的研究进展。本书对基于GPU/CPU系统复杂构造逆时偏移成像、复杂构造区深度域速度建模等一些关键技术方法做了介绍，并从三维逆时叠前深度偏移在盐下成像、碳酸盐岩地区的高密度全方位地震资料处理、吐哈与酒泉盆地复杂构造地震成像、冀东南堡古潜山构造带的地震叠前成像等实际应用方面介绍了不同领域的针对性保真成像处理措施及应用效果。

本书可供从事地震资料处理方法研究的科技人员参考。

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前 言

近年来，岩性油气藏逐渐成为我国油气增储上产的重要领域，而岩性分析对于地震偏移成像结果的保幅性具有很高的要求，但是早先的叠前深度偏移方法主要是以构造成像为目标。因此，地球物理界针对不同类型的保幅叠前深度偏移方法开展了大量研究工作。但岩性地层油气藏是受区域构造和沉积相带等多重因素控制，由于其复杂隐蔽，勘探难度相对较大。在地震剖面上，岩性储层地震响应的显示可信度取决于地震处理中的保真度。

目前，绝对地震保真处理是难以做到的，但相对保真处理是可以做到的。这就对地震资料的处理提出了更高的要求，要求保幅，即要求在处理流程上尽量不用破坏相邻地震道间振幅关系的模块。针对岩性油气藏勘探中的地震处理问题，本书提出了相对保真处理方法，即宽频相对保真处理的 4 条关键原则：(1) 保护有效频带。有效频带的拓宽要以资料的信噪比为依据，对低信噪比地震资料进行高频拓宽，要控制反褶积算子的频带宽度和主频，反褶积的主要作用应该是在有效频带内提升高频成分的能量，要避免在有效频带高频端出现严重陷频。(2) 保护低频，尤其是 3～8 Hz 的低频。要避免出现如高分辨率高信噪比处理将 10 Hz 以下的低频信息压制掉、为消除面波采用强 f—k 去噪使低频段的有效信息大量损失等情况。(3) 保振幅。不采用 RNA 等修饰模块，要避免破坏地震道振幅的横向关系。(4) 保相位。处理中不采用破坏相位关系的模块，零相位反褶积和地表一致性反褶积不会破坏相位关系。相对保真处理的剖面与高分辨率高信噪比处理的剖面相比，较真实地反映了地下砂体储层地震响应。本书在讨论相对保真处理或高分辨率高信噪比处理方法时，还考虑了地震资料采集方式对地震处理的影响。地震宽频采集是相对保真处理的基础。本书根据剖面反射特征和频谱特征，分析和讨论了地震采集震源和观测方式对高分辨率高信噪比方法处理的资料或对相对保真方法处理的资料的影响。

在以往的地震勘探实践中，为了满足构造解释需求，地震资料成像追求了信噪比，对资料的保真度和保幅性考虑较少。如今，随着油气勘探精细化程度的推进，地震资料成像处理的保真度要求越来越高。近几年，笔者在这方面开展了大量的研究工作，逐步形成了保真成像的研究思路及方法流程。

本书在对地震资料的相对保真处理方法进行研究的基础上，详细介绍了基于射线理论的 Kirchhoff 积分偏移方法和基于波场延拓的单程波偏移及波动方程逆时偏移的方法原理，并介绍了各自保幅偏移算法的研究进展。本书对基于

GPU/CPU 系统复杂构造逆时偏移成像、复杂构造区深度域速度建模等一些关键技术方法做了介绍，并从三维逆时叠前深度偏移在盐下成像、碳酸盐岩地区的高密度全方位地震资料处理、吐哈与酒泉盆地复杂构造地震成像、冀东南堡古潜山构造带的地震叠前成像等实际应用方面介绍了不同领域的针对性保真成像处理措施及应用效果。针对这些地区存在的地震成像、构造解释等技术难点，开展了地震叠前成像及解释一体化的深入研究，形成了针对性的地震叠前成像技术系列。

对于成像方法来讲，目前常规的积分法地震成像方法难以刻画盐下成像，而双程波动方程偏移（WEM）方法可在复杂深层盐构造上产生优质图像。本书采用逆时偏移成像技术解决了盐下成像问题，对垂直断层、盐丘侧翼、盐丘等倾角较大的构造成像效果显著提高，消除了盐丘速度异常对下伏地层造成的畸变，使盐下地层在深度域能够准确成像。本书针对碳酸盐岩地震资料开展了高密度全方位的成像技术研究，形成了高密度全方位地震资料的叠前成像技术流程，其中的关键技术包括：高保真全方位噪声压制技术、叠前提高纵向分辨率技术、全方位数据规则化技术、全方位高精度偏移速度建模技术、分方位角叠前深度偏移技术、各向异性叠前深度偏移、逆时偏移技术等。以逆时偏移为主的叠前深度偏移结果准确地刻画了复杂区块的地下构造形态及断裂位置，尤其是能够更加清晰地刻画背斜腹部断块、小断距断层，从而为构造解释提供了可靠的资料基础。利用新的叠前深度偏移成果进行精细构造解释，储层预测等综合研究，重新落实了研究区的构造细节，进一步认识了断裂特征以及地层展布规律。本书还将非对称走时叠前时间偏移和逆时叠前深度偏移相结合，很好地解决了横向速度变化对成像的影响，在构造复杂、倾角大的地方成像效果要优于以前的研究成果，取得了明显的成像效果，最终处理成果也很好地体现了各种地质特征，值得推广应用。目前从理论上讲，三维逆时深度偏移是最为精确的成像方法，这是叠前深度偏移成像技术发展的必然。它与 FWI 速度估计方法相结合是精确成像的发展方向。

本书在研究过程中，坚持科研与生产紧密结合，及时地将研究形成的针对性技术系列应用于油田勘探实践，利用新的研究成果，精确落实了一批区块的整体构造形态和局部构造特征，优选了有利钻探目标，取得了较好的应用效果。

本书前言由王西文执笔；第 1 章由王西文执笔；第 2 章由吕彬、王宇超、韩令贺执笔；第 3 章由王宇超、刘文卿、王小卫、徐兴荣、吕彬、曾华会、鲁烈琴、赵玉莲执笔；第 4 章由刘文卿、王西文、吕彬执笔；第 5 章 5.1 节由刘文卿、张静、邵喜春执笔；第 5 章 5.2 节由王小卫、田彦灿、张涛执笔；第 5 章 5.3 节由苏勤、肖明图、李海亮、吕彬、邵喜春执笔；第 5 章 5.4 节由田彦灿、

曾华会、张涛执笔。全书由王西文负责修改和统稿。

本书内容涉及的研究项目，得到了中国石油勘探与生产分公司、塔里木油田分公司、玉门油田分公司、吐哈油田分公司、冀东油田分公司、中国石油勘探开发研究院中亚俄罗斯研究所等单位的支持。本书的编写得到了中国石油勘探开发研究院西北分院杨杰院长等领导和专家的支持与帮助。在本书正式出版之际，谨向他们表示衷心的感谢！

由于编写者水平所限，书中一定存在不妥之处，诚恳希望广大读者批评指正。

Preface

In recent years, lithology reservoir has gradually become the major field of reservoir gain in China, while the lithology analysis poses high requirements for amplitude preservation of seismic migration results, but the previous prestack depth migration methods mainly focus on structural imaging. Therefore, a lot of study has been carried out in terms of amplitude preservation prestack depth migration method by the circle of geophysics. Meanwhile, the reservoir of lithology formation is under the control of multiple factors such as regional structures and depositional facies belts and representing high exploration difficulty due to its being complicated and concealing. On seismic profile, the display reliability of seismic response of lithology formation is subject to the fidelity of seismic processing.

Currently, it is difficult to realize absolute seismic fidelity preservation processing, but relative fidelity preservation processing is possible, which poses higher requirements for seismic data processing, requesting amplitude preservation, i. e. it shall avoid adopting the module that will damage the amplitude relationship of neighboring seismic channels in the processing procedure. In view of the seismic processing problem of lithology reservoir exploration, relative fidelity preservation processing method is represented in this book, i. e. the 4 critical principles for wide-frequency relative fidelity preservation processing (1) protection of effective band. The widening of effective band shall be based on SNR of data, high-frequency widening shall be conducted for the low SNR seismic data, the band width and dominant frequency of deconvolution operator shall be controlled. The main effect of deconvolution shall be the elevation of energy of high-frequency component within the effective band to avoid the occurrence of serious notching in the high-frequency end of effective band. (2) Protection of low frequency, especially that of 3～8 Hz. The scenarios that low frequency information suppressed due to high resolution, high SNR processing or significant loss of low frequency end effective information with adoption of strong *f-k* denoising etc. shall be avoided. (3) Amplitude preservation. Modification module such as RNA shall not be applied to avoid damaging the lateral relationship of seismic channel amplitude. (4) Phase preservation. The module that will damage phase position shall be avoided during processing. Zero phase deconvolution and surface consistent deconvolution will not damage relationship of phases. Compared with high-resolution high SNR processed profile, relative fidelity preservation processed profile could reflect seismic response of subsurface sand reservoir quite genuinely. While the discussion on the processing method of relative fidelity preservation processing or high-resolution high SNR, the impact on seismic processing by acquisition mode of seismic data is also elaborated in this book. Seismic broadband acquisition is basis for relative fidelity preservation processing. Based on profile reflection traits and spectrum characteristics, the impact on the data processed with high-resolution, high SNR method or data processed with relative fidelity preservation method by means of seismic acquisition source and observation approach is also analyzed and discussed.

In the previous seismic exploration, in order to satisfy the requirements of structural interpretation, SNR was given much more attention for seismic data imaging and the consideration for fidelity and amplitude preservation of data was insufficient. Nowadays, with the promotion of deliberation of oil and gas exploration, the requirements for fidelity of seismic data processing is much higher. In recent years, the author has done a lot in this aspect and the research idea and methodology for fidelity preservation imaging are gradually formed.

Based on study on relative fidelity preservation processing method, the method & principle of the Kirchhoff integral migration method based on ray theory, the one-way wave equation migration based on wave field extrapolation and two-way wave equation reverse time migration are elaborated. Meanwhile, the study status of respective amplitude preservation migration algorithm is introduced. The methods of critical technology including reverse time migration imaging based on GPU/CPU system for complicated structures and depth domain velocity modeling for complicated structural zone etc. are represented. In the mean time, the pertinent fidelity preservation imaging processing measures and application performance applied in practice for different fields including subsalt imaging of 3D prestack reverse time migration, high density, all-round seismic data processing for carbonate region, seismic imaging for complicated structures in Tuha and Jiuquan Basins, seismic prestack imaging of buried hill structural zone in Nanpu of Jidong Oilfield. In view of the technical difficulties of seismic imaging and structural interpretation etc. existing in these regions, in-depth study on seismic prestack imaging and integrated interpretation is carried out with the formation of pertinent technical series for seismic prestack imaging.

In terms of imaging method, it is difficult for the current regular integral seismic imaging method to delineate subsalt imaging, while the two-way wave equation method (WEM) could generate premium image for complicated deep salt structure. The reverse time migration imaging technology adopted in this book solves the problem of subsalt imaging, which significantly improves the imaging quality for the fairly large dip structures such as vertical fault, salt dome flank and salt domes etc. , eliminating the distortion caused to the underlayer by abnormal velocity of salt dome, making the subsalt formation capable of being accurately imaged in depth field. Study on high density all-round imaging technology in terms of carbonate seismic data is carried out in this book with the formation of prestack imaging technical flow for high density all-round seismic data, of which the critical technologies are: high fidelity all-round noise suppression technology, enhancing prestack vertical resolution technology, all-round data regularization technology, all-round high accuracy migration velocity modeling technology, sub-azimuth prestack depth migration technology, anisotropic prestack depth migration as well as reverse time migration technology etc. The results of prestack depth migration dominated by reverse time migration accurately delineates the subsurface structural pattern and location of fault for complicated block, especially capable of clearly delineating abdominal block of anticline, small displacement fault and consequently, providing reliable basis of data for structural interpretation. By utilizing results of new prestack depth migration, comprehensive study such as fine structural interpretation and reservoir prediction is conducted, structural details in the study area is reconfirmed, and the fault characteristics as well as the regularity of formation distribution is further understood. In this book, also the asymmetrical traveltime prestack time migration and prestack reverse time migration are combined, which solves the impact on imaging for lateral velocity variation well. Where the structures are complicated and the dip is large, the performance of imaging is much better than the previous results of study and the final processing results represent various geological characteristics, which is worth popularization quite well. Currently, theoretically, 3D reverse time depth migration is the most accurate imaging method, which is surefire result of development of prestack depth migration imaging technology and being the direction of development for accurate imaging when combined with FWI velocity estimation method.

During the study for this book, the R&D was closely integrated with production and pertinent technical series formed during study was applied for oilfield exploration timely. With the application of new study results, the overall structural pattern and local structural characteristics of a series of blocks were accurately confirmed and favorable targets of exploration and drilling were optimally selected with the achievement of excellent application performance.

The preface is by Wang Xiwen; Chapter 1 by Wang Xiwen; Chapter 2 by Lv Bin, Wang Yuchao and Han Linghe; Chapter 3 by Wang Yuchao, Liu Wenqing, Wang Xiaowei, Xu Xingrong, Lv Bin, Zeng Huahui, Lu Lieqin and Zhao Yulian; Chapter 4 by Liu Wenqing, Wang Xiwen and Lyu Bin; 5. 1 of Chapter 5 by Lv Wenqing, Zhang Jing and Shao Xichun; 5. 2 of Chapter 5 by Wang Xiaowei, Tian Yancan and Zhang Tao; 5. 3 of Chapter 5 by Su Qin, Xiao Mingtu, Li Hailiang, Lv Bin and Shao Xichun; 5. 4 of Chapter 5 by Tian Yancan, Zeng Huahui and Zhang Tao. The whole book is modified and revised by Wang Xiwen.

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Due to the proficiency of the author, comments and questions in terms of contents of the book are warmly welcome.

目　录

contents

1 地震资料相对保真处理方法研究

1.1 引言

岩性地层油气藏受区域构造和沉积相带等多重因素控制，具有一定的分布规律和较大勘探潜力，但由于其隐蔽复杂，勘探难度相对较大。我国岩性地层油气藏近年来取得一批大突破和大发现，剩余资源潜力大，是增储上产的重大现实领域[1~4]。

为了有效识别岩性油气藏，对地震资料的处理提出了更高的要求[5~7]。首先，要提高地震资料的分辨率，要求在处理出的地震资料上识别薄砂层、砂体尖灭点等地质特征；第二，要求保幅，在处理流程上尽量不用破坏相邻地震道间振幅关系的模块。但是，人们往往在识别薄层上很下工夫，不断拓宽地震资料频带，提高主频，出现了多种以提高地震主频为目标的高分辨地震处理方法。

提高地震资料分辨率的处理，主要由反褶积方法完成[8~19]。反褶积方法是地震资料处理过程中的重要手段。为了提高地震资料的分辨率，可以设计高频反褶积算子，以达到分辨薄层的目的。但是，高频反褶积算子的频宽和主频由什么原则来确定，是不是可以不加限制地提高高频反褶积算子的主频，这都是需要探讨的问题。

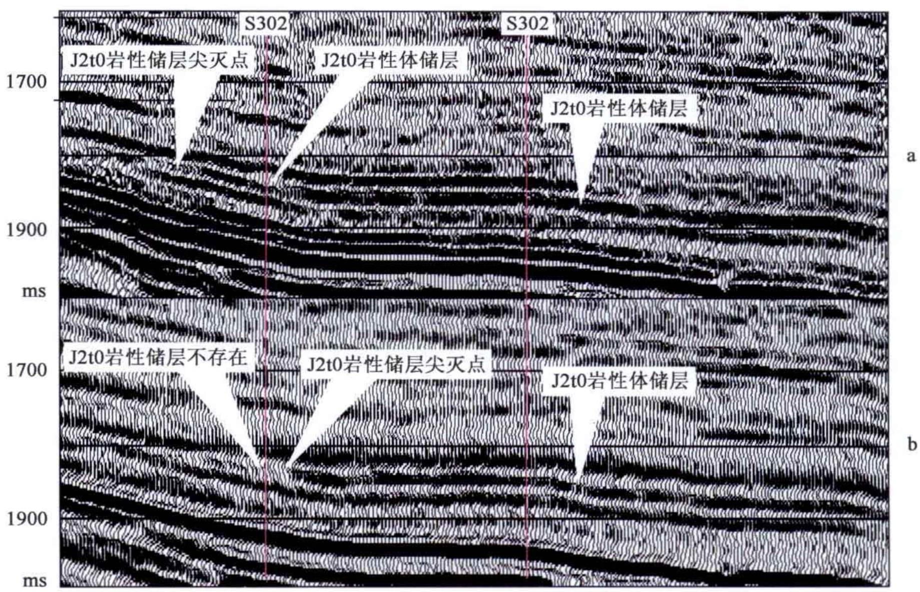

图 1.1.1　过 S302　S303 井的常规（a）地震处理剖面与相对保真（b）地震处理剖面对比

图 1.1.1 是在准噶尔盆地陆西地区的过 SN31 井区岩性油气藏的地震处理剖面对比。图 1.1.1a 采用的是高分辨率、高信噪比地震处理技术。从所示的地震剖面上解释出了 SN31 井

区 J2t0 的岩性储层（通过钻井也证实了是砂岩岩性储层），但从剖面上看，SN31 井区 J2t0 岩性储层连续性好（图中标示所示，在 S302 井位置，向储层上倾方向延伸了 1km 以上，岩性储层才尖灭），为此，在这一整装岩性油藏部署了一批井，图中剖面上所示的 S302 井，S303 井也是其中的井，但是钻探效果存在着很大差异。S303 井储层好，是高产油井；但是 S302 井储层很差（岩性发生变化，J2t0 层以泥岩为主）。

因此，对图 1.1.1 上的数据进行了分析，认为这是由于处理过程中过分地强调了高分辨率、高信噪比，使处理结果的保真度变差，直接导致在地震剖面上反映岩性储层地震响应失真。

在地震剖面上，岩性储层地震响应显示的可信度取决于地震处理中的保真度。目前，绝对地震保真处理是难以做到的，但是相对保真处理是可以做到的。图 1.1.1b 是 2006 年根据图 1.4.1 流程重新处理出的相对保真剖面。在图中明显看出，在 S302 的位置 J2t0 岩性储层反射很弱，表示储层已不存在。在地震剖面上识别出的 J2t0 岩性储层尖灭点位于 S302 井位置岩性储层下倾方向近 300m，这与已完钻 S302 井的数据相吻合。

这就提出了一个问题，在岩性油气藏勘探中，地震资料处理是关键。只有最大限度将储层物性的地震响应真实地反应到地震处理后的剖面上，才能利用地震数据有效地识别岩性储层。

针对上述问题，在准噶尔盆地石东地区，选一条过石东 2 井、石东 4 井的 8km 二维高分辨率攻关试验线，分析了高分辨率、高信噪比处理和相对保真处理的结果，提出了地震资料相对保真的处理方法。

相对保真地震资料处理[5]包括以下几个方面：(1) 保护有效频带。有效频带的拓宽要以资料的信噪比为依据，对低信噪比地震资料进行高频拓宽，要控制反褶积算子的频带宽度和主频，反褶积的主要作用应该是在有效频带内提升高频成分的能量，要避免在有效频带高频端出现严重陷频。(2) 保护低频，尤其是 3～8 Hz 的低频。要避免出现如高分辨率高信噪比处理将 10 Hz 以下的低频信息压制掉、为消除面波采用强 $f-k$ 去噪使低频段的有效信息大量损失等情况。(3) 保振幅。不采用 RNA 等修饰模块，要避免破坏地震道振幅的横向关系。(4) 保相位。处理中不采用破坏相位关系的模块，零相位反褶积和地表一致性反褶积不会破坏相位关系。相对保真处理的剖面与高分辨率高信噪比处理的剖面相比，较真实地反映了地下砂体储层地震影响。

在讨论相对保真处理或高分辨率高信噪比处理方法时，不能忽略地震资料采集方式对地震处理的影响。地震宽频采集是相对保真处理的基础。在地震试验测线上，从剖面反射特征和频谱特征分析和讨论了地震采集震源和观测方式对高分辨率高信噪比方法处理的资料或对相对保真方法处理资料的影响。

1.2　关于地震采集震源和观测方式对高分辨率高信噪比处理的讨论

图 1.2.1 是准噶尔盆地石东地区白垩系清水河组砂层底界的等 t_0 图，位于石东 2 井井区和石东 4 井井区黄色区域清水河组油层的分布范围，但从以往的地震资料上很难解释这两口井之间的储层分布特征。为此，2002 年部署了过石东 2 井和石东 4 井的地震试验测线（蓝色线），目的是研究提高野外地震数据采集质量的方法，以满足岩性油气藏勘探的需要。

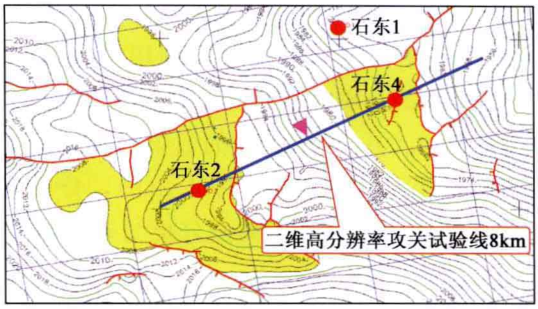

图 1.2.1　石东地区白垩系清水河组砂层底界等 t_0 图

过石东 2 井和石东 4 井的地震试验测线长 8km，采集因素为：(1) 单井激发，激发井深为 85～139m，单井药量 4kg，井数 1 口，总药量 4kg，炮距 5 0m，1200 道接收，道距 5m (或 240 道接收，道距为 25m)；(2) 组合井激发，激发井深为 6m，单井药量 2kg，井数 10 口，总药量 20kg，炮距 50m，1200 道接收，道距为 5m (或 240 道接收，道距为 25m)；(3) 可控震源激发，震源台次 4 台×6 次，扫描频率是 8～90Hz，炮距 25m，300 道接收，道距为 25m。采用高分辨率、高信噪比处理流程 (图 1.2.2) 对资料进行了提高分辨率处理，以弄清石东 2 井至石东 4 井之间清水河组油藏的分布特征。在处理流程中，为提高分辨率采用了叠前和叠后两次零相位反褶积；为提高信噪比采用了随机噪声衰减修饰处理。

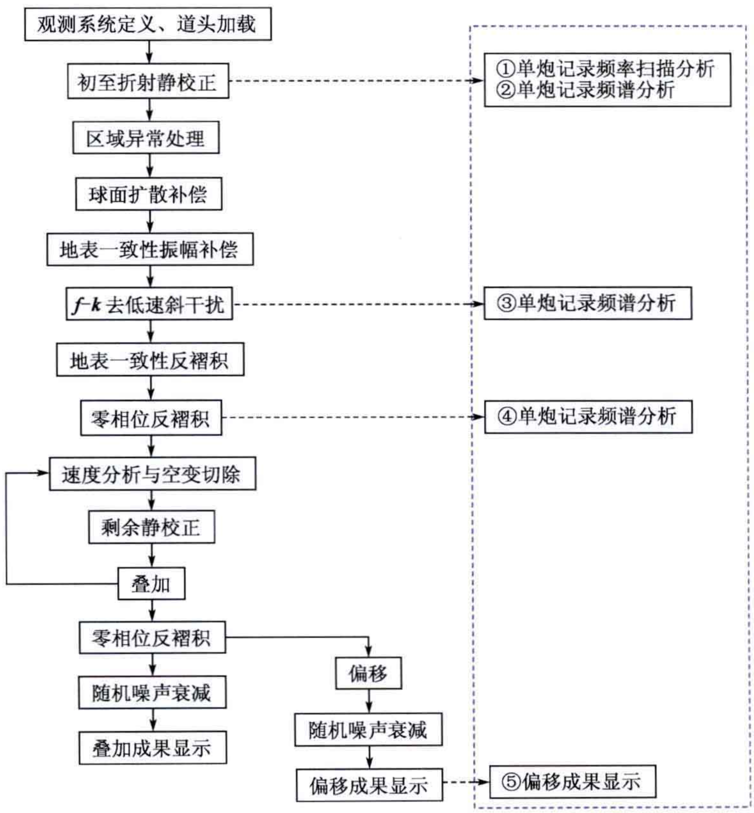

图 1.2.2　高分辨率、高信噪比地震资料处流程