

第567次香山科学会议·各向异性地球物理与矢量场技术



各向异性地球物理与矢量场

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摘要 地球介质电阻率、极化率、速度和品质因子等物理性质的各向异性是广泛存在且被证明不可忽视的, 因此, 在地球学和固体地球电磁场研究中, 各向异性问题的讨论由来已久, 且是最近十多年来的前沿领域与热点。最近几年随着信息技术的快速发展, 以及地球物理从一维到二维、三维和不同高度的矢量、立体张量观测技术的发展, 使得研究更复杂的各向异性介质及地球物理响应矢量数据的发掘和应用成为可能, 从而给现有的地球物理理论、方法和技术带来了严峻的挑战。尤其信息科学领域云计算技术和大数据研究与应用的蓬勃兴起, 大量地球物理观测数据的利用和共享成为一种发展趋势。第567次香山科学会议“各向异性地球物理与矢量场技术”旨在通过对国内外各向异性地球物理和矢量场前沿研究的介绍、分析, 会同后续云计算、地震学与矢量地球物理场观测仪器与技术3篇专业文章的详细展开, 发掘、总结各向异性理论方法与矢量场研究中急需解决的关键科学和技术问题, 以促进基础性、共性问题的攻关与探索。

关键词 各向异性, 电磁, 地震, 矢量, 大数据

早在18, 19世纪, 地球科学工作者就发现了地球介质弹性和电性各向异性的存在^[1~3], 对于各向异性介质的研究在20世纪获得了广泛的关注^[4~12]。尤其大量岩石物理实验证明, 一些岩石的弹性和电性各向异性已达到了不可忽略的程度^[13~24], 地球介质各向异性研究也已成为解决多尺度复杂地球科学问题的重要手段, 同时推动了各向异性理论与观测技术的快速发展^[25~34]。20世纪末期地球物理矢量场观测仪器与技术成本的降低, 大规模的观测实验和室内并行计算技术等的应用, 使得研究复杂各向异性介质成为可能, 在青藏高原等深部结构、圈层划分、地球

动力学等科学研究和油气、煤田、矿产资源勘探领域产生了一些有益的尝试和应用^[35~39]。

随着电子工业和信息技术的发展, 地球物理观测仪器与技术正在向低成本、大规模、海量数据与长时间连续观测的方向发展, 使得现有的、基于各向同性、串行式的、标量场的地球物理理论和方法技术受到挑战, 也给研究更复杂的地球介质及其物理场的变化提供了深入发展的契机。如何在越来越多的海量、并行、分布式地球物理数据的基础上, 发展更符合地球介质客观实际的各向异性理论与矢量数据解译技术, 为更精细地解剖深部地球结构与物性变化

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提供理论与技术支撑,并进一步推动基于网络、云、大数据的矢量地球物理场的理论模拟、反演和分析技术发展,将成为未来地球物理学科发展面临的机遇与挑战.因此,在分布式数据采集的基础上,讨论利用矢量地球物理场数据反演地球介质各向异性结构的可能性及存在的关键科学与技术问题是当务之急.其重点在于讨论:在更复杂的、更逼近地球介质真实情况的各向异性条件下,地震波场与电磁场的传播特征及矢量观测模式下所可能引发的、需要我们面对的基础理论革新和关键技术储备.第567次香山科学会议“各向异性地球物理与矢量场技术”从电性和地震各向异性介质模型和地球物理场响应基础理论的角度讨论现有地震学与固体地球电磁学理论和技术的局限性,以及由矢量场观测推动的新理论、新方法和新技术的发展方向.

1 地震各向异性与多分量地震波场

1.1 勘探地震各向异性与多分量地震波场

中国改革开放以来30多年的经济持续快速增长有力地推动了油气、煤炭等能源勘探的发展,也带动了地震各向异性理论与多分量地震技术在该领域的实验和应用^[40].尽管中国的地震各向异性理论研究和多波地震实验起步较晚^[11],但30多年来科研院所和企业联合攻关使得中国在地震各向异性基础理论方面已经跟上了国际水平;在多分量地震技术所涉及的仪器、采集、数据处理与解译等技术和软件方面异军突起,尤其在陆地多分量地震技术应用及软件系统方面已走在世界的前沿^[41].例如,在中国的各个油气田已累积采集了近5000 km²的三维三分量地震数据;海洋四分量地震数据更是高达10000 km²,且四分量采集已经成为海洋地震勘探的常规手段,多波地震数据的使用使得地震解决地质问题的能力有了很大的提高^[42].

但同时也应该看到,现有的地震各向异性理论针对中国复杂的地质构造和复杂多变的应用条件还存在诸多的不适应性,需要进一步深入研究.例如除地震速度各向异性外,其他弹性模量的各向异性、品质因子及其频散效应的各向异性研究尚需要拓展;针对不同构造期次所形成的不同方向、不同尺度断裂和裂缝的叠加及其分离识别问题,现有的各向异性理论尚难以解决;基于慢纵波的双相或多相介质各

向异性理论仍然缺乏有效、适用的理论模型,尚难以直接应用于流体的检测.地震各向异性理论研究与实际应用间尚存在较大的空间,需要结合中国实际地质情况进一步加大应用试验、开发的力度.

虽然中国多分量地震解译的软件技术已获得长足的进步,但相对于目前成熟应用的纵波地震技术,多分量地震数据处理、解释、反演尚有很多的关键技术需要突破.尤其针对深海环境的多分量地震数据的充分利用,尚需要突破半空间和固体介质假设,在考虑海洋流体动态变化的条件下发展高精度的定位、波场重建和矢量数据利用技术.而进入21世纪以来,蓬勃发展的漂缆与拖缆、垂直缆等多缆多分量数据的联合应用,深海海底地震系统(ocean bottom system, OBS)、海底地震节点(ocean bottom node, OBN)、海底电缆(ocean bottom cable, OBC)等不同采集方式及其数据的综合利用,勘探和开发地震中广泛使用的四分量时移地震、垂直地震剖面(vertical seismic profiling, VSP)技术等所形成的海量、实时、矢量地震数据给地震解译与信息发掘提出了更严峻的挑战.这种挑战不仅仅表现在现有地震理论发展的滞后性方面,而且也会给现有的、建立在串行通讯、作坊式制造基础上的、封闭的地震技术研发与应用体系带来冲击.但同时也应该看到,这也是中国占领未来矢量地震技术制高点的发展契机.

1.2 各向异性介质条件下的天然地震与微震

地震各向异性的研究最早起源于天然地震领域的探索^[9,43].就地壳和地幔尺度而言,地表接收到的地震观测信号中叠加了不同深度介质层的地震信号,可以从地表观测分析中得出不同深度的各向异性特征;而在相同层位的地震波里,还可以提取到构造、断裂和应力及其变化的信息(图1),已有的大量研究已经揭示了这些现象^[45~50].尽管人工压裂所产生的微震信号在能量量级和频率特征上与天然地震存在差异,但基本理论模型和震源函数的差异主要体现了研究目标尺度和范围的变化.在天然地震和人工压裂微震研究中,各向异性介质对于地震信号产生、传播的影响是类似的,需要着重考虑的是不同尺度裂缝、断裂的频率响应效应.而Crampin等人^[45,51]、Gao和Crampin^[52,53]关于应力积累和应力释放的实验所揭示的现象,从实验室物理机制上反映了微震与天然地震研究的共性,也为不同尺度各向异性研究

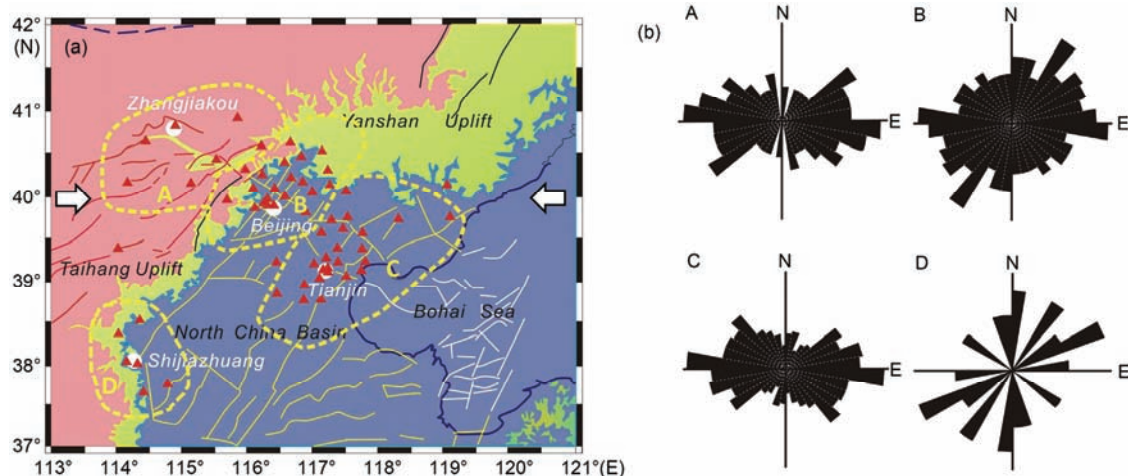


图1 华北地区区域构造和等面积投影玫瑰图。(a) 华北地区区域构造(黄色实线)和主应力方向(白色箭头); (b) 快波偏振方向的等面积投影玫瑰图具有良好的对应性, 其中A~D分别对应(a)中的4个分区。华北地区由横波分裂获得的快波偏振优势方向与区域构造和主压应力方向的对比呈现了良好的一致性^[44]

Figure 1 Regional tectonics in North China and superimposed equal-area rose diagrams. (a) Predominant polarizations of fast shear-waves in North China indicating the regional tectonics (yellow solid lines) and principal compressive stress direction (white arrows); (b) superimposed equal-area rose diagrams corresponding to the zone marked A, B, C and D in dashed lines in (a)^[44]

的关联提供了物理基础。在油田的微震监测中, 利用横波分裂分析也发现了浅层地壳的各向异性呈现出与来自天然构造地震信号里提取的中上地壳各向异性类似的结果。如在英国北海油田, 依据井间记录观测到的结果反映了地壳里的各向异性具有小区域的空间分布^[54](图2), 这种区域分布特征与更大尺度的天然地震资料分析结果一致^[46~48,50]。研究者在同样的微震事件资料中, 还发现了横波分裂随时间变化的证据, 并认为这些观测与应力控制的微破裂有关, 反映了应力场的变化, 这个结果与天然地震的结果同样非常吻合^[51~53]。

在资源开发应用研究中, 随着油气田开发后期压裂微震监测的大规模应用以及地震固定、流动台站等观测技术的发展和海量数据的获得, 给系统研究不同深度、不同尺度各向异性及其发育程度以及地应力场的定量预测提供了客观条件, 也需要各向异性研究领域从全空间各向异性介质条件下微地震的发生、地震波传播过程的物理与数值模拟、野外联合观测研究出发, 既解决微震定位精度问题, 也为大尺度的地震动力学研究和地震预测提供更有力的解决方案。

2 电性各向异性与矢量电磁场

中国对于电性各向异性的研究与地震类似, 均起步20世纪80年代, 相对发展较快的时期是20世纪

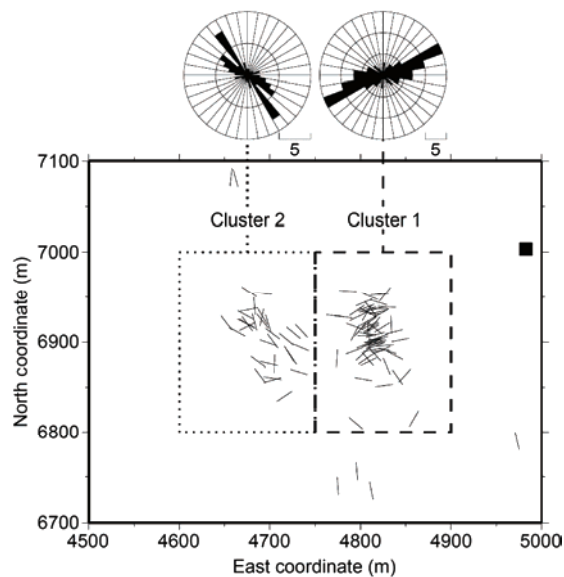


图2 两个相邻区域微震观测资料横波分裂揭示快波偏振方向存在差异性^[54]。快波偏振方向等面积投影图对应两个区域里的微震事件

Figure 2 Predominant polarizations of fast shear-waves from microseisms in North Sea indicating spatial difference between two close zones^[54]. Two equal-area rose diagrams are corresponding to two zones of microseismic events

末和最近十几年。但这些研究大多分布在地球深部和天然地震预报领域^[55,56], 也以电性各向异性正演模拟和电磁异常的解译为主^[57~65], 在资源勘查领域应用较少。自21世纪以来, 陆地与海洋、地面与空中、

井中与地下等不同观测方式和矢量场采集技术的快速发展,进一步推动了电各向异性理论和方法技术的研究^[66~69],并带动了各向异性观测和反演的起步;并行计算技术的发展也给电各向异性的研究提供了有力工具,使得三维正演模拟精度和计算速度得以极大提高,矢量场数据的处理和各向异性参数反演具备了快捷高效的平台,也引起领域研究的广泛关注,取得了一系列的成果^[70~73];同时引导着电磁、地震向一体化观测和联合反演的方向发展^[74,75].

但针对强电性各向异性介质,如图3所示,急需从三维各向异性正反演和观测的角度论证各向异性对电磁场传播的影响程度,厘清不同尺度各向异性的响应机理,从而发展更好体现宏观各向异性特征的张量场观测技术.国内外相关研究表明,为分辨和解释地下介质的电各向异性,电磁多分量方位观测及张量观测技术必不可少^[58,60,61].

3 矢量场观测的意义

物体在空间具有6个自由度,即沿迪卡儿坐标系X, Y, Z三个直角坐标轴方向移动的平动自由度和绕3个坐标轴旋转的转动自由度.当前地震领域应用的多分量检波器,只记录了垂直和水平平移分量地震

数据,而没有采集转动自由度分量,使得记录的地震波矢量场信息不够全面,影响后续的数据处理.斯坦福大学(Stanford University)近10年来一直倡导除目前采集的线性运动三分量数据外,进行3个旋转分量数据采集与应用的重要性,并进行了可行性的研究^[77]. Barak等人^[78,79]在常规海洋四分量地震记录压力和迪卡儿坐标系下3个方向的线性位移振动的基础上,强调增加3个分量的、记录质点旋转运动的旋转检波器的重要性;通过一个简单的水下散射体的波场模拟,如图4所示,说明了七分量记录的地震波场对于有效地描述不同类型波的振动轨迹,恢复波场的空间矢量特征的意义;并从去噪的角度阐释了利用七分量记录去除面波和折射波的方法和技术优势.

美国地调局曾在尼加拉瓜近海做过一次地震与电磁的联合观测^[80],如图5所示.观测期间适逢一次M5.4地震的发生.观测数据中所发掘出的有趣现象——磁场与地震振动的相似性,如图6所示,说明这种观测与研究的意义不仅仅在于天然地震预报可从地震波和电阻率两个角度展开^[55,56],并相互印证,矢量观测的应用也使得不同场信号间的相互转化成为可能.同时我们也应看到,在复杂的深海海洋环境调查中,在现代传感器、互联网+技术的支持下,综合地震、EM调查进行系统研究的重要性,以及地震与电磁联合的可能光辉前景^[81].

4 云技术与地球物理大数据

云技术与大数据是信息科学领域近些年的研究热点^[82~84].基于传感器和互联网+模式的云计算与大数据的融合发展对未来地球物理领域的技术走向是有现实启示意义的^[85,86].海量地球物理数据与互联网行业的大数据都具有数据规模大的特点,但不完全具备一般意义上的大数据4V(数据容量大(volume)、数据类型多(variety)、数据商业价值高(value)、数据处理速度快(velocity))特点;且由于地球物理数据处理分析是基于特定的数学物理模型,一般大数据分析云计算技术不能简单搬到地球物理领域,因此,地球物理领域的云计算与大数据技术需要结合地球物理应用展开针对性的探索和研究.

21世纪以来信息技术发展所带来的陆地、海洋、空天不同观测方式的并存与相互约束,以及不同维度、不同场的矢量信息间的相互关系,实时动态信息的采集、传输和实时处理分析,不仅仅要求未来地球

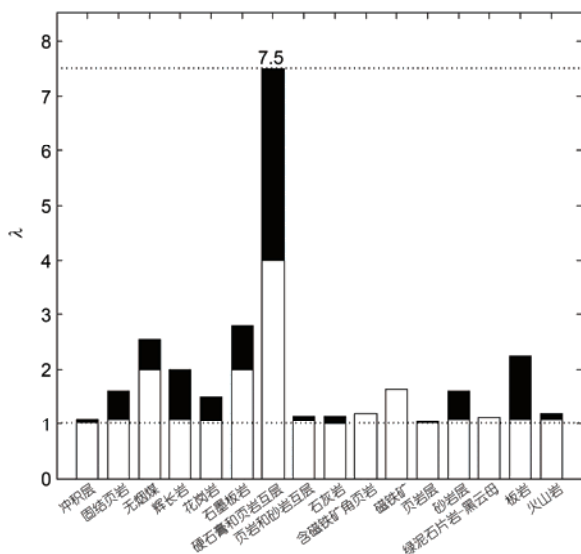


图3 实验室测定的一些岩石和岩层的电阻率各向异性系数.纵坐标为电阻率各向异性系数,定义为垂直层理方向和沿层理方向电阻率比值的平方根^[76]

Figure 3 Electrical anisotropic coefficients of rocks and formations measured in laboratory, which are defined as the square root of the vertical and horizontal resistivity ratio^[76]

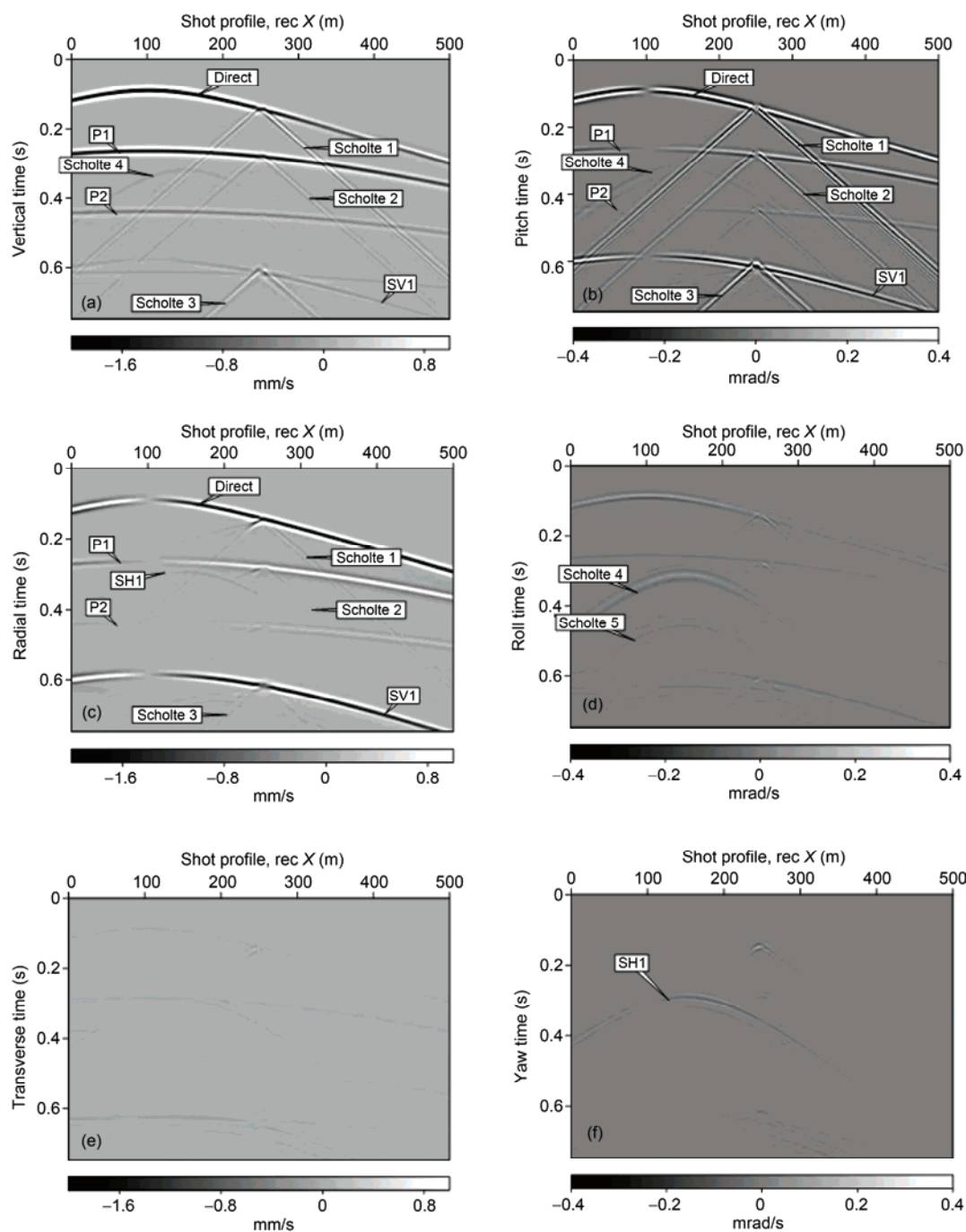


图4 数值模拟线性与旋转六分量炮记录对比。(a), (c), (e)为X, Y, Z方向平动三分量记录; (b), (d), (f)为沿Y, X, Z轴旋转的旋转记录^[78]

Figure 4 Numerical simulations of orthogonal linear and rotational 3-component seismic signals. (a), (c), (e) Translational shot records in X, Y, and Z axis; (b), (d), (f) the rotational records that rotated around Y, X and Z axis^[78]

物理探测技术需要紧密结合大数据与云技术, 还将以典型的不同空间维度、矢量特征、关系型结构、超高计算能力需求、PB级的I/O数据传输等特点给云技术在该领域的应用提出挑战. 为此, 国外一些大型的石油企业和地球物理、大数据公司已经启动了融合的

研究. 例如法国CGG公司与美国Teradata公司前些年启动了一个联合的大数据项目, 计划基于Hadoop大数据基础软件研发一个面向地震勘探领域的平台; 中国石油化工集团公司(中石化)自2011年开始了Hadoop技术在地震处理解释中的应用研究. 截至目

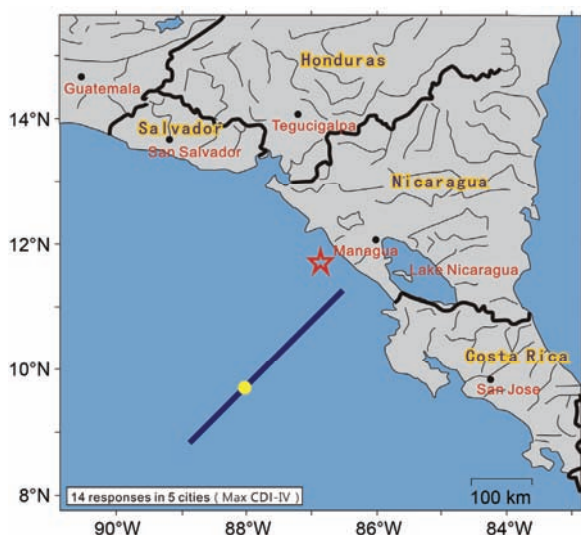


图5 美国地质调查局项目实施地点示意图。此图同时显示了发生在近尼加拉瓜海岸附近的一次M5.4地震的地震烈度。红色星号表示震中位置，蓝色线为EM测线，黄色圆点是三分量地震与EM的联测点^[80]

Figure 5 USGS report pertaining to the earthquake (indicated by the red star) that occurred during the SERPENT EM survey. The blue line indicates the EM ocean-bottom node lines, where the yellow dot is the position of the composite sensor which had a three-component translational geophone in addition to the EM sensors^[80]

前，中石化已搭建了基于Hadoop大数据技术、面向地震处理解释应用的数据管理平台，开发了适用于地震数字信号处理、全局性求解和迭代算法的并行架构，实现了地震常规处理、地震成像和地震反演的全并行化；面向全球市场发布了基于大数据技术的 π -Frame地震一体化软件平台；并进一步实现了面向软件生态系统^[87,88]的基础架构设计。

鉴于此，第567次香山科学会议还重点讨论了互联网+技术发展所带来的基于云的存储、计算策略在地球物理大数据领域应用的可能性与存在的问题，包括稀疏数据插值与冗余数据的压缩问题以及地球物理数据采集、处理、解释和反演技术可能发生的连锁响应与思路革命。

5 讨论与展望

第567次香山科学会议经过与会地球物理领域地震、电磁和信息技术领域专家的充分讨论，总体上形成如下的共识。

(1) 地震与电磁各向异性的研究是固体地球物理学的前沿和热点，也是学科发展的未来方向。在已有的各向异性理论、模型研究基础上，当前以及以后

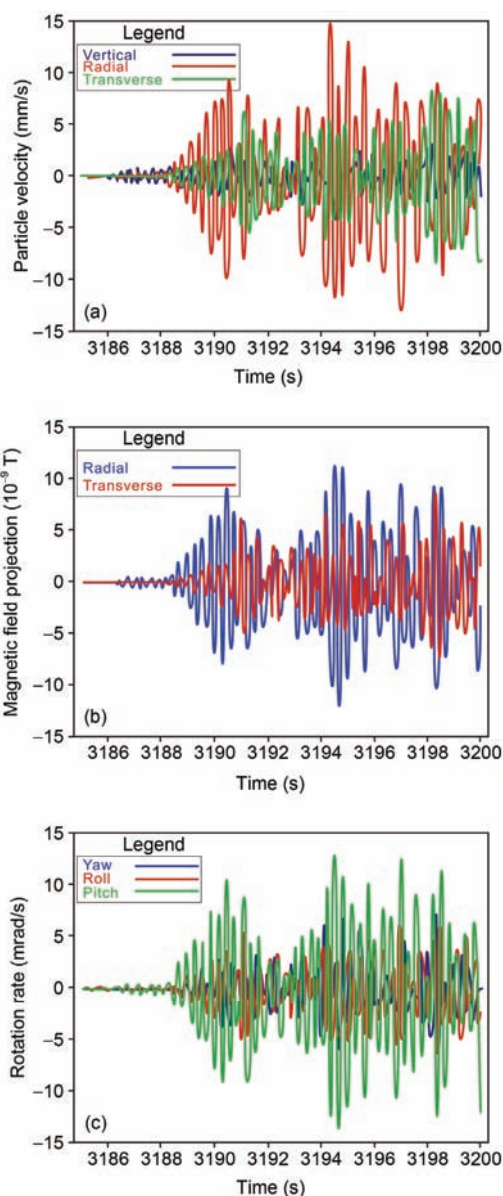


图6 调查期间发生的地震前14 s记录。通过旋转使切向分量最小化已对三分量地震记录进行了处理。(a) 记录的三分量振动速度；(b) 磁场在2个水平磁棒上产生的投影；(c) 通过二分量磁场水平分量换算得到的地震旋转分量^[80]

Figure 6 Data of the first 14 s of the earthquake that occurred during the SERPENT survey. Horizontal component data are rotated to minimize the energy on the geophone transverse component. (a) Particle velocity recorded by 3C geophone; (b) deviations in projection of magnetic field on 2C horizontal magnetometer components; (c) three components of rotation rate derived from the 2C magnetometer data. Note the strong amplitudes of the radial geophone component and how there is some correspondence between it and the pitch rotational component^[80]

相当长时间需要重点关注：电性和弹性各向异性产生理学及其关联性，从微观和宏观两种尺度进行各向异性的岩石物理实验、物理模型和数学模型的探

索,既要为地球物理的建模和反演服务,也要寻找地震各向异性之间可能的关联性,为电磁和地震的联合反演、解释提供理论依据;建立逼近真实地球介质的地球物理模型,开展不同尺度各向异性模型的电磁场与地震波场正演计算和物理模拟研究是地球物理学的核心,也是复杂矢量场解释的基础;矢量场的联合反演不仅仅可以使得我们获得地球介质更客观的认识,也将降低地球物理反问题的多解性。但针对中国复杂地球动力学条件的、适用于多期次构造运动所产生的多尺度各向异性及其频率响应特征等的各向异性模型与理论急需构建与发展。

(2) 现代传感和信息技术的发展已使地球物理矢量场的观测成为现实,也必将推动地球各向异性的研究进一步快速发展。各向异性地球物理研究依

赖于矢量场的观测,矢量电磁场与地震波场的充分利用也是逼近真实地球介质属性的唯一出路。但针对各向异性探测目标,矢量地球物理场的全息获取需要从观测和解译两个方面入手,着重解决低成本矢量场观测、矢量解译方法,重点是矢量分离与合成、矢量成像等关键技术问题,推动矢量场的观测与解译跨越现行的标量阶段。

(3) 充分运用现代互联网技术,突破现有地球物理观测静态模式,推动动态观测;改变现有数据存储与共享模式,形成数据的实时交互、互联互通;改变现有地球物理数据孤立封闭的处理模式,向开放、融合、联合、实时在线的方向发展;改变现有地球物理装备与软件技术的小作坊研发模式,向基于云和大数据的生态系统过渡。

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Summary for “各向异性地球物理与矢量场”

Anisotropic geophysics and vector field

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It has been proved that the physical anisotropies of earth medium, such as resistivity, electric susceptibility, velocity, and quality factor, et al., exist and can't be ignored. For this reason, researches on anisotropy began tens of years ago and now become a hotspot in the field of seismology and geo-electromagnetism in recent years. Promoted by development of information sciences and technology, especially driven by technological progresses of sensor, storage and communication of big dataset, the observations of geophysical field have been upgraded to 2- and 3-dimensional, multi-component vector and tensor measurements at different elevations and spatial sizes, such as 6-component seismic and 5-component MT acquisition provided the possibilities of anisotropic inversion and more precise prediction on physical parameters in geosciences. However, serious challenges have been faced by the traditional geophysics, just because the theoretical principles, methods and techniques of geophysics were built on the basis of scalar observation, and massive vector data are observed and their sharing and utilization become an incontrovertible trend. Thus, in this No.567 Xiangshan-Science Conferences, the progresses and problems in the study of anisotropic geophysics and vector field were introduced and analyzed according to 4 sections. First, different scale and types of vibrations from 6-component earthquake, 3-component seismic exploration and micro-seismic monitoring, and the relations in between are presented and discussed. Secondly, numerical simulations and inversions of resistivity anisotropy are given more discussions; especially on the non-uniqueness of anisotropic inversions for apparent resistivity, tensor observation and azimuthal acquisition were also addressed. Thirdly, the joint geophysical measurements from different altitudes, including well logging, underground geophysical prospecting, airborne and satellite geophysical observations are expected to be used on land, in the ocean and in the air. Finally, instruments of vector seismic sensing and tensor MT and CSAMT, processing techniques of vector signals and software system, communication and storage of big geophysical datasets, including advanced technologies on compressed sensing, were introduced respectively. All these presentations could not be covered in detail within one paper, though, the basic scientific and technological problems about computational geophysics, active or passive seismology, and anisotropic electromagnetism will be focused on, while the detailed discussions on different geophysical fields will follow in other papers, so that the issues on the fundamentals and generality of anisotropic geophysics could be studied extensively in the future.

anisotropy, seismology, magnetotellurics, vector field, big data

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