

西太平洋俯冲带岩石圈变形研究

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摘要 全球海洋岩石圈的最大弯曲与大地震发生在俯冲带。当弯曲应力超过岩石承受范围, 就会产生正断层和地震, 海水沿着正断层进入上地幔并发生蛇纹石化, 引发浅源地震并可能造成灾难性海啸。选取西太平洋最具代表性的日本、伊豆-小笠原、马里亚纳和雅浦俯冲带以及汤加-克马德克俯冲带, 归纳近些年的地球物理观测及地球动力学模拟的结果, 对比分析了不同俯冲带挠曲正断层的分布特征, 并探讨了俯冲板块变形与地震之间的相关性, 以揭示俯冲板片弯曲变形及相应的正断层与潜在板块水化特征。

关键词 板块弯曲; 弯曲正断层; 脆性破裂带; 板块水化; 西太平洋

俯冲带是地震和火山活动最频繁的区域, 也是地球内外物质与能量循环的主要场所。全球主要有 14 条活动俯冲带, 大部分位于太平洋板块周缘, 其中西太平洋俯冲带主要包括日本、伊豆-小笠原、马里亚纳、雅浦和汤加-克马德克俯冲带等(图 1(a))。大洋岩石圈在俯冲前缘发生弯曲, 形成地球最深的区域—海沟^[1], 当板块弯曲所积累的应力超过了岩石圈的屈服极限, 岩石圈就会发生破裂,

并形成正断层和相应的板内地震^[2-6](图 1(b))。这些正断层可将流体带至板块深部, 引起板块水化。俯冲带板块水化主要以地幔蛇纹石化的方式进行^[9]。这些水化的上地幔岩石随着俯冲作用被带至地球深部, 会随着温度升高、压力增大而发生脱水作用, 从而诱发中源地震^[4]。深部流体继续向上运移, 促使围岩熔点降低和熔融, 并在岛弧区释放至地表形成火山弧^[7-8]。通过研究俯冲板块的挠曲变

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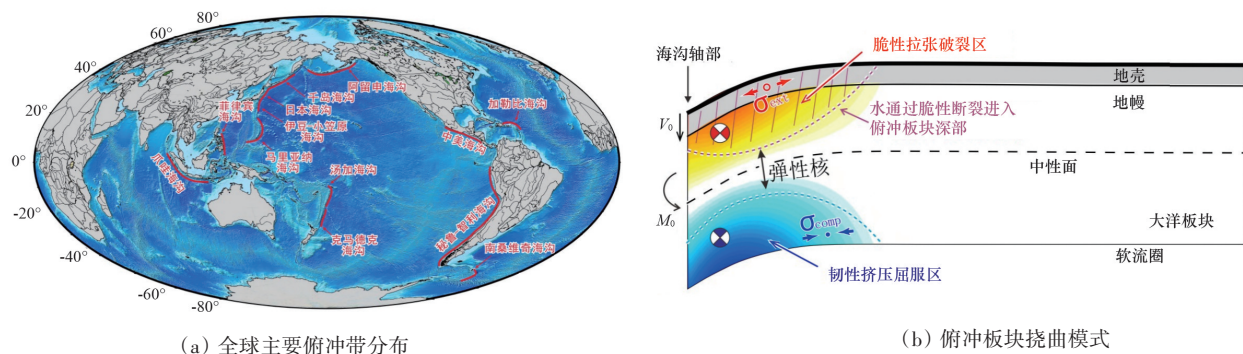


图1 全球主要俯冲带分布和俯冲板块挠曲模式

形、应力状态和破裂区分布,探究俯冲带地震规律和流体循环过程,是俯冲带动力学的重要研究方向之一^[9]。

1 西太平洋俯冲带深部结构与变形研究

西太平洋拥有古老的俯冲板块,其最老的板块形成于约距今 160 Ma(距今 1.6 亿年)之前^[10]。而根据大洋岩石圈冷却模型^[11],正常大洋的水深会随着板块年龄的增加而加深,因此,西太平洋俯冲形成的海沟深度普遍较深。近年来,随着海洋探测技术的提升,不少学者对西太平洋俯冲带深部结构和变形进行了研究。结果显示沿俯冲带走向,俯冲板块洋壳厚度变化不大^[12-15],但其挠曲形态^[16-17]、岩石圈有效弹性厚度^[18-19]和海沟轴部载荷^[5, 20-21]等构造参数均存在较大差异。

1.1 日本-伊豆-小笠原-马里亚纳俯冲带

日本-伊豆-小笠原-马里亚纳俯冲带是太平洋板块的西边界,测深数据显示海沟深度由北向南逐渐增大。其中,马里亚纳海沟最南段的“挑战者深渊”是全球最深的点,深度可达 $(10984 \pm 25) \text{ m}$ ^[22]。西太平洋发育众多海山和海底高原(图 2(a)),不少海山或海底高原已经开始进入俯冲,例如马里亚纳俯冲带北部的小笠原海底高原和南部的卡罗琳海脊(图 2(a))。正是因为这些海底高原的俯冲,改变了原本俯冲带的走向。板块回溯研究显示,伊豆-小笠原-马里亚纳-雅浦俯冲系统在约 30 Ma 之前是几何形态较为平直的海沟。约 20~25 Ma 之前

海沟南部的卡罗琳海脊与俯冲带发生碰撞,俯冲板块经历了不同程度的回撤与旋转,最终演变成今天的弧形^[23-24]。这个过程使海沟的长度增加了约 25%^[25]。

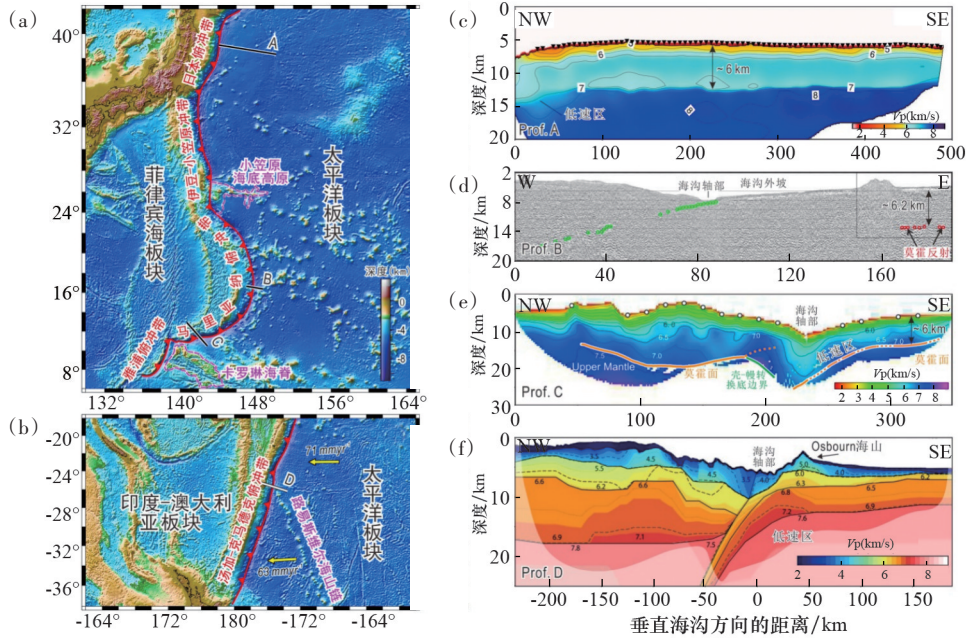
沿海沟走向,俯冲板块的地壳的厚度变化不大,约 6 km(图 2(c)~(e)),板块的挠曲深度却从俯冲带北部的约 3 km 增加至南部的约 5 km。通过对俯冲板块挠曲变形的分析,日本-伊豆-小笠原-马里亚纳俯冲带远场的岩石圈有效弹性厚度(T_e ,表征岩石圈抗拒挠曲的参数,越大代表岩石圈越难发生挠曲)可达 44~59 km,而靠近海沟的区域, T_e 减小至 23~42 km。这是由于挠曲形成的断层作用和高应力下的黏性变形而导致岩石圈弹性强度损失所致^[20,26]。同时,远场的高 T_e 说明要使俯冲板块弯曲至现今的深度,需要在海沟轴部加载巨大的力。反演结果显示,海沟轴部垂向剪力($-V_0$)最大可达 $3.17 \times 10^{12} \text{ N/m}$,其刚好位于在马里亚纳海沟的“挑战者深渊”^[120]。

1.2 汤加-克马德克俯冲带

汤加-克马德克俯冲带位于太平洋板块的西南部,太平洋板块向西俯冲至印度-澳大利亚板块之下形成汤加-克马德克海沟。该海沟是世界第二深的海沟,其最大深度约 10787 m^[27]。海沟轴部的板块年龄变化范围为 87~109 Ma^[10]。随着俯冲作用的进行,路易斯维尔海山链靠近海沟并开始俯冲(图 2(b))。地震速度结构显示,海山区域的地壳明显增厚,海山的俯冲也使海沟深度明显变浅(图 2(f))。增厚的地壳会导致海山体俯冲过程中产生高浮力,阻碍其进一步俯冲^[28]。岩石圈挠曲变形分

析显示,汤加-克马德克俯冲板块远场的 T_e 厚度为44~52 km,海沟附近的 T_e 减小至14~28 km,减小比例最高达60%,远高于日本-伊豆-小笠原-马里亚纳俯冲系统^[21]。而通过地形观测也发现,汤加-克

马德克俯冲带发育大量的挠曲相关正断层,且断层的断距普遍较大,很大程度降低了俯冲板块的挠曲刚度。



注:剖面A修改自文献[12],剖面B修改自文献[13],剖面C修改自文献[14],剖面D修改自文献[15]。

图2 穿过西太平洋俯冲带的广角速度结构剖面和多道地震剖面

2 西太平洋俯冲板块的挠曲正断层

挠曲相关正断层是由俯冲板片的挠曲变形超过岩石圈的屈服极限而产生的脆性变形所形成的。它们通常平行于海沟走向,具有一定的断距。通过多波束数据 (<https://www.ngdc.noaa.gov/maps/autogrid>),研究者对阿留申海沟、伊豆-小笠原海沟、马里亚纳海沟和汤加-克马德克海沟的挠曲正断层的垂向断距进行了统计分析^[7],并与中美海沟正断层断距^[2]对比,结果显示中美海沟的挠曲相关正断层的断距比较小,单条断层的断距都在100 m之下,而阿留申海沟、伊豆-小笠原海沟和马里亚纳海沟的断距都属中等,单条断层的断距通常在200~400 m,个别断层断距约800 m。汤加-克马德克海沟的断距普遍非常大,通常在400~1000 m,个

别断层断距可达1500 m以上(图3)。这也解释了为什么挠曲模型中汤加-克马德克海沟的 T_e 减小比例如此之大。

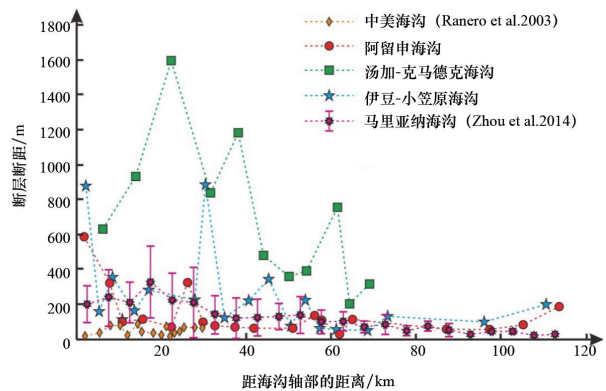


图3 不同俯冲带挠曲相关正断层断距与距海沟轴部距离之间的关系

值得注意的是,阿留申海沟、伊豆-小笠原海沟和马里亚纳海沟都具有越靠近海沟轴部,断层断距越大的特点,而中美海沟的断层断距与距海沟轴部的距离没有明显的关系。汤加-克马德克海沟最大断距的断层出现在距离海沟轴部 20~40 km 处。此外,Zhou 等^[17]指出马里亚纳海沟大部分正断层的倾向是向着海沟轴部,而阿留申海沟和伊豆-小笠原海沟约有 45% 的反倾向断层,而汤加-克马德克海沟约有 36% 的反倾向断层。

此外,统计显示年轻的中美海沟挠曲断层只出现在距离海沟轴部约 40 km 范围以内,板块年龄较老的汤加-克马德克海沟,断层最远处距离海沟轴部约 70 km,而年龄最老的海沟和伊豆-小笠原俯冲带挠曲断层可发育至距离海沟轴部约 110 km^[17],这也反映了年龄越老的板块,其弯曲变形的波长越长。

3 西太平洋俯冲带的板块水化

弯曲断层除了可能引起板内地震之外,还可将流体带至地球深部,引起地幔的蛇纹石化,促进流体在地球内-外的循环。地幔的蛇纹石化会导致地震 P 波速度在海沟外缘隆起的深部呈低速特征(见图 2(c)和(e)~(f)俯冲板块地幔的低速区),例如智利海沟^[3,29-30]、中美海沟^[31]、汤加海沟^[15]、阿拉斯加海沟^[32]和马里亚纳海沟^[33]等。因此,利用地震波速估算板块的含水量成为一种非常有效的手段^[3]。通过布设于马里亚纳海沟中部的宽带海底地震数据的瑞利波进行分析,Cai 等^[33]获得了马里亚纳海沟中部地壳和上地幔的地震速度结构剖面。结果发现,地幔蛇纹石化导致的低 P 波速度区域在莫霍界面下方延伸约 24 km,结合对俯冲地壳中含水量的估计。马里亚纳海沟中部的的水通量约为 $(94 \pm 17) \text{Tg} / (\text{Ma} \cdot \text{m})$,是前人结果的约 4.3 倍^[34]。

除了直接观测之外,通过数值模拟也可对俯冲板块的含水量进行估算,主要方法包括热-化学模拟^[34]和应力-屈服模拟^[26,35-36]等。其中,应力-屈服模拟是利用岩石圈挠曲模拟计算在现今的挠曲变形状态下三维空间应力分布,然后比较板块挠曲应

力和对应深度的岩石圈屈服包络线的大小,计算岩石圈变形的屈服区域(yield zone)。屈服区代表了脆性正断层能达到的最大理论深度,也表示板块水化区域的理论最大值。利用该方法,Zhang 等^[26]计算了马里亚纳海沟的三维应力分布和屈服区域,估算了板块的水通量,并与观测^[33]比较吻合。同时,他们指出马里亚纳海沟南部水通量约为北部的 1.15 倍。

4 结论

西太平洋俯冲带是板块年龄最老、海沟最深和板块挠曲程度最大的俯冲系统。其洋盆发育了众多海山和海底高原,对海沟的几何形态产生了较大影响。海沟附近发育了丰富的挠曲正断层。这些断层除了会诱发板内地震之外,也是流体进入板块内部和俯冲带深部的主要通道。西太平洋俯冲板块因其年龄老,具有较高的刚度,形成的断裂分布广且断距大,进一步促进流体进入地幔,并引起地幔蛇纹石化。因此,西太平洋俯冲板块的水化作用强,其水通量也高于其他俯冲带。

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Lithospheric deformation in western Pacific subduction zones

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Abstract The greatest flexural bending of the oceanic lithosphere and major earthquakes occur at subduction zones. When the bending stresses exceed the rock yield strength, pervasive normal faulting and extensional earthquakes would be generated within subducting plates. Normal faulting provides conduits for fluids to reach the upper mantle and facilitates serpentinization. Extensional earthquakes could also trigger tsunamis. Thus, better understanding flexural bending, stress distribution, and brittle failure of the subducting plate is essential to study the mechanism of earthquake and Earth's water cycle. Based on summary of geophysical observations and geodynamic simulations of the most representative Japan, Izu-Bonin, Mariana and Yap subduction zone and Tonga-Kermadec subduction zone in the western Pacific Ocean, this paper presents overview of characteristics of plate bending, bending-related normal faulting and corresponding brittle yield zone. The distribution characteristics of bending-related normal faults in different subduction zones were analyzed, and the correlations between plate deformation and earthquakes were discussed. It reveals the potential plate hydration characteristics of bending plates with normal faults. This study provides a basis for the future research on the plate deformation mechanism of subduction zones.

Keywords plate bending; bending-related normal fault; brittle yield zone; plate hydration; western Pacific Ocean ●



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