RELICT SLAB AND YOUNG PLUME: SEISMIC VIEW OF THE PRESENT TIME WYOMING LITHOSPHERE

残留板块及地幔柱:怀俄明克拉通的上地幔地震图像

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Abstract: Since nearly two decades ago, many temporary arrays have been deployed in the Archean Wyoming province and its neighboring areas. Due to the small station spacing (up to 2 km) of these array deployments, it is now possible to image the seismic structure in the Wyoming crust and upper mantle with a resolution scale comparable to active source profiling studies. Remarkable agreements between the passive and active source studies are found in the crust and shallow upper mantle. A high velocity dipping structure down to >150 km is revealed from tomography at the southern craton edge. Supported by other lines of evidence, a frozen-in fossil subduction slab model at the craton margin is preferred, which indicates that lateral slab accretion may be an important mechanism during the early craton assembly. High velocity lower crust magmatic underplates are present in the northern and central craton, but are perhaps inexistent in the south, indicating that they are related to possible different cratonization processes among the craton subprovinces. The spatial coincidence of these relict seismic structures with the surface sutures suggests the early lithospheric responses to various mantle deformation processes have been well preserved. Young tectonisms, for example the Yellowstone hotspot, have significantly altered the crust and lithosphere in the western side of the craton.

Key words: Wyoming; craton; lithosphere; seismic imaging; mantle plume; wedge

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摘 要:介绍了近年来天然地震体波和面波层析成像以及接收函数在怀俄明克拉通地区的应用。怀俄明克拉通地区的地壳和上地幔结构可以归结为克拉通成型时期的残存高速度异常以及进行中 Yellowstone 低速地幔柱。在克拉通南部边界缝合带地区以及在中部和北部下地壳中保存着一些高速度结构。南部边界缝合带地区的高速度倾斜上地幔结构与人工地震剖面 LithoProbe 在北美各个克拉通边界所记录的上地幔倾斜反射体一致。作为一个可能的上地幔消减板块残留体,这个倾斜上地幔结构显示出板块叠加可能是一个普遍的克拉通成型过程。在克拉通缝合带的莫霍面和上地幔深度,人工地震的研究结果显示板块叠加过程形成一个楔形体,体现出克拉通上地幔的较高粘度系数。接收函数的转换波共转换点叠加技术显示出这种楔形体存在于整个怀俄明克拉通的南部边界。接收函数和基于噪声的瑞利波层析成像图像显示出在克拉通地壳增厚地区存在下地壳高速体。作为早期岩石圈分裂过程残留的火成岩侵入体,这种下地壳高速体存在于较早成型的克拉通北部和中部地区,显示出南部克拉通地区不同的形成机制。克拉通的西部地区受到 Yellowstone 地幔柱的影响。层析成像显示低速的地幔柱从黄石地区向下延伸到至少 500 km。在消蚀岩石圈的同时,岩浆侵入

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体沿着 hotspot track 在中地壳大量的形成，并引起下地壳岩石的横向流动。

关键词：怀俄明；克拉通；岩石圈；地震成像；地幔柱；楔形体

1 Wyoming craton formation and deformation

Archean cratons are the regions in the world whose crust has remained stable for billions of years. Bleeker[1] reports 35 pieces of preserved cratonic segments in the world. Since the past decades consensus has been reached that the craton keel is buoyant and mechanically strong to retain the craton's longevity[2-3]. Questions regarding the craton formation and deformation processes, however, still remain. For example, how craton keels formed in the first place is still open for debate. Two classes of cratonic lithospheric roots formation are proposed[4-5], one invoking on one or more hot plumes, and the other proposing accretion by shallow subduction in either a continental or arc setting.

A well-suited region to study the craton formation and deformation is the Wyoming province in the northwestern United States (Fig. 1). This is a >100000 km^2 Archean province surrounded to its three sides by Proterozoic collisional orogens[6-8]: the Great Fall tectonic zone from north, the Dakota segment of the Trans-Hudson Orogen from east, and the Cheyenne belt[9] from south. The western limit of the craton is poorly constrained. Foster et al[10] suggest it may lie in the eastern limit of the Sevier fold and thrust belt in southwestern Montana. The craton is middle to the Late Archean in age[8,11]. The northern and central subprovinces were cratonized >ca 2.80 Ga, with a unique enriched $^{207}Pb/^{204/}Pb$ isotropic signature in the Archean rocks, which suggests an even earlier period of crustal contraction recorded in the subprovinces[6]. On the other hand, the southern province, known as the southern accreted terranes (SAT)[12], is 2.65-2.63 Ga in age and represents episodes of juvenile terrane accretion analogous to modern plate-tectonic processes[12]. More details of the geologic and tectonic history of the province can be found in a series of papers[6,8,10,12].

The deformation history of the Wyoming province can be traced back to as early as in late Archean: for example, pervasive deformation is recorded in the gneisses (>2.8 Ga) and discrete shear zones in the north and central subprovinces between 2.75-2.55 Ga[8]. Episodes of Proterozoic rifting are recorded in mafic dyke swarms in the ranges of southern accreted terranes (2.1-2.0 Ga) and in the western region of the Wyoming province (1.5-1.4 Ga). These rifting events are related to the Proterozoic passive margin along the Cheyenne belt (the southern border) and the Belt basin formation (the western border), respectively[8]. Younger (0.80-0.70 Ga) dykes are found along the western margin of the craton, reflecting more rifting along the western craton border and perhaps the development of the proto-Pacific Ocean[13]. Mueller and Frost[6] suggest the extension and mafic dyke emplacement may contribute significantly to the lower crustal mafic underplating in the Wyoming province. The 70-40 Ma Laramide uplifts are widely spaced in Wyoming. Chamberlain et al.[8] notice the first-order orientations and distributions of uplifts follow the tectonic trends of the subprovinces established in the Middle to Late Archean. This suggests that the long-lived Precambrian lithospheric features and weak zones have potential influences on the subsequent tectonic events.

Recent high density seismic array deployments, including the USArray Transportable array and many PASSCAL temporary arrays in the Wyoming province, provided an unparalleled opportunity to image the fine scale seismic structures of the cratonic crust, lithosphere and upper mantle. In this paper we summarize some of the recent teleseismic results from those array deployments. Findings from these teleseismic studies correlate well with those from active source seismic profiles, and together they reveal detailed structures in the Wyoming cratonic crust and lithosphere. Correlation of the seismic images with surface geology suggests the structural heterogeneities in the craton crust and upper mantle have been preserved since the craton formation, and remained intact during later subsequent tectonisms.

2 Fossil cratonic structures: Relict slab, wedge tectonics and 7.x layer

2.1 Relict slab

Since 1993 several PASSCAL temporary arrays have been deployed along the southern border of the province (Fig. 2a). One of the main goals was to study the seismic structure across the Proterozoic Cheyenne belt, the only well exposed boundary[6,14] that separates the craton from its Proterozoic orogens. A north-dipping slab like

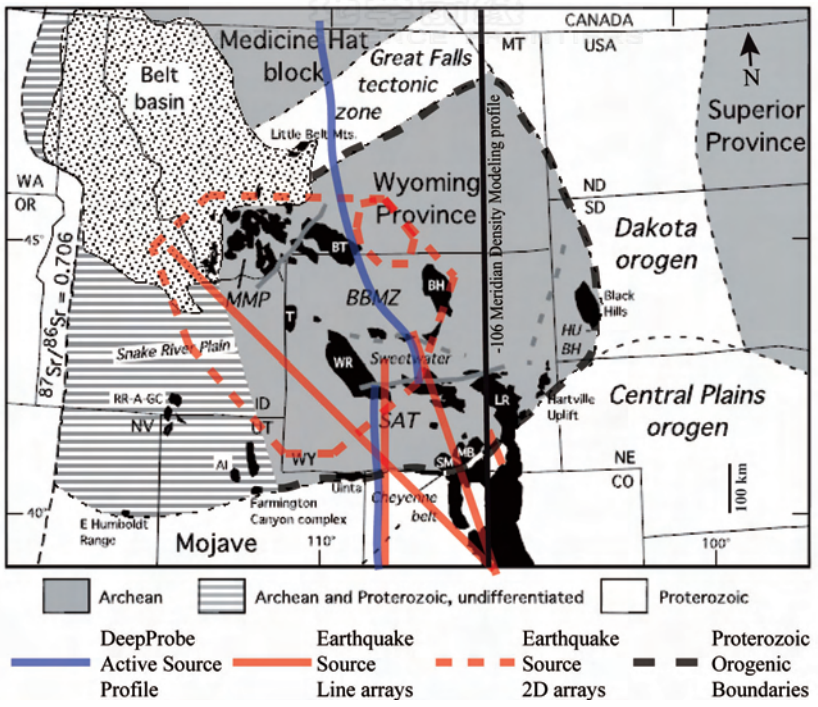

Fig. 1 Wyoming Province, its Proterozoic Orogens, and seismic arrays(Map modified from [6])

The DeepProbe active profile is shown as the blue lines. The passive source lines/arrays are the solid and dashed lines in red. The neighboring Proterozoic orogens are shown in dashed black line.

high velocity anomaly in the shallow upper mantle is found near the Wyoming/Colorado state border by the P- and S-wave tomography study of the CD-ROM project[15]. Given the spatial coincidence of the Cheyenne belt with the north dipping slab-like high velocity feature, a Proterozoic subduction slab trapped in the Archean Wyoming lithosphere has been proposed[15-16]. This proposal is supported by lateral continuity of the high velocities under the Cheyenne belt from other temporary array and regional tomographic studies[17-18] (Fig. 2), and by a thermo-barometric analysis of xenolith samples from the nearby Stateline District[19], in which a distinct depleted Archean-type signature is found in the upper (down to 140 km) sub-continental lithospheric mantle (SCLM). Interestingly this study shows underlying is a more metasomatised lower lithosphere, which assembles Proterozoic SCLM sections worldwide.

More support for the fossil slab hypothesis comes from the shear wave splitting study of the CD-ROM north line[20], in which the apparent splitting parameters can be modeled as from a northerly dipping anisotropic structure across the Cheyenne belt (CB). Synthetic tomographic experiment is conducted to test the anisotropic effects of a dipping fast axis anomaly in the isotropic tomographic inversion[15]. Remarkable consistencies between the inverted tomographic image and the prediction from an anisotropic synthetic slab model are observed (Fig. 3), therefore favor the high velocity anomaly being also anisotropic. The anisotropy within the high velocity anomaly is consistent with lattice preferred orientation developed in the anisotropic minerals in a fossil oceanic slab. Another evidence is from the receiver function common conversion stack image[21] along the CD-ROM north line CC'. North of the CB a continuous layering below the Moho depth is observed in the Wyoming lithosphere. This layering is however truncated by the high velocity slab where it is present. Further to the south across the CB the receiver function image shows different style of layering in the Proterozoic accretionary terranes. The truncation and change of the receiver function layering style suggest distinct lithospheric fabrics across the CB.

Fossil slabs are commonly reported to reside in the cratonic lithosphere in the North American continent[22-25]. Beneath the northern province boundary, where the Great Falls Tectonic zone separates the Wyoming craton from the Medicine Hat Block[6], an active source study[26] has revealed two north dipping reflectors in the upper mantle. These dipping reflectors are interpreted as relict subducted slabs, entombed during the collision between the Wyoming and Medicine Hat

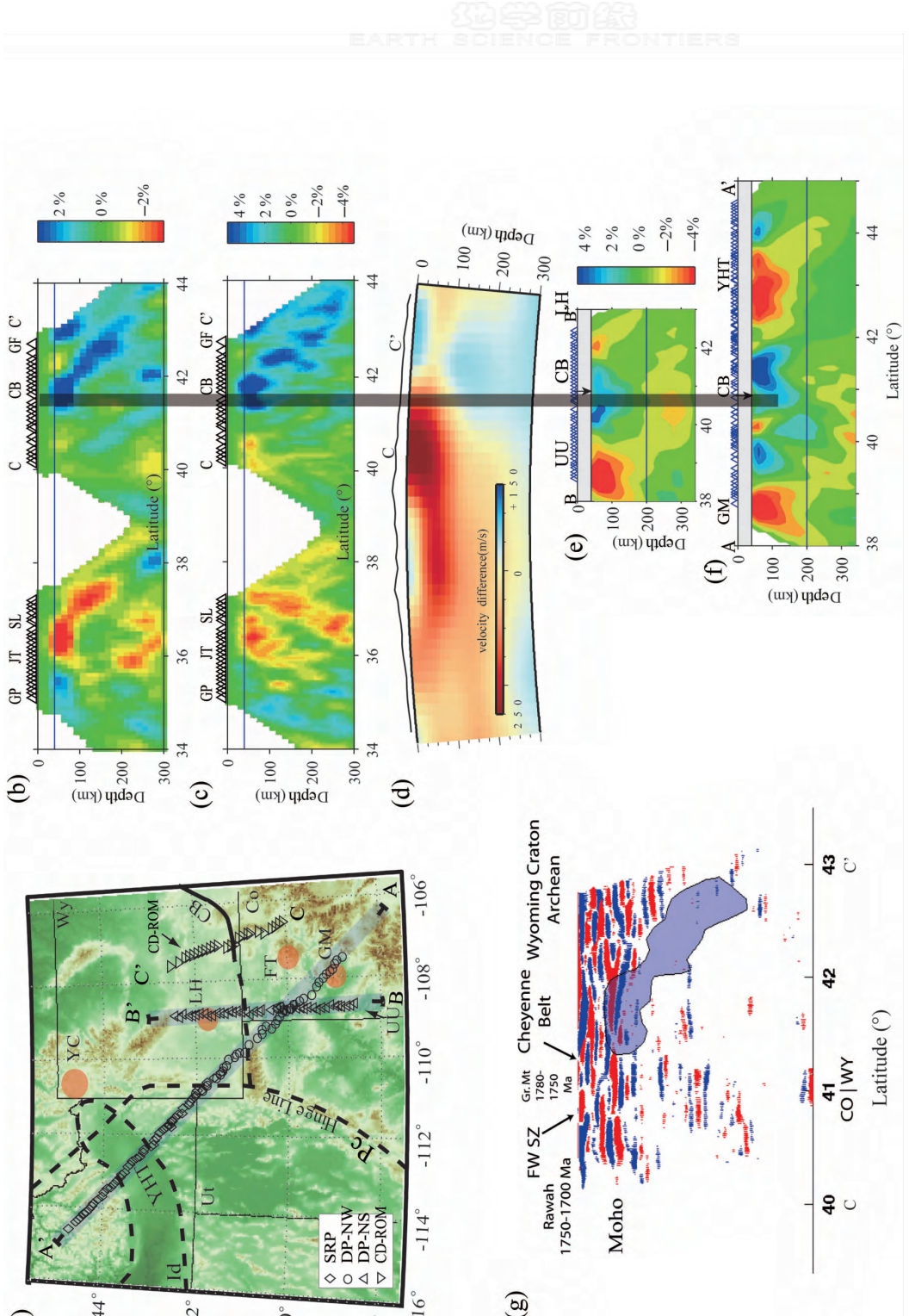

Fig. 2 The Cheyenne slab; Relict slab segments in the southern Wyoming province upper mantle

(a) Locations of seismic arrays used for tomography. Pink circles are volcanic fields; YC, Yellowstone Caldera; LH, Leucite Hills volcanic field; FT, Flat Tops volcanic field; and GM, Grand Mesa volcanic filed. Other labels are; YHT, Yellowstone Hotspot Track; UU, Uncompahgre uplift; and CB, Cheyenne Belt. PC Hinge Line is the eastern margin of the Precambrian rifted margin of the North American craton. (b) P-wave tomographic profile[15] along the north part of line CC'. CB is the Cheyenne belt. GF is the GeochronFront[54], which is spatially coincident with the subprovince boundaries in central and southern Wyoming province. The high velocity anomaly associated with the Cheyenne belt is indicated by the light dark vertical line. (c) S-wave tomographic image[15]. (d) Surface wave tomography image[18] along the same profile in (b) and (c). (e) and (f). P-wave tomographic images along BB' and AA'[17], respectively. (g) Comparison of the P-wave tomographic image (contoured for the high velocity north dipping structure only) with the lithospheric layering (velocity gradients) from receiver functions[21]. The depth extends to 300 km. Note the truncation of the layering across the slab. The x-axis in (b)-(g) is projected latitude in degrees along the profiles.

block[26]. In fact, more relict slab related upper mantle reflectors are reported from the active source LithoProbe studies[27] throughout the North American cratonic region. This suggests fossil subduction may be probably ubiquitous during the welding of cratonic pieces and their Proterozoic orogens in the Precambrian time, at least in the North American continent.

2.2 Wedge tectonics

Another commonly observed feature in the craton margin crust and shallow upper mantle is the so-called wedge tectonics[28], inferred from deep seismic reflection profiles and summarized in the cartoon in Fig. 4a. According to this model, the more rigid cratonic lithosphere appears to form a wedge of uppermost mantle rock into the lithosphere of juvenile blocks in a convergence setting[28]. Along the Cheyenne belt, several teleseismic receiver function images confirm this wedge structural geometry: for example, P- and S-wave receiver function common conversion point stacking images from a 2-km spacing density array reveal two positive velocity gradients in the depth between 40 and 60 km[29]. In this paper the two velocity gradients are inferred as double-Moho, with the shallow one being the Moho of the Archean crust, and the deeper slightly dipping one being the downward-thrusted Moho of the Proterozoic crust. This double-Moho is consistently observed in the receiver functions along the whole southern border of the Wyoming province[21,30-32] (Fig. 4 and 5).

If the proposal for the north-dipping deep thrust Proterozoic Moho is true, it complements the remnant fossil subducted slab model from the tomographic studies. Taken together, these tomographic and receiver function observations suggest that fossil subduction is well preserved beneath the southern border of the Wyoming province, and the tectonic slab stacking may have played an important roles in the Precambrian lithosphere growth.

2.3 The 7.x layer

One prominent observation in the Archean crust is the preservation of a high velocity and high density lower crustal layer, or the 7.x layer, first reported by active source studies along the Deep Probe lines[26,33]. The name of this 7.x layer comes from the high P-wave velocity (7.5-7.9 km/s) in the layer modeled in the active source studies[26,33]. The 7.x layer is interpreted as magmatic underplates in the lower crust (Fig. 6a). A gravity profile along longitude 106°W, parallel to the DeepProbe lines, indicates the high density lower crustal underplate extends much further to the east (Fig. 6b). With the high data fold teleseismic Billings array waveforms, receiver function images for the first time confirm the existence of the 7.x layer in the northern Wyoming subprovince[34] (Fig. 6c), where a striking high velocity contrast is observed on top of the Moho interface. Follow up studies using all available seismic stations in the region, including the USArray Transportable Array, map this 7.x lower crustal layer into a much larger region where thickened crust is observed (Fig. 6d-e). For example, shear wave tomographic images from ambient noise imaging technique[35] confirm this high velocity lower crust is present in the regions where receiver function images show a thickened crust with a secondary positive velocity gradient above it (Fig. 6e).

Based on xenoliths data from the Medicine Hat block and Great Falls tectonic zone, Gorman et al[26] propose a Proterozoic origin for the lower crust underplate. Noticing the coincidence of the 7.x layer with the oldest subprovinces and the thinning and vanishing of the 7.x layer in the southern province, Chamberlain et al.[8] argue the underplate is Late Archean in age and may be related to the widespread magmatism between 2.9 Ga and 2.75 Ga in the northern subprovince. An interesting observation is that the 7.x layer ends at the Oregon Trail Structure[8] which is the boundary between the central and southern subprovinces. The homogenous lateral distribution of the 7.x layer in the north and central subprovinces is consistent with the proposal that those subprovinces are quite distinct from the southern accreted terranes.

3 Young tectonic deformation: Yellowstone hotspot

A young tectonism that significantly deformed the lithosphere in the Wyoming province since its stabilization is the Neogene Yellowstone hotspot system. This is a famous continent type hotspot proposed by Morgan[36]: the hotspot track started around 17 Ma in SE Oregon and migrated 700 km northeasterly to its current location in Yellowstone. The seismology, geodynamics, volcanism and tectonics aspects of the hotspot are discussed in many papers[37-38]. Here we show some tomographic representation of the hotspot in the upper mantle to illustrate that the cratonic lithosphere has been significantly deformed by the upwelling plume, and the base of the lithosphere is perhaps in the middle of delamination process.

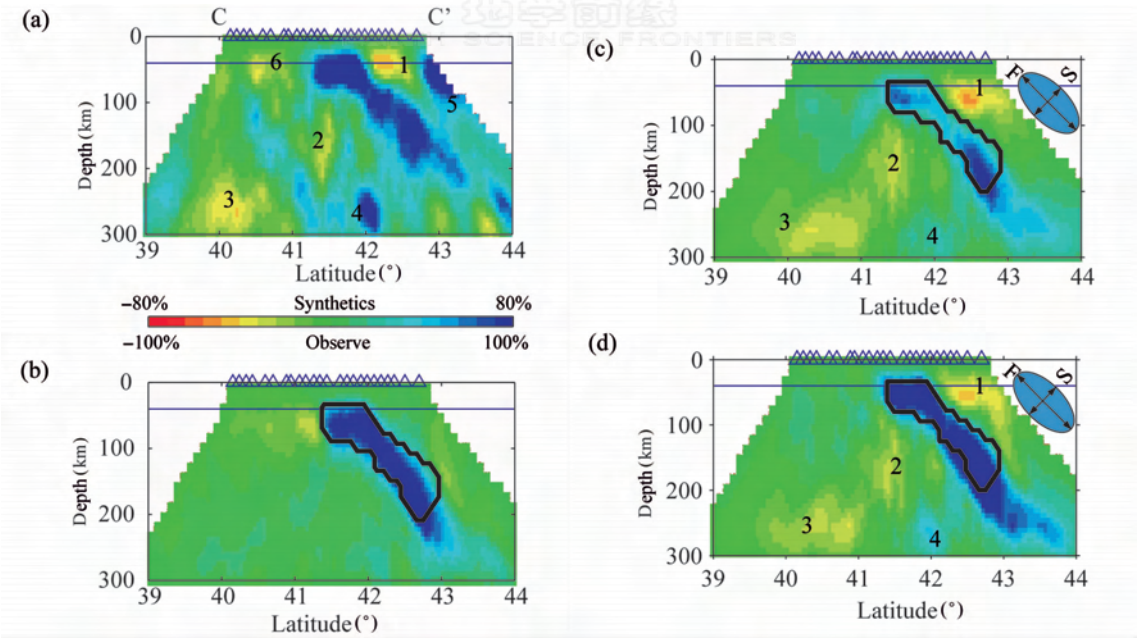

Fig. 3 P-wave anisotropic synthetic inversions[15] showing the tomographic image can be reconstructed from a combined isotropic high velocity anomaly and the fast symmetry axis anisotropy within it

The profile is along CC' in Fig. 2. The fast axis is parallel to the dip of the high velocity. (a) P-wave inversion results from real data. (b) Synthetic inversion results for an isotropic slab model taking from the 2% contour region in the high velocity slab region in (a). The slab within the contour is recovered well. (c) Synthetic inversion results for a purely anisotropic slab model input (8% peak-to-peak to the background model in the slab and no isotropic velocity perturbation). The fast and slow velocity axes of the slab are shown as the simplified velocity tensor to the upper right corner. Note artifacts are present (labeled as 1 to 4) due to the isotropic tomographic inversion compensating the anisotropic path effect along and perpendicular to the slab. The slab itself is recovered but with very small amplitude recovery. (d) Final synthetic model which combined the isotropic variation (b) and the anisotropy variation (c). Note the similarity between the inverted images from the synthetic and the real data: the slab, low velocity artifact 1 to 4. Other features (5 and 6) are not modeled. Amplitudes in (b) to (d) are scaled to 80% of (a). Figure from Yuan and Dueker[15].

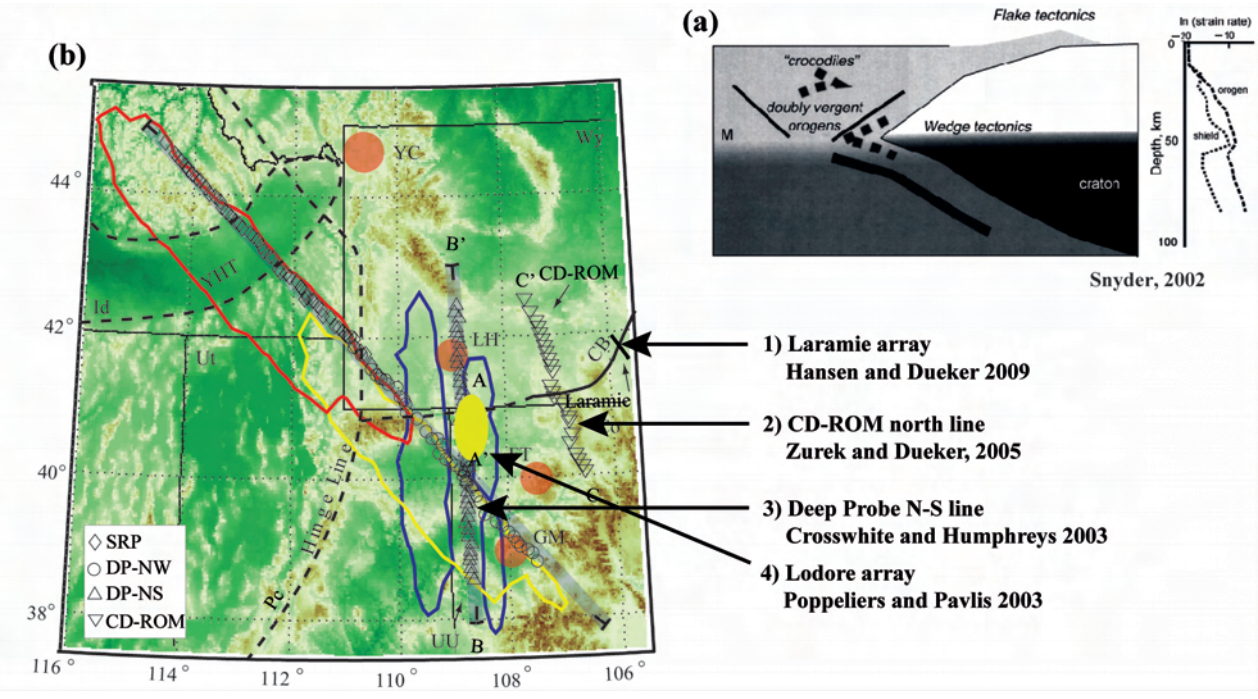

Fig. 4 Wedge tectonics

(a) Wedge Tectonics model proposed from active source profiling. Figure from Snyder[28]. Note the high viscosity cratonic lithosphere wedges into the weak young lithosphere during a continental orogeny. The black lines are the dipping reflectors from active source study. (b) Array locations showing where the Wedge occurs along the Cheyenne belt, revealed from receiver functions: (1) Laramie array[29]; (2) CD-ROM array[21]; (3) DeepProbe passive line[30]; and (4) Lodore 2D array[31].

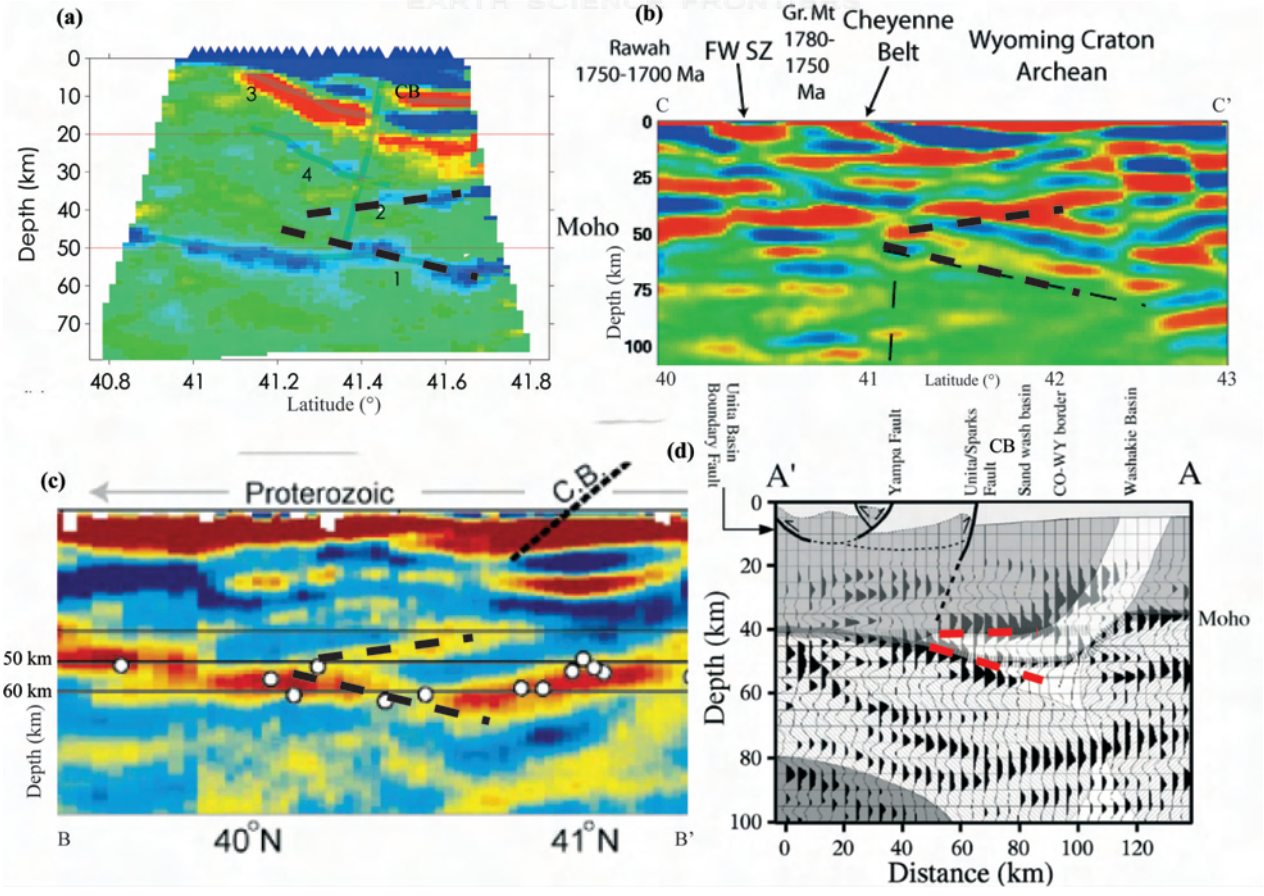

Fig. 5 Receiver function studies showing the wedge tectonics along the Cheyenne belt

(a) Laramie array[29]; (b) CD-ROM array[21]; (c) DeepProbe passive line[30]; and (d) Lodore 2D array[31]. The "Crocodile" shape indicated by the two dashed lines at the Moho depth along the Cheyenne belt (labeled as CB) shows the location of down-thrusted Proterozoic Moho (top) and the Archean Moho (bottom). Note the positive velocity gradient (e. g., the Moho) is blue in (a), red in (b) and (c), and black in (d).

Figure 7 shows a 3D rendering of the Yellowstone plume image inverted from the P-wave traveltime residuals recorded at available broadband stations before 2006[39]. The surface aperture of the station coverage is up to 600 km therefore guarantees good resolution down to at least 500 km. A pronounced low velocity "pipe" extends from surface beneath the Yellowstone park down to over 500 km. Strikingly, at the depth where the plume penetrates the 410 km discontinuity, the topography of the interface shows a "depression" from receiver functions[40] (Fig. 7b-d), consistent with a warm upwelling crossing the olivine phase change boundary[41]. This upper mantle plume image is confirmed by other tomographic studies[42-45]. More recent tomographic images that take advantage of the USArray Transportable Array data and the finite frequency kernels[46-47], show that the plume may extend deeper, and may loosely connect to a much larger pond of low velocities at >1000 km depth.

The plume has significantly modified the crust and lithosphere in the western side of the province. As illustrated in the diffusive and ballistic Rayleigh wave tomographic inversion images[35], at 80 km the cratonic lithosphere has much slower velocities along the Eastern Snake River Plain than its surroundings (Fig. 14 of Stachnik et al. [35]). This implies that in responding to the time progressive North American plate shear, the plume has significantly indented the cratonic lower lithosphere along the hotspot track. Mantle derived and fractionated ferro-basalts, or the so-called Mid-crustal mafic sill complex[48], originated from the plume-lithosphere interaction[49], are consistent with observations from Rayleigh wave tomography and receiver function studies[34-35] along the hotspot track. This mid-crust mafic fill was first detected from an active source seismic profiling study[48]. The plume-lithosphere interaction has caused about

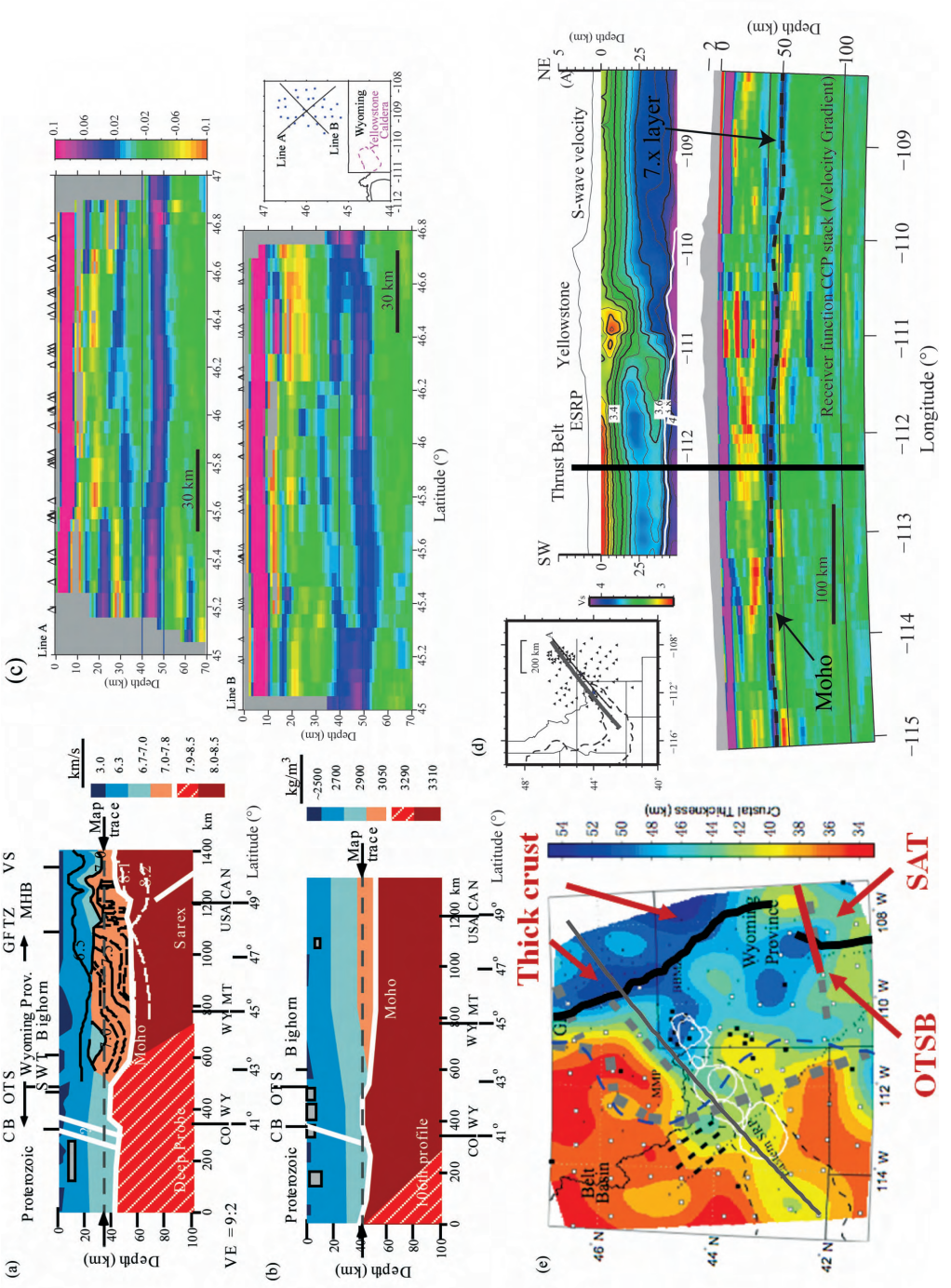

Fig. 6 Lower crust mafic underplating in the Wyoming Province

(a) Active source profile modeling along the DeepProbe line[33]. Figure from Chamberlain[8]. The location of the profile is indicated as the blue lines in Figure 1 and also in (e) as the thick black lines. Note the 7. x P-velocity layer between 20 and 40 km depth beneath the Wyoming province. This layer vanishes near the Oregon Trail Structure (OTS), the boundary between the central and southern subprovinces in Wyoming[8]. (b) Density profile modeling along the-106 longitudinal line[33]. Figure from Chamberlain[8]. Note the high density lower crustal layer is consistent with the 7. x layer in a). (c) Receiver function stacking images along two lines from the Billings array in the north subprovince[34]. The colors indicate velocity gradient at depths. Note the two positive gradients at 25 to 50 km depth range. The deeper one is the Moho, and the shallower one is the top of the 7. x lower crust mafic layer. (d) Comparison between the shear wave speed image[35] and receiver function stacking image[34] along a profile (location in the inset and also in e). Note the high velocity lower crust north of Yellowstone agrees with the positive velocity gradient from the receiver function image. (e) Crustal thickness map showing the thickened crust correlating with the spatial distribution of the 7. x lower crustal mafic layer. The black line denotes the DeepProbe active line in the region. The dark gray line shows the receiver function line in (d). Other labels are: OTSB, the Oregon Trail Structure Boundary separating the north and central subprovinces from the Southern Accreted Terranes (SAT).

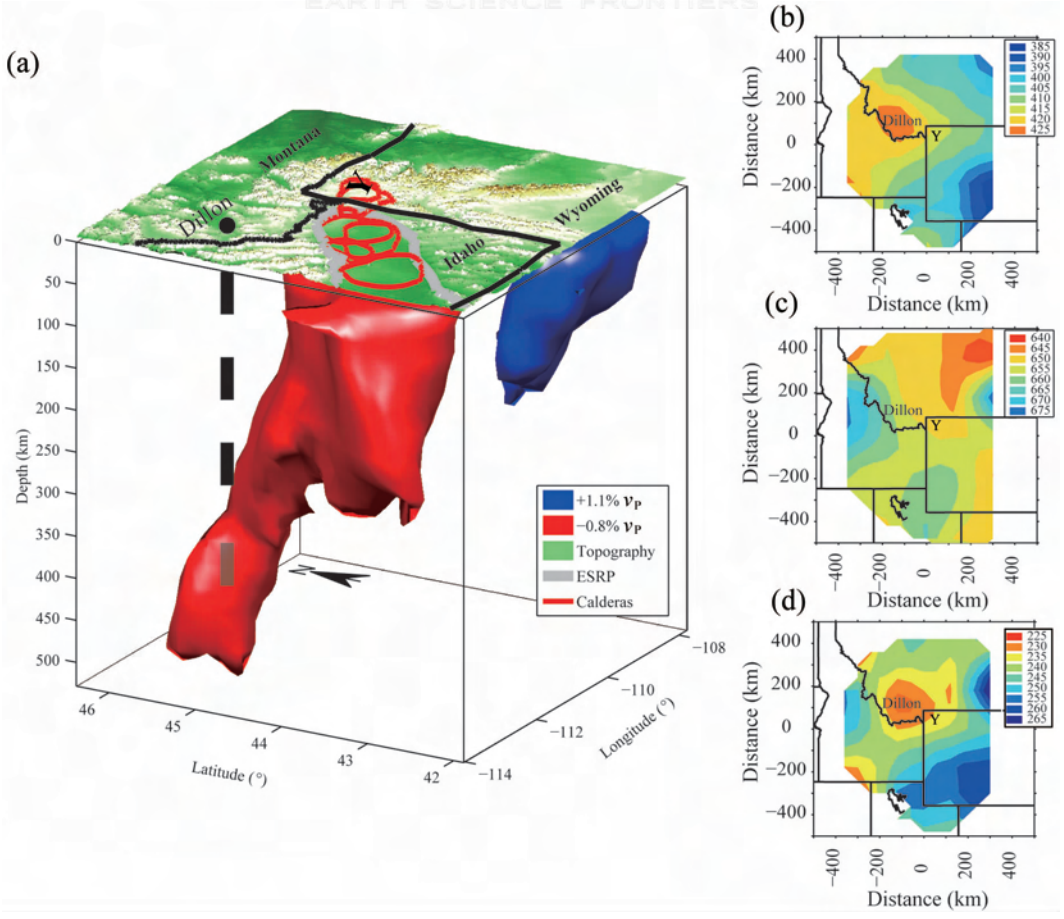

Fig. 7 Yellowstone plume

(a) 3D rendering of the Yellowstone P-wave tomographic results[39]. Red is the iso-surface of the low velocity contour at 0.8%, which extends to at least 500 km. Beneath Dillon, Montana, where the plume penetrates the 410 km discontinuity, the receiver function study[40] reveals a depression of the topography of this discontinuity (b). (c) Topography of the 660 km discontinuity. No corresponding uplifting of the topography is observed. (d) The transition zone thickness. Figures in (b) to (d) are from Fee and Dueker[40]. The x- and y-axes in (b)-(d) are relative distance (in km) from the Yellowstone Caldera (labeled as Y).

10 km thick magmatic injection to the crust[35], which has triggered significant outward flow of the Eastern Snake River Plain lower crust[34-35]. The overall plume flux is small, however, based on observations of the small plume conduit imaged from tomography[39,43,50] and nearly uniform distribution of the anisotropy fast symmetry axis from shear wave splitting measurements[51-52].

On the sides of the hotspot track, the plume may have already triggered lower lithosphere delamination, as suggested by tomographic images[39,45] in shallow upper mantle in west-central Wyoming (Fig. 7a). A recent lithospheric thickness map based on surface waves[53], derived from rapid changes of azimuthal anisotropy directions with respect to depth, shows a much thinned lithosphere in the western Wyoming province, which would be consistent with the delaminated lithosphere proposal.

4 Summary

Passive source seismic array deployments have provided unique opportunities to image the fine scale structure of the Wyoming craton crust and upper mantle. Consistencies between the passive and active source images suggest that the passive source seismic imaging is capable of revealing fine scale structure, and can be laterally extensive and remains low cost. Results from various methods of seismic processing reveal coherent images of the relict crustal and lithospheric structures in the craton. The coincidence of the seismic structures with the surface geological structures suggests those are fossil structures, which may be frozen-in during

the early craton formation processes. The inferred wedge tectonics and relict slab along the craton margin also indicate that slab accretion may have played important roles in early cratonic formation. Young mantle upwelling, i. e. the Yellowstone plume seems to erode the cratonic lithosphere by causing thinning and delamination, while on the other hand has contributed to crust growth through injecting magmas into the craton lithosphere. Lastly the seismic images in general reflect only the current state of the craton upper mantle; integration seismology with surface geology, geodynamics and geochemistry is essential to further improve our understanding of the craton evolution.

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投 稿 预 告

欢迎向主题专辑投稿　也欢迎非主题投稿

《地学前缘》为双月主题性期刊，欢迎按专辑主题投稿，也欢迎非主题投稿，因本刊设有“非主题来稿选登”。

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具体专辑名为“地震及相关研究”，“水资源与环境”。

(2)2011 年第 1,2 期“地球物质科学”主题：

具体专辑名为“花岗岩成因”，“变质作用与造山带演化”。

(3)2011 年第 3,4 期“地球结构、构造与动力学”主题：

具体专辑名为“大陆地质与大陆构造”。

(4)2011 年第 5 期专辑名为“中国土壤碳库与全球变化”。

第 6 期专辑名为“成矿流体动力学”。

(5)2012 年第 1,2 期专辑名为“油气沉积地质”。