

RESEARCH ARTICLE

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Key Points:

- Widespread chemical remagnetizations in the Dabashan fold and thrust belt resulted from the action of the orogeny during the Middle-Late Jurassic
- Internal mixing of original pore fluids is suggested as the mechanism for remagnetization of the Permian strata
- The pattern of orogeny-induced fluids migration is determined from the thrust zone to fold zone

Supporting Information:

- Supporting Information S1

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Fluid Migration and Widespread Remagnetization in the Dabashan Fold and Thrust Belt, China

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Abstract To better understand the fluid migration in orogenic zones and associated chemical remagnetization, we have conducted a detailed magnetic, petrographic, and strontium isotope study in an important orogenic belt of China, the Jurassic Dabashan fold and thrust belt. This belt formed by the continued collision of the North and South China blocks after the Late Triassic closure of the Paleo-Tethys Ocean. Samples were collected in a variety of rock units of Ediacaran to Permian age, in both the thrust and the fold belts. Paleomagnetic analysis indicates that all the samples were remagnetized and carry a Middle-Late Jurassic paleo-direction. Rock magnetic data and scanning electron microscopy observations found that the proposed remagnetization is carried by framboidal magnetite, which likely formed by the replacement of pyrite. The pervasive nature of the chemical remagnetization in these units and belts and its temporal and spatial association with the orogeny suggest that it resulted from the alteration of orogeny-induced fluids. Sr-isotopic analysis of the units that are thought to be remagnetized suggests that the sediments in the thrust belt were altered by externally derived evolved fluids, whereas the Permian samples in the fold belt were altered by internal pore fluid mixing during the orogeny. Together with the lithological and structural features, we conclude that the external orogenic fluids migrated preferentially along thrust faults and unconformities but were blocked by layers of low-permeability gypsum. Our results help to constrain the origin of widespread remagnetization in South China.

1. Introduction

Orogenesis causes fluids to migrate from fold and thrust belt to foreland basins due to the effects of compression and gravity (Bethke & Marshak, 1990; Elmore et al., 2012; Garven, 1995; Oliver, 1986). For zones of convergence, Oliver (1986) proposed a model whereby migrating fluids play a key role in numerous geological processes, such as transport of minerals, diagenesis, chemical remagnetization (CRM) of sediments, and hydrocarbon migration. Several case studies have been conducted, mainly in the Appalachian and Cordilleran orogenies, the South China Block, and the Tibetan Plateau, to study the relationship between orogenic fluids, hydrocarbon migration, Pb-Zn mineralization, and CRM (e.g., Appel et al., 2012; Elmore et al., 1993; Enkin et al., 2000; Gong et al., 2019; Huang et al., 2019; Jackson et al., 1988; McCabe & Elmore, 1989; Miller & Kent, 1988; Weil & van der Voo, 2002; Zhang et al., 2016, 2018, 2019). Yet, there are still gaps in our understanding of the role of migrating fluids and remagnetization in orogenic belts, including (1) how the fluids migrate in different lithological units and tectonic zones during the orogeny and (2) how CRM occurs in response to the migrating fluids?

The Jurassic Dabashan fold and thrust belt is ideal for investigating these questions, as it represents a typical orogenic belt behavior in a convergence zone. These belts formed during the Jurassic convergence of the North and South China blocks after the closure of the Paleo-Tethys Ocean in the latest Triassic (Dong et al., 2013; Gilder & Courtillot, 1997; Yang et al., 1992; Figure 1). There are also well-exposed strata of varying lithologies (e.g., carbonates, shales, mudstones, and gypsum) and structures (e.g., faults and unconformities) in both the fold and thrust belts. In this study, we conducted an integrated magnetic, petrographic, and Sr-isotope investigation of several lithological units in both fold and thrust belts to better understand the pattern of orogenic fluid migration and corresponding CRM in the Dabashan fold and thrust belt.

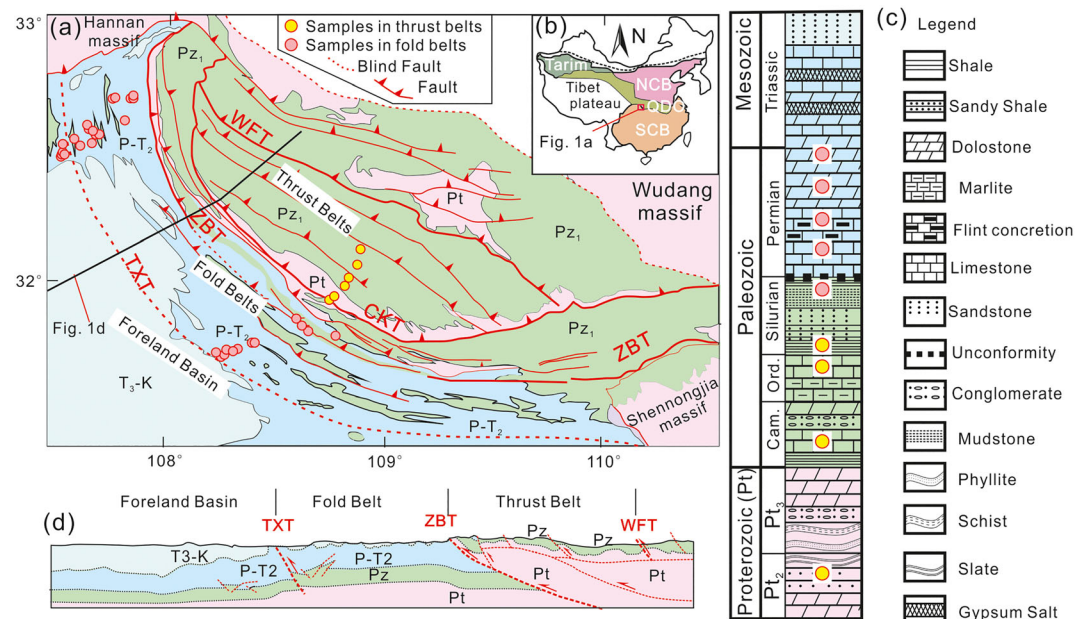


Figure 1. (a and b) Simplified geological map of the Dabashan fold and thrust belt (South China) illustrating tectonic zones and rock types in the region, as well as the sampling locations for this study. (c) Proterozoic-lower Mesozoic stratigraphic column of the Dabashan fold and thrust belt. (d) Cross section of the Dabashan fold and thrust belt showing sampling locations. WFT = Wafangdian thrust; ZBT = Zhenba thrust; TXT = Tiexi thrust; SCB/NCB = South China Block/North China Block; QDO = Qinling–Dabie orogen; Pz₁ = early Paleozoic; P–T₂ = Permian–Middle Triassic; and T₃–K = Late Triassic–Cretaceous.

2. Geological Setting

The Dabashan fold and thrust belt is located in the northwestern margin of the South China Block (SCB; Figure 1; Dong et al., 2013; Li et al., 2015; Li, Dong, et al., 2013; Zhang et al., 2001). During the Permian–Early Triassic, the northeastern part of the SCB initially collided with the North China Block (NCB), and then the entire SCB rotated clockwise relative to the NCB. In the Late Triassic–Early Jurassic, the Paleo-Tethys Ocean had closed in the west, and the western part of the SCB including our study area started to collide with the NCB (Jiao et al., 2019; Yin & Nie, 1993; Zhao & Coe, 1987). Due to the slab pull of eclogitized mafic crust in the subducted SCB, the two blocks continued to converge during the Jurassic, forming the Dabashan fold and thrust belt (Dong et al., 2011, 2013; Zhang et al., 2001). During this convergence, deformation of the Dabashan fold and thrust belt generally propagated southward (Dong et al., 2013). The main structures in the fold belt formed during the Middle–Late Jurassic, with an angular unconformity between folded Jurassic units and Lower Cretaceous red beds in the fold belt, and >3,000 m Middle Jurassic syn-tectonic sediments in the foreland basin (Chen et al., 2008; Li et al., 2015; Liu et al., 2006).

The Dabashan fold and thrust belt is arcuate in shape and contains a thrust belt, a fold belt, and a foreland basin, which are separated by two north dipping faults, that is, the Zhenba–Chengkou and Tiexi faults (Figure 1; Dong et al., 2006; Li et al., 2015; Li, Dong, et al., 2013; Li, Zhang, et al., 2013). In the thrust belt, the thrusts are widely spaced in the north but closely spaced in the south. The thrusts widely cut through the Archean to Mesoproterozoic metamorphic basement, Neoproterozoic metamorphic rocks, and Cambrian–lower Silurian sediments. The fold belt is separated from the thrust belt by the Zhenba–Chengkou Fault and comprises a large number of anticline and syncline fold pairs (Figure 1). The strata there include Silurian mudstone and shale, Permian to Middle Triassic marine carbonate, Low–Middle Triassic gypsum, and Upper Triassic–Jurassic sandstone (Figure 1). The Permian carbonates unconformably overlie Silurian shale and mudstone (Figure 1c). South of the Tiexi blind fault, the foreland basin zone formed in response to thrust loading and development of the Dabashan thrust belt; it comprises mainly Middle Jurassic to Lower Cretaceous sandstone and mudstone (e.g., Hu et al., 2012; Shi et al., 2012).

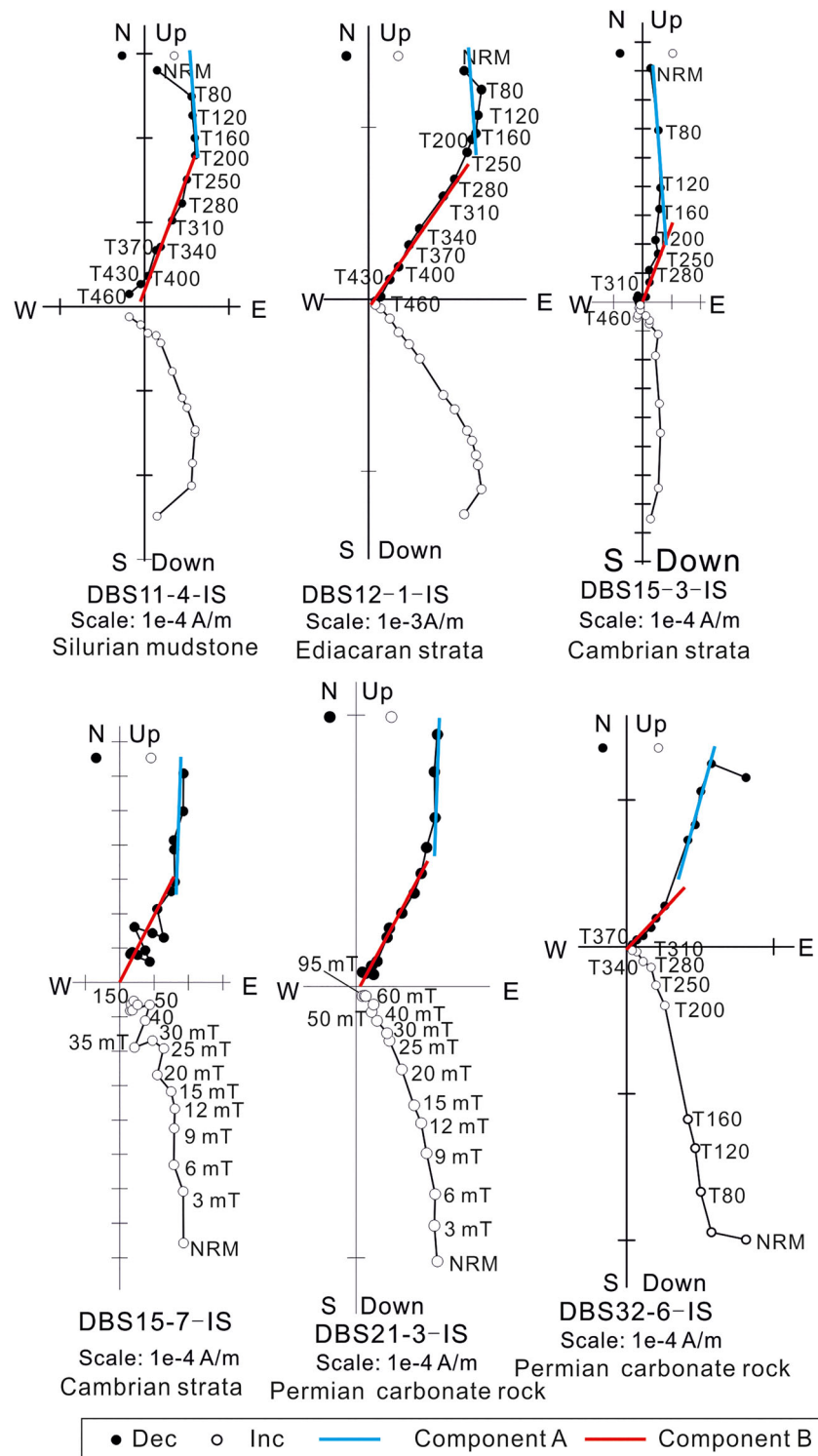


Figure 2. Progressive demagnetization plots for representative samples: (a) DBS11-4-IS (thermal), (b) DBS12-1-IS (thermal), (c) DBS15-3-IS (thermal), (d) DBS15-7-IS (AF), (e) DBS21-3-IS (AF), and (f) DBS32-6-IS (thermal). Characteristic remanent magnetization (ChRM, Component B) and viscous remanent magnetization (VRM, Component A) are highlighted on the figure. Solid (open) circles or triangles show projections in the horizontal (vertical) plane.

Table 1
Site-Mean ChRM Directions for Samples From the Dabashan Fold and Thrust Belt

Site	S/D	N/N ₀	Site location	D _g (deg)	I _g (°)	D _s (deg)	I _s (°)	k	α ₉₅ (deg)
<i>Permian Fm. Carbonate</i>									
DBS01	132/63	05/07	N31.690°; E108.295°	30.3	47.2	243.5	67.8	48.7	11
DBS03	110/35	08/08	N31.713°; E108.322°	16.3	59.5	222.5	85.1	64.9	7
DBS04	120/59	09/09	N31.717°; E108.346°	19.2	58.8	221.5	61.2	81	6
DBS07	1/88	08/09	N31.754°; E108.428°	16.8	55.4	57.5	−7.2	261	3
DBS10	303/47	06/06	N31.836°; E108.643°	28	52.3	29.9	5.4	233.5	4
DBS18	101/28	12/13	N32.514°; E107.556°	24.9	61.4	102.4	83.4	123.8	4
DBS20	242/56	07/07	N32.493°; E107.541°	23.2	50.2	2.1	5.6	49.3	9
DBS21	155/76	06/07	N32.496°; E107.542°	28.8	47.9	278.9	44.8	199.2	5
DBS22	26/56	08/08	N32.490°; E107.542°	16	45.3	63	29.9	50.4	8
DBS24	352/71	06/06	N32.529°; E107.623°	20.7	59.6	55.6	3	329.9	4
DBS25	245/75	08/08	N32.553°; E107.675°	17.2	54.7	358.3	−11.6	505.9	2
DBS26	238/3	09/09	N32.605°; E107.663°	17.2	51.8	14.5	49.8	55.9	7
DBS28	148/58	08/08	N32.576°; E107.696°	20.9	54.5	276.2	55.5	356	3
DBS29	160/50	07/08	N32.575°; E107.700°	22.4	55.6	297.1	55.3	87.5	6
DBS30	245/67	07/07	N32.576°; E107.709°	14.2	54.2	356.8	−5.7	43	9
DBS31	318/74	08/08	N32.693°; E107.764°	17.1	56.9	31.3	−12.7	119.4	5
DBS32	180/32	05/07	N32.691°; E107.757°	26.9	53.4	0.3	64.2	74.6	8
DBS33	167/34	07/07	N32.708°; E107.858°	17.5	57.1	354.7	55.7	463.5	2
DBS34	305/35	09/09	N32.707°; E107.859°	12.8	55.8	21.8	22.3	219.3	3
DBS35	340/52	05/05	N32.707°; E107.862°	16.2	62.4	46.7	19.2	621.1	3
DBS36	136/45	05/08	N32.626°; E107.831°	23.2	57.2	267	71.4	631.5	3
Mean value				20.7	55.0	12.0	46.3	216	2
<i>Silurian Fm. Mudstone and Shale</i>									
DBS02	312/45	07/08	N31.700°; E108.306°	35.6	47.6	37.7	2.8	21.4	13
DBS05	120/59	02/05	N31.723°; E108.357°	21.9	54.5	221.5	65.8	294.9	14
DBS06	150/56	06/06	N31.749°; E108.429°	19.6	48.4	291.9	56.9	125	6
DBS08	328/34	06/08	N31.820°; E108.669°	28.1	42	35.8	11.3	42.3	10
DBS09	279/31	05/06	N31.824°; E108.658°	32.9	36.5	28.1	7.6	24.6	15
DBS11	210/31	06/08	N31.803°; E108.770°	23	37	3.6	27.7	433.8	3
DBS17	136/77	05/11	N32.142°; E108.885°	23	23.1	287.7	66	45.2	11
DBS19	337/70	04/05	N32.498°; E107.544°	22.9	46.8	37.9	−12.3	249.6	6
DBS23	168/54	07/08	N32.554°; E107.603°	21.6	39.6	325.5	46	36.4	10
DBS27	173/39	06/06	N32.589°; E107.673°	20.4	67.2	300.9	56	79.4	7
Mean value				25.2	44.4	3.1	44.1	43	7
<i>Ediacaran and Cambrian Strata</i>									
DBS12	231/56	07/09	N31.963°; E108.744°	32.9	46.9	2.9	13.4	55.6	8
DBS13	260/64	06/08	N31.965°; E108.752°	17.4	44	10.1	−15.6	245.7	4
DBS14	324/88	05/08	N31.991°; E108.804°	36.4	41.1	35.5	−44.1	62.5	10
DBS15	310/86	07/08	N32.027°; E108.820°	29.1	26.9	21.7	−57.4	26.2	12
DBS16	327/31	06/06	N32.066°; E108.847°	15.3	51.5	29.7	25.5	96.2	7
Mean value				26.7	42.4	18.7	−16.0	49.9	11

Note. D_g = mean declination value in geographic coordinates; I_s = mean inclination value in stratigraphic coordinates; α₉₅ = 95% confidence ellipse on the mean direction; N/N₀ = number of specimens (N) used to determine the mean direction relative to the total number of specimens demagnetized (N₀); k = precision parameter; and S/D = strike/dip.

3. Sampling and Methods

3.1. Paleomagnetic Analysis

To investigate the characteristic remanent magnetization (ChRM) of the Dabashan fold and thrust belt, 280 cored and oriented samples from 36 sites were collected along two NE-SW trending transects perpendicular to the belt (Figure 1a). In the fold belt, we collected samples from Permian and Silurian strata in anticline-syncline pairs for the purposes of applying fold tests. In the southern part of thrust belt, we collected Ediacaran-early Silurian samples (Figure 1a).

Cores were cut into cylinders 22 mm in length and 25 mm in diameter. The natural remanent magnetizations (NRMs) of the samples were measured on a cryogenic rock magnetometer (2G-755), which is

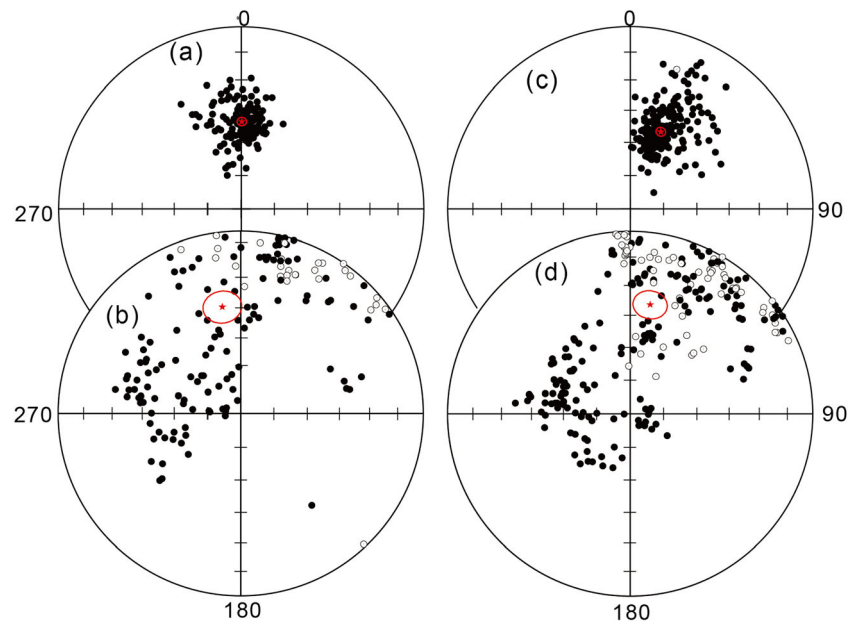


Figure 3. Equal area stereographic projections of the lower-temperature Component A (VRM) in (a) geographic and (b) tilt-corrected coordinates for all samples. (c) Equal area stereographic projections of the higher-temperature Component B (ChRM) in (c) geographic and (d) tilt-corrected coordinates.

housed in a magnetically shielded room at Nanjing University. Some of the samples were thermally demagnetized typically in 13–15 steps up to 570°C (at steps of 20–50°C), while the remaining samples were alternating field demagnetized at steps of 5–10 mT to a maximum value at 150 mT (typically ~15 steps; Figure 2). Principal component analysis was used to calculate the NRM component directions (Kirschvink, 1980). Selected ChRM directions typically had a maximum angular deviation (MAD) < 10° (anchored fit).

3.2. Rock Magnetic Analysis

To determine the coercivity of the magnetic minerals, ASC IM-10-30 impulse magnetizer and Agico JR-6A spinner magnetometer were used in combination to measure isothermal remanent magnetization (IRM)

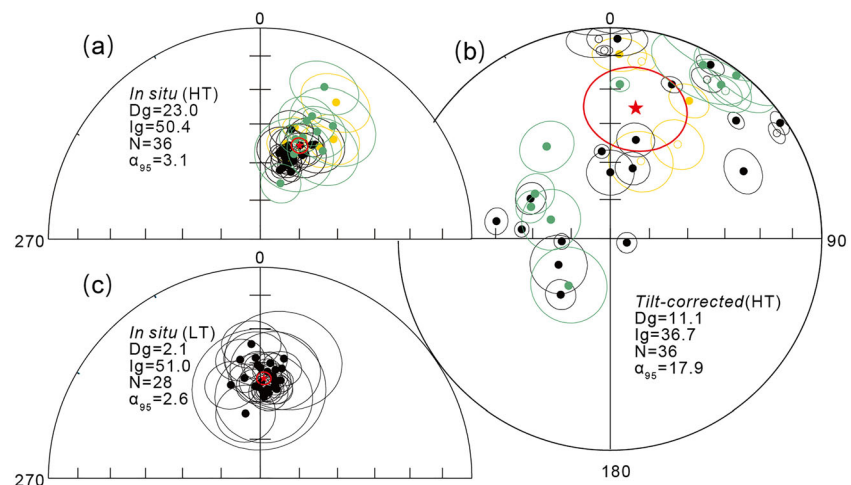


Figure 4. Site-mean ChRM directions in (a) geographic and (b) stratigraphic coordinates. (c) Low-temperature components shown in geographic coordinates. D_g , I_g , D_s , and I_s = declination and inclination values in geographic and stratigraphic coordinates, respectively; α_{95} = 95% confidence cone. Black circles = Permian samples; blue circles = Silurian samples; yellow circles = Ediacaran-Cambrian samples; and red stars = mean directions.

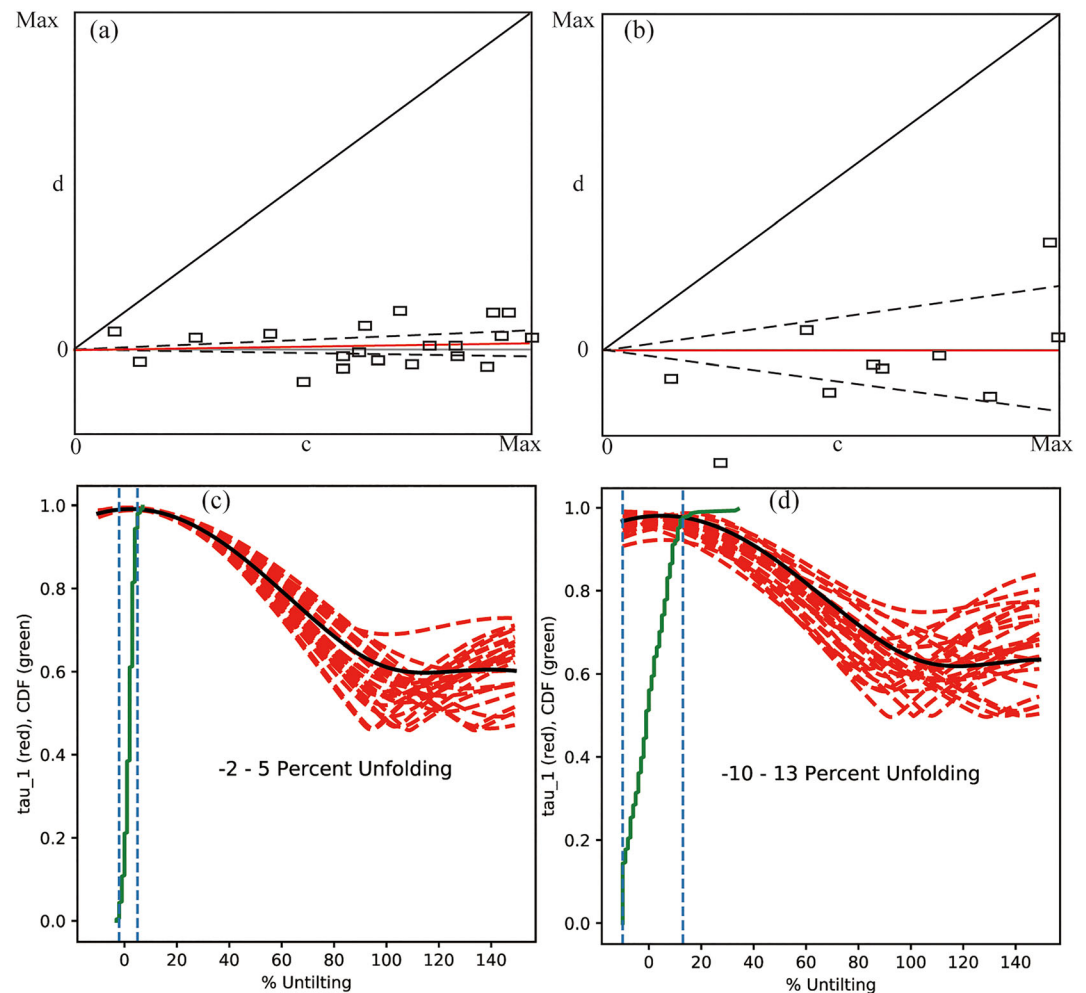


Figure 5. Results for the direction-correction tilt test (Enkin, 2003) result for (a) Permian samples and (b) Silurian samples. Results of the Tauxe et al. (2016) fold test conducted using the PmagPy software of foldtest_magic by Tauxe et al. (2016) for (c) Permian samples and (d) Silurian samples. In the (c) and (d), the solid black curves represent maximum eigenvalue as a function of unfolding. The red dashed curves represent a sampling of the first 25 bootstrapped results. The green solid line represents the cumulative distribution function (CDF) of the percent unfolding required to maximize for all the bootstrapped data sets. The blue dashed lines represent 95% confidence bounds on the % unfolding that yield the most clustered result.

acquisition curves (up to 2,400 mT) of 16 representative samples. The unmixing technique of Kruiver et al. (2001) was then used to analyze IRM acquisition curves. To further characterize the magnetic mineralogy, the 16 representative samples were sequentially magnetized along the Z, Y, and X axes at fields of 2.4, 0.4, and 0.12 T, respectively, and then, the samples were stepwise thermally demagnetized up to 690°C (in 23 steps; Lowrie, 1990).

3.3. Microscopy Imaging

Eighteen polished thin sections were characterized using optical microscopy to determine the level of diagenesis. A Supra-55 Sapphire scanning electron microscope (SEM) equipped with an Oxford Aztec X-Max 150 EDS (energy dispersive spectroscopy) was used for high-resolution mineralogical and textural characterization of five fresh fragments and 14 thin sections. During all the SEM observations and EDS analysis, we set the instrument at a 15-kV accelerating voltage.

3.4. Strontium Isotope Analysis

To constrain the nature of the fluids, Sr-isotope analyses were conducted on 37 representative samples using a Triton thermal ionization mass spectrometer at Nanjing University. In one outcrop section,

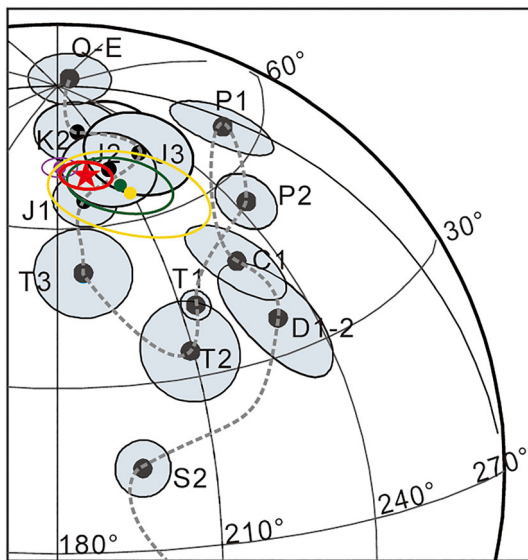


Figure 6. ChRM virtual geomagnetic poles plotted with the apparent polar wander path for the South China Block. The purple oval represents the ChRM of Permian strata, the green oval represents Silurian strata, and the yellow oval represents Ediacaran-Cambrian strata. The red star and oval represent the ChRM of all strata.

Permian carbonate samples of D3–D22 were collected systematically across the Formation with two underlying Silurian silicate samples of D1–D2. In the thrust belt, five representative carbonate samples from Cambrian were selected. In order to dissolve these samples, the carbonate samples were treated with weak acid, that is, acetic acid, while the muddy shale samples were treated with nitric and hydrofluoric acids, which dissolve silicate rocks. The ratios were normalized relative to standard reference materials (SRMs) of National Institute of Standards and Technology (SRM 987 = 0.710250 ± 0.000013). In order to calculate initial $^{87}\text{Sr}/^{86}\text{Sr}$ values, the Rb/Sr ratio (Table S1 in the supporting information) was also analyzed on an Aurora M90 inductively coupled plasma mass spectrometer at Nanjing University. The initial values of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio are calculated from the measured present-day values using the equation $^{87}\text{Sr}/^{86}\text{Sr}_{\text{ancient}} = ^{87}\text{Sr}/^{86}\text{Sr} - ^{87}\text{Rb}/^{86}\text{Sr} (e^{\lambda t} - 1)$, where $\lambda = 1.42 \times 10^{-11}$ (Banner, 2004).

3.5. Clay Mineral Analysis

Clay minerals from the Silurian mudstones and Permian carbonates were extracted from the insoluble residue that remained after carbonate and organic matter dissolution in weak acid and hydrogen peroxide, respectively. To characterize the relationship between remagnetization and the smectite-illite transition, we also conducted X-ray diffraction (XRD) experiments on eight oriented and naturally dried samples and four ethylene glycol-saturated samples with using a X'TRA XRD system ($2\theta = 2$ –

35°; scan rate = 1.2°/min; CuK α ; voltage = 40 kV; current = 40 mA). The detailed experiments were conducted following the methods of Zhao (2015).

4. Results

4.1. Paleomagnetism

Most samples yielded reliable magnetic directions after thermal and alternating field demagnetization (Table 1 and Figure 2). In general, two magnetic components were recognized for the Ediacaran-Permian samples. Component A (the lower temperature component) was isolated typically in five steps up to 200° C or for alternating fields typically in six steps up to 15 mT (Figure 2) and had a site-mean direction of D (Declination) = 2° and I (Inclination) = 51° (number of sites = 36 and $\alpha_{95} = 3^\circ$; Figures 3 and 4) which is close to the present-day field of I = $\sim 49^\circ$. Component B is the ChRM, and it was isolated on heating typically in nine steps from $\sim 200^\circ\text{C}$ to 460°C and for alternating fields typically in nine steps from 20 to 100 mT (Figure 2).

In the Permian strata, the average site-mean ChRM direction is D_g (declination in geographic coordinates) = 21°, I_g (inclination in geographic coordinates) = 55°, number of sites = 21, and $\alpha_{95} = 2^\circ$ (before tilt correction) and D_s (declination in stratigraphic coordinates) = 12.0°, I_s (inclination in stratigraphic coordinates) = 46°, number of sites = 21, and $\alpha_{95} = 23^\circ$ (Table 1 and Figures 3 and 4). The directions of the ChRMs cluster in the geographic coordinates but are more scattered in the stratigraphic coordinates, for example, α_{95} increases from 2° to 23°, suggesting posttilting acquisition. To test for the timing of remanence acquisition relative to the age of folding, we applied two fold tests for regional sites in the fold belt (Enkin, 2003; Tauxe et al., 2016), both of which show negative results, indicative of postfolding remanence acquisition (Figure 5). A regional tilt test was conducted since the samples were collected from less than five sites in a single fold, which is not sufficient for robust statistical analysis of individual fold tests.

In the Silurian and Ediacaran-Cambrian strata, the samples yielded the ChRMs of $D_g = 25^\circ$, $I_g = 44^\circ$, number of sites = 10, and $\alpha_{95} = 7^\circ$ for Silurian samples and $D_g = 27^\circ$, $I_g = 42^\circ$, number of sites = 5, and $\alpha_{95} = 11^\circ$ for Ediacaran-Cambrian samples. The ChRMs from Silurian and Ediacaran-Cambrian strata are slightly different from the ChRM in the Permian strata. After comparison of the ChRM mean pole position for the

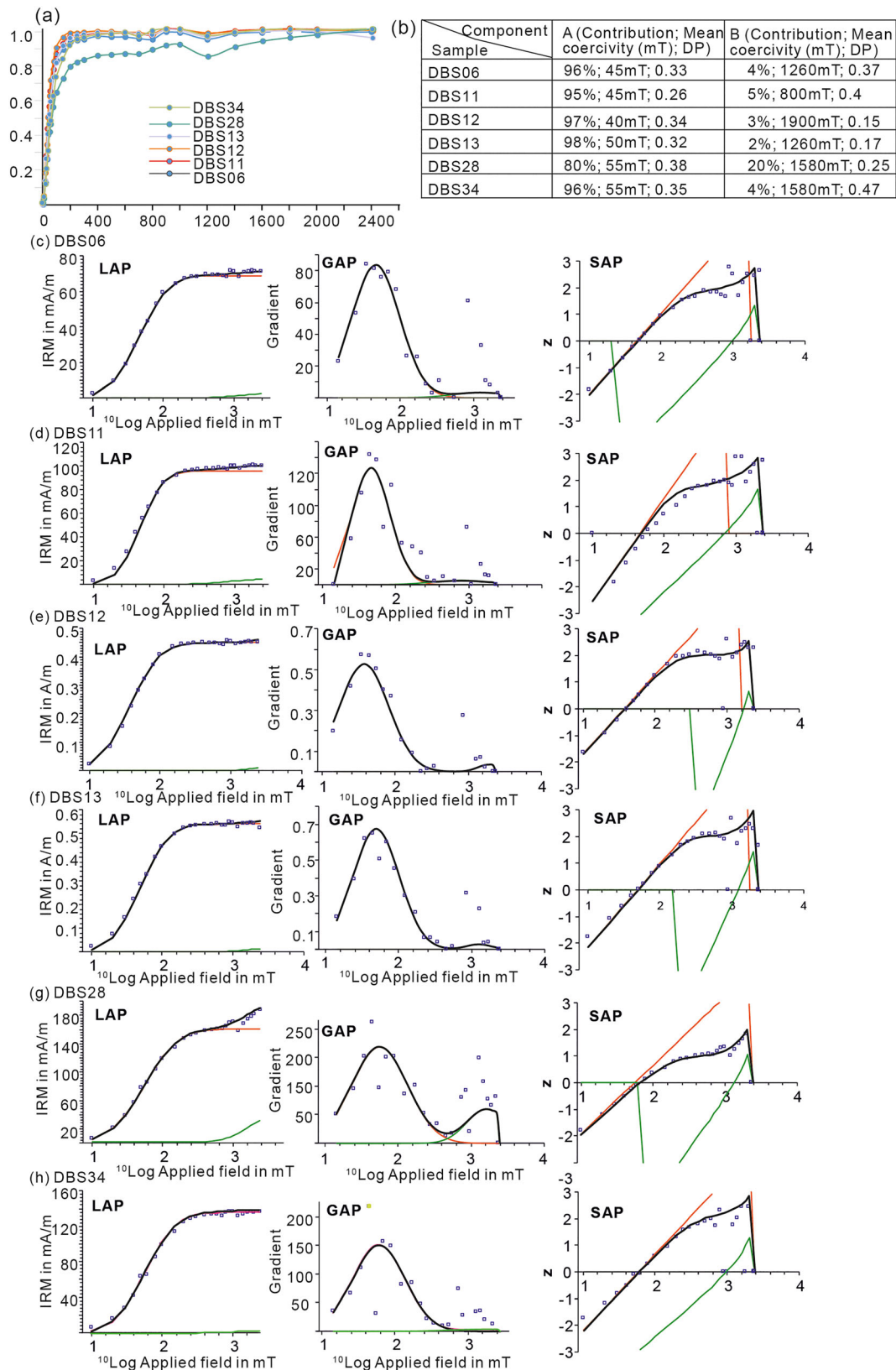


Figure 7. (a) IRM acquisition plots for representative samples. (b) Results of IRM analysis using the method of Kruiver et al. (2001). Also shown are examples of linear (LAP), gradient (GAP), and standardized acquisition plots (SAP) for samples from sites (c) DBS06 (muddy shale), (d) DBS11 (muddy shale), (e) DBS12 (sandstone), (f) DBS13 (sandstone), (g) DBS28 (carbonate), and (h) DBS34 (carbonate).

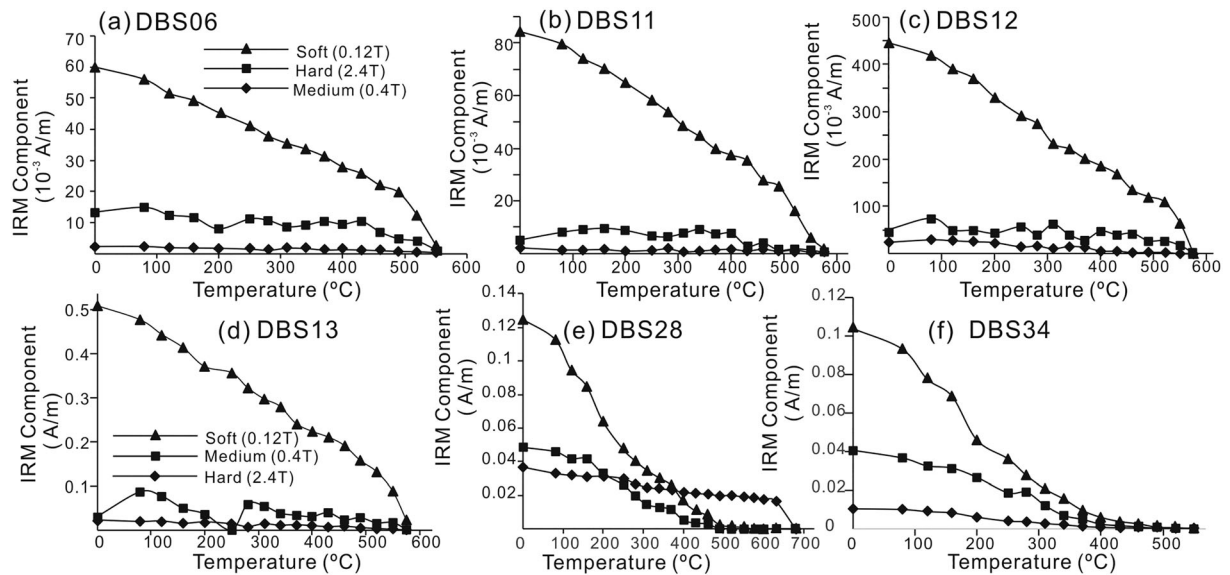


Figure 8. Triaxial IRM thermal demagnetization curves (Lowrie, 1990) for samples (a) DBS06, (b) DBS11, (c) DBS12, (d) DBS13, (e) DBS28, and (f) DBS34. The samples were sequentially magnetized with three perpendicular IRMs in fields of 2.4, 0.4, and 0.12 T.

Silurian, Ediacaran-Cambrian and Permian data with the apparent polar wander (APW) path for South China, we found that the poles of three ChRMs lie close to the Middle-Late Jurassic pole position (Figure 6; Yang & Besse, 2001; Zhang et al., 2015).

4.2. IRM Acquisition and Triaxial IRM Thermal Demagnetization

The majority of samples display IRM acquisition curves that increase steeply and reach >90% of saturation IRM by 0.2 T, for example, samples from DBS06, DBS11, DBS12, DBS13, and DBS34 (Figure 7). IRM acquisition curve analysis (Kruiver et al., 2001) suggest that these samples contain two components: (1) a component making up 95–98% of the signal with a mean coercivity of ~50 mT and dispersion parameter (DP) of 0.26–0.42 and (2) a second component (2–5%) with a mean coercivity of 800–1900 mT and DP of 0.15–0.47 (Figure 7), which indicate mostly low coercivity magnetic carriers, that is, magnetite. In contrast, the remaining samples represented by samples from site DBS28 only reaches ~80% of the maximum IRM value by 0.2 T (Figure 7) and does not saturate at the maximum applied field of 2.4 T. Two components were identified: Component 1 represents 80% of the total remanence, with a mean coercivity of 55 mT and a DP of 0.38, and Component 2 represents 20% of the total remanence, with a mean coercivity of 1,580 mT and a DP of 0.25 (Figure 7), indicating a high coercivity magnetic phase like hematite.

Samples were subjected to triaxial IRM thermal demagnetization after Lowrie (1990). Samples DBS06, DBS11, DBS12, DBS13, and DBS34 fully demagnetized at ~570°C, which is indicative of magnetite (Figure 8). In contrast, the magnetically “hard” fraction identified through IRM analysis found at site DBS28 did not fully demagnetize until ~680°C and the “soft” and “medium” fractions demagnetized by ~500°C (Figure 8); such behavior is indicative of the presence of hematite (hard fraction) and magnetite (soft and medium fractions).

4.3. Petrography and Scanning Electron Microscopy Observations

In the Permian limestone samples, under the optical microscope, we found micritic calcite was dominant; in places, the micritic calcite has been converted to coarsely crystalline sparry calcite (Figure 9a). Fusulinid foraminifers were also found to be an important component.

Framboidal iron oxides and iron sulfides were common in the pores and fractures of the Ediacaran-Permian samples in the SEM images (Figures 9b–9g). The rock magnetic characteristics and shape of these phases indicate they are authigenic magnetite. The atomic ratio of sulfur and iron from the EDS analysis suggests the iron sulfide is pyrite. The magnetite and pyrite were particularly common in the quartz and calcite

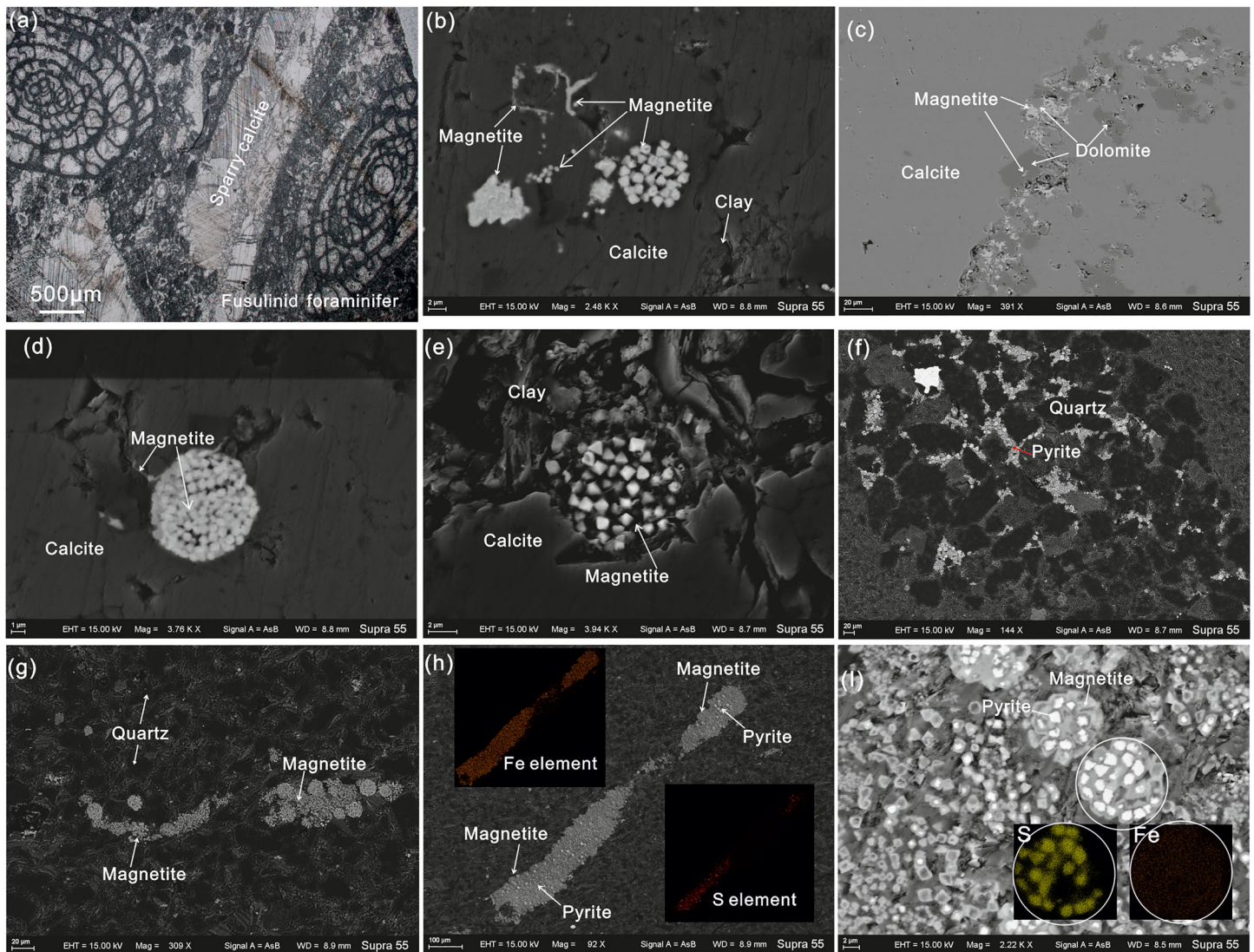


Figure 9. Transmitted light and backscattered images showing: (a) fusulinid foraminifers and sparry calcites in Permian limestone samples, (b and c) authigenic magnetite minerals distributed along fractures, (d and e) framboidal magnetite in pores, (f and g) authigenic pyrite and magnetite within pores in quartz and calcite interparticle porosity, and (h and i) abundant framboidal particles, with pyrite in the center and magnetite at the rim.

interparticle pores (Figures 9f and 9g). In some limestone samples, magnetite and pyrite were found in dolomitization areas with high porosities (Figure 9c). In some thin sections, we observed framboids containing pyrite particles in the center of the framboid, with magnetite at the edges (Figures 9h and 9i).

4.4. Strontium Isotope Data

Strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios of all the Permian limestones generally plot within the range of Permian seawater (0.7069–0.7081; McArthur et al., 2001, 2012). In an outcrop with almost the entire Permian formation, $^{87}\text{Sr}/^{86}\text{Sr}$ values of carbonate samples from the base to top of the Permian formation have a narrow range of 0.7070–0.7075 with a mean of 0.7072 (Figure 10), and 17 of all 20 samples are at the range of 0.7070–0.7073. (The complete data table can be found in <https://doi.org/10.6084/m9.figshare.13022879>.) The Cambrian carbonate sample yielded $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the range of 0.7097–0.7101, which are radiogenic relative to their coeval seawater $^{87}\text{Sr}/^{86}\text{Sr}$ data (0.7082–0.7091; Halverson et al., 2007; Li, Zhang, et al., 2013). The Silurian muddy shale samples yield very high Sr-isotope ratios, in the range from 0.726 to 0.758, mainly due to the samples' detrital origin.

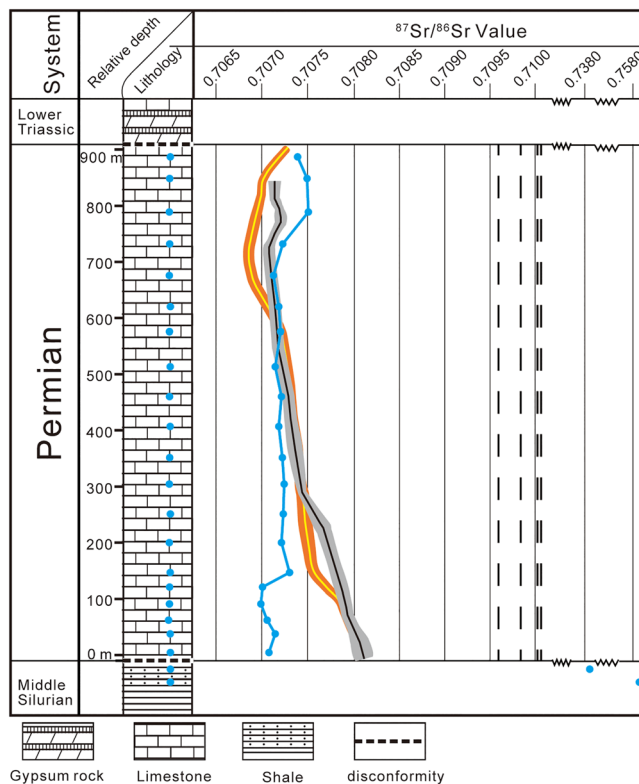


Figure 10. $^{87}\text{Sr}/^{86}\text{Sr}$ curves of Permian strata (blue points and line) in this study and coeval seawater (yellow line modified from McArthur et al., 2012; black line modified from Wang et al., 2018). The orange and gray fields represent the Sr error ranges of the coeval seawater curves. The dotted lines are the reference lines of chemically evolved fluids in the thrust belt. Note the break in the x axis for Sr isotopes, which allowed plotting of the data for Silurian samples.

4.5. Clay Mineral Analyses

The amount of extracted clays (0.2–110.9 mg) varied from 0.003 to 1.858 wt.% (<https://doi.org/10.6084/m9.figshare.13022879>) and shows a weak correlation with NRM ($R^2 = 0.0323$; Figure S1). Based on XRD analysis, the clay minerals were identified as mainly illite and chlorite; smectite was not present (Figure S1).

5. Discussion

Using a combination of both thermal and alternating field demagnetization, ChRMs were identified in a variety of rock units of Ediacaran to Permian age, including clay-rich black shales, mudstones, sandstones, dolomites, and limestones in the Dabashan thrust and fold belt. Fold tests suggest that ChRM was acquired after folding, and the mean pole position aligns with the regional APW path for the mean Middle-Late Jurassic direction (Figure 6). From these observations, we conclude that the ChRM is a remagnetization recorded during the Middle-Late Jurassic.

We argue that the remagnetization was due to chemical processes and not a thermal or viscous remanent magnetization (VRM) from the following reasons: (1) fluid inclusion and bitumen reflectance data in the fold belt yielded maximum temperatures of 192–240°C (Li, Dong, et al., 2013; Li, Zhang, et al., 2013), whereas the unblocking temperatures of ChRMs in the laboratory are ~500°C. By further comparing the time-temperature relaxation curve of Pullaiah et al. (1975), the maximum unblocking temperature in the laboratory should be more than 400°C in the geological process, which is much higher than actual maximum temperatures obtained from fluid inclusions and bitumen reflectance. The ChRM is therefore unlikely to be a VRM; (2) SEM suggests that the main ChRM carrier is authigenic framboidal magnetite, distributed along fractures and pores, formed by the oxidation of the pyrite (Figures 9h and 9i). The oxidization may have been induced by the abrupt change of redox condition from reductive to oxidative during or after the orogeny (Huang et al., 2019). These observations suggested that the ChRM is a CRM.

5.1. What Is the Origin of the CRM?

The data suggests that chemical remagnetization process occurred during the Middle-Late Jurassic. Therefore, the age of CRM acquisition appears postfolding but could also be coeval with formation of the orogeny, that is, similar to orogeny-related remagnetization carried by magnetite in the Appalachians (e.g., Miller & Kent, 1988), or very shortly after folding (Wilkinson et al., 2017).

Remagnetization is often associated with clay diagenesis or hydrocarbon migration (Elmore et al., 2012; Katz et al., 1998). Both mechanisms can be excluded in this case: (1) Clays are not pervasive in the remagnetization rock units, which, together with the lack of correlation between clay content and NRM intensities, and iron in authigenic magnetite appears not to be sourced from the smectite-illite as expected if it was due to clay diagenesis but rather from the altered pyrites. Both these observations suggest that clay diagenesis is an unlikely mechanism. (2) It is also unlikely that hydrocarbon generation or migration generated the remagnetization given the low concentration of organic material in these rocks.

We suggest that the Jurassic orogeny caused the widespread CRM in the Dabashan fold and thrust belt. This is supported by the tectonic history of the region where the scissor-like suturing processes of the SCB and NCB during the Triassic caused widespread and progressively westward younging of the CRMs in the SCB (Jiao et al., 2019). Due to the uplift and deformation by the Jurassic orogeny, it is likely that a large volume of fluids migrated leading to alteration in the fold and thrust belt. Additionally, the sudden uplift of marine carbonate rocks will have likely caused abrupt changes in the redox conditions to a more oxidative state. This is supported by the apparent oxidation of pyrite to form authigenic magnetite (Figures 9 h and 9i), which

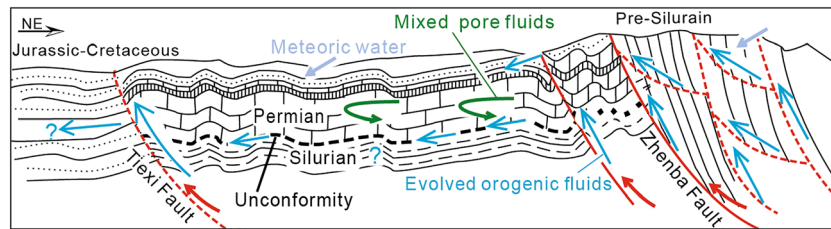


Figure 11. Schematic cross section of the Dabashan fold and thrust belt illustrating the inferred migration route of fluids that caused the widespread remagnetization. It is inferred that the Triassic gypsum deposits prevented vertical migration of the meteoric water and externally derived evolved fluids. The evolved fluids are suggested to have migrated preferentially along thrust faults and unconformities. Red lines represent the faults, blue arrows represent movement of evolved orogenic fluids, and green arrows represent mixing of pore fluids.

lead to the remagnetization. We propose that fluid circulation due to the Jurassic orogeny and the abrupt change of redox condition is the mechanism behind the remagnetization process (e.g., Huang et al., 2019).

5.2. Pattern of Fluid Migration

Orogeny-induced fluid migration and alteration were likely responsible for the widespread Jurassic CRM in the Dabashan fold and thrust belt. However, based on the Sr-isotopic data of the fluids, the pattern of fluids migration in Dabashan fold and thrust belt varied in different units and belts.

In the thrust belt, the $^{87}\text{Sr}/^{86}\text{Sr}$ values of the carbonate samples from Cambrian strata are greater than the composition of seawater reference values during the times of deposition (Figure 10), indicating that the original sediments were altered by evolved fluids (Figure 11). In the fold belt, the $^{87}\text{Sr}/^{86}\text{Sr}$ values of the carbonate samples from Permian strata are still in the range of Sr values of coeval seawater (Figure 10), indicating that the contribution of external evolved fluids to alteration of the Permian strata is insignificant during the Jurassic orogeny. From the base to the top of the Permian Formation, the $^{87}\text{Sr}/^{86}\text{Sr}$ data are relatively invariable and with a mean similar to that of the Permian seawater (Figure 10). This likely indicates that the Permian original pore fluids were mixed within the formation. This is supported by three other lines of evidence from Permian strata and its overlain and underlain strata: (1) At the boundary of the Permian and Silurian strata, the closest distance between the Silurian and Permian samples for Sr isotope is less than 5 m, and Silurian $^{87}\text{Sr}/^{86}\text{Sr}$ values are very high, but the adjacent Permian carbonate samples show relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ values (Figure 10). This suggests that possible evolved orogenic fluids did not flow from the Silurian to the Permian rock units but rather flowed along the unconformity between the Silurian and Permian strata. (2) Above the Permian strata, low-permeability gypsum deposits in Lower Triassic strata would have inhibited significant vertical migration of meteoric water and radiogenic fluids through the crust. (3) Based on vein and fluid inclusion studies (Li, Dong, et al., 2013; Tan et al., 2016), overpressurized conditions (150–200 MPa) likely occurred in the Permian strata. This overpressure is thought to be due to the large-scale compression and thrusting of Jurassic orogeny and the sealing nature of the gypsum deposits in the upper strata (Ge & Garven, 1992).

We suggest that evolved orogenic fluids have altered and remagnetized the Ediacaran-Cambrian strata due to the Jurassic orogeny, probably through the widespread thrust faults and related fractures in the thrust belt (Kirschner et al., 1999); however, the Permian strata have become remagnetized via internal remixing of original pore fluids (Figure 11). Such remagnetization in original pore fluids has been suggested previously for the Western Canada sedimentary basin (Cioppa et al., 2003).

6. Conclusions

We conducted an integrated magnetic, petrographic, and Sr-isotope investigation of Ediacaran-Permian strata in the Dabashan fold and thrust belt. Widespread Middle-Late Jurassic CRM occurred in the belts, which was likely caused by alteration of orogeny-induced fluids and abrupt change of redox condition due to the uplift and deformation. The pattern of fluid migration varied from the thrust to fold zone. In the thrust belt, Sr-isotopic data suggest that radiogenic orogenic fluids migrated along thrust faults and fractures. In the fold belt, the evolved fluids do not appear to have migrated through the rock units but

preferentially migrated along unconformity surfaces and fractures and were constrained by low-permeability gypsum deposits (Figure 11). This case study provides an improved understanding of fluid flow in orogenic regions, as well as the origin of the widespread remagnetization in China.

Data Availability Statement

The data for the work in this paper can be downloaded from the figshare website (<https://doi.org/10.6084/m9.figshare.13022879>). Supporting information figures can be found in the supporting information.

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