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Key Points:

- The Chinese Altai and East Junggar are revised using the potential field, geological, and geochemical data
- Geophysical domains result from the Devonian and Permian tectonometamorphic and magmatic reworking
- No prominent deep-seated discontinuity defines the Erqis Zone challenging its tectonic importance

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Revision of the Chinese Altai-East Junggar Terrane Accretion Model Based on Geophysical and Geological Constraints

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Abstract Potential field data analysis, geology, and geochemistry are used to revise the terrane accretion model of the Chinese Altai and East Junggar. Major gradients of potential field data demarcate significant crustal structures and their continuity in depth. These data demonstrate that the distribution of geophysical anomalies does not match with terranes boundaries defined previously. Instead, heterogeneously developed NE/SW-trending gravity and NW-SE magnetic anomalies in both units correlate with Devonian and Permian tectonometamorphic zones, respectively. Geophysical data also indicate a dense lower crust of the East Junggar confirmed by previous igneous petrology studies and seismic experiment. The northern tip of this dense crust coincides with the main gravity gradient beneath the Chinese Altai and a prominent magnetic high located above a NW/SE-trending zone of Permian granulites. This zone forms a boundary between north- and south-dipping gravity and magnetic anomalies that are interpreted as reflecting quasi-symmetrical extrusion of the Chinese Altai crust. In contrast, all geophysical data show the absence of a prominent deep-seated discontinuity which can be correlated with the Erqis Zone. These data are compared with corresponding data sets from southern Mongolia allowing the proposition of a new geodynamic model for the studied area. This model involves (1) accretionary stage characterized by Late Devonian joint evolution of the East Junggar and Chinese Altai characterized by N-S trending orogenic fabrics and (2) Early Permian oroclinal bending associated with underthrusting of the dense Junggar basement beneath the Chinese Altai and the development of NW-SE trending deformation zones in both units.

1. Introduction

Accretionary orogens develop along convergent plate boundaries during long-lived Pacific-type subduction by accretion of oceanic sediments, volcanic arcs, backarcs, and more rarely continental ribbons (e.g., Cawood et al., 2009). Accreted blocks of oceanic and continental origin characterized by distinct lithostratigraphic and tectonic evolutions and separated from each other by deep-seated strike-slip faults or sutures are called tectonostratigraphic "terranes" (e.g., Coney et al., 1980; Jones et al., 1983). These terranes are accreted to each other after their formation, and therefore, they are commonly called "accreted terranes" to underline their late attachment to a continental landmass.

The Central Asian Orogenic Belt (CAOB) is one of the largest accretionary orogens worldwide (Figure 1 inset) formed from Neoproterozoic to Mesozoic times by continuous accretion of various terranes (Şengör et al., 1993; Windley et al., 2007). It can be subdivided into two main parts: the eastern Mongolian and the western Kazakhstan collage systems, which consist of Precambrian ribbon continents and Late Proterozoic to Early Paleozoic arcs, backarcs, and accretionary complexes (e.g., Şengör & Natal'in, 1996; Xiao et al., 2018). These vast orogenic systems are limited in the south by collage of amalgamated small continental blocks, Paleozoic arcs, and accretionary complexes north of the Tarim and North China cratons (Figure 1). According to Şengör et al. (1993), Wilhem et al. (2012), and Xiao et al. (2015), the two giant Mongolian and Kazakhstan systems are separated from each other by the giant Char-Erqis Zone that accommodated their complex attachment during Paleozoic times. In northwestern China, it separates two distinct domains: the

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Figure 1. Tectonic map of the Mongolian collage system and the adjacent Kazakhstan collage constituting the central part of the CAOB (modified from Kröner et al., 2010; Parfenov et al., 2003; Şengör et al., 1993).

lithologically heterogeneous Chinese Altai interpreted as an Early Paleozoic accretionary prism affected by Devonian metamorphism and magmatism and the weakly to unmetamorphosed East Junggar Paleozoic sediments and volcanics (Jiang et al., 2016; P. Li et al., 2019; Xiao et al., 2009). Separating the Chinese Altai and the East Junggar, the Erqis Zone is either interpreted as a suture (Coleman, 1989; Xiao et al., 2009) or a giant sinistral shear zone along which were exhumed and sheared high-grade Permian metamorphic complexes (Briggs et al., 2007; Buslov, 2011; Laurent-Charvet et al., 2003; P. Li, Sun, et al., 2016; P. Li et al., 2019). The Chinese Altai itself and the southerly East Junggar were divided into "subsidiary" tectonos-tratigraphic terranes separated by vertical fault zones (Windley et al., 2002; Xiao et al., 2004). The Chinese Altai and East Junggar geological units continue to the east to Mongolia, where they were previously interpreted as accreted highly contrasting terranes separated by the Bulgan Fault, which has been interpreted by many as a continuation of the Erqis Zone (Badarch et al., 2002; Xiao et al., 2004).

In theory, the accreted terranes (arcs, backarcs, and continental ribbons) should show not only contrasting tectonostratigraphy but also contrasting geophysical signatures. Therefore, the assemblages of accreted terranes are often examined using potential field data especially because they revealed contrasting magnetic and gravity physical properties (e.g., Banka et al., 2002; Burton, 2010; Glen et al., 2007). The physical properties of the rocks are primarily controlled by the lithology but also by the tectonometamorphic and magmatic events that can modify the density of rocks (Smithson, 1971) and the concentration of magnetic minerals (e.g., Martelat et al., 2014). As the magnetic and gravity data are the sum of potential field responses from sources located at different levels in the lithosphere, they provide information on physical properties at depth intervals that are not available from seismic methods. The potential field methods thus enable to define the geometry of geological bodies and tectonic units that can be correlated with the surface geology and tectonostratigraphic records (e.g., Godin & Harris, 2014; Martínez Catalán, 2012; Stewart & Betts, 2010).

Recently, the Mongolian part of the CAOB was examined using potential field methods in order to characterize deep crustal nature of main terranes and boundaries (Guy et al., 2015; Guy, Schulmann, Munschy, et al., 2014). Surprisingly and unlike other archetypal accretionary systems (Alaska, Lachlan belt in



Australia), the potential field anomalies of the Mongolian CAOB do not match with the principal tectonic boundaries separating terranes identified by previous studies (Badarch et al., 2002). Instead, it was found that (1) the magnetic signals match with the location of Permo-Triassic magmatic provinces, (2) the shallow gravity lineaments coincide with steep NW-SE trending deformation zones of Permian age (Guy, Schulmann, Clauer, et al., 2014), and (3) the deep crustal gravity signal beneath Devonian-Carboniferous oceanic terranes corresponds to low-density felsic crust of relaminated Cambrian arc (Guy et al., 2015). In light of these findings, the geophysical characterization of the Chinese Altai and East Junggar represents a pivotal task because of their supposed "terrane" architecture and first-order geodynamic significance of the Erqis Zone separating these two superunits.

In the present paper, the geophysical structure of the Chinese Altai and adjacent East Junggar was studied by means of the potential field methods in order to examine the magnetic and gravity signatures of the suspect terranes defined in this area. Different and complementary data filtering techniques were applied to constrain the structure of the crust from shallow levels to depth, to investigate the continuity of the deep-seated sources, and to provide a 3-D spatial representation of magnetic and gravity gradients. The analysis of geophysical anomalies was completed by the comparison between the Paleozoic lithologies of adjacent Chinese and Mongolian "terranes" and their principal structural trends deduced from regional structural geology. This approach was used to correlate structural and geophysical lineaments in the Chinese Altai and East Junggar with their Mongolian counterparts provided by Guy, Schulmann, Munschy, et al. (2014) and Guy et al. (2015). We also reassessed the timing of their mutual attachment using detrital zircon age patterns of Devonian-Carboniferous sequences. Combination of geology and geophysics allows us to decide as whether the common geodynamic evolution of the Chinese Altai and East Junggar and the corresponding Mongolian units started long before or during proclaimed Permian activity of the Erqis Zone. Finally, the tectonic significance of main geophysical anomalies is proposed and discussed in the frame of the Devonian accretionary and Permian oroclinal bending events.

2. Geological Background of the Chinese Altai and the East Junggar

In the western part of the Mongolian collage, three tectonic zones were previously defined (Figure 1): (1) the Lake Zone in the northeast, which is composed of Neoproterozoic-Cambrian volcanic arcs and accretionary complexes (Kröner et al., 2010; Zonenshain & Kuzmin, 1978); (2) the Mongol-Altai Zone in the center, which includes also the Chinese Altai and which corresponds to a Cambrian-Ordovician volcanic and sedimentary wedge (Xiao et al., 2010); and (3) the East Junggar in the south-south-west which is a Devonian-Carboniferous oceanic domain (Fang et al., 2015; Huang et al., 2018; Jian et al., 2005). The boundary between the Chinese Altai and East Junggar is demarcated by the Erqis Zone (EZ) active from the Carboniferous to Permian (Buslov et al., 2004; P. Li et al., 2015; Zhang et al., 2012).

2.1. Geological Setting

Windley et al. (2002) and Xiao et al. (2004) synthesized the lithotectonic evolution of the Chinese Altai and proposed a model of its formation by a progressive accretion of terranes. Five NW-SE oriented tectonostratigraphic units were interpreted as suspect terranes (the Qiongkuer-Abagong and the South Altaishan terranes in the south, the Central Altai, the North Altaishan, and the Northwest Altaishan in the north, Figure 2) that were defined as metamorphic, island arc, continental magmatic arc, fore arc, accretionary prism, and microcontinental Precambrian blocks separated by steep strike-slip faults.

This complex metasedimentary and magmatic assemblage is delimited from the southerly Devonian-Carboniferous oceanic East Junggar domain by the EZ (e.g., D. Li, He, et al., 2016; Xiao et al., 2009). This zone was traditionally interpreted as a giant wrench fault accommodating ~1,000 km of left-lateral displacement at 290–280 Ma (Buslov et al., 2004; Şengör et al., 1993). In most of the recent structural studies, the EZ was described as a major transpressive shear zone (e.g., Buslov, 2011; Laurent-Charvet et al., 2003; P. Li et al., 2015, 2017) resulting from the juxtaposition of the Mongolian and Kazakhstan oroclines during the final amalgamation of the CAOB. However, the presence of Devonian ophiolitic fragments around the EZ led some authors to interpret it as a Permian suture between the intraoceanic Junggar arc and the Chinese Altai accretionary wedge (Coleman, 1989; Xiao et al., 2004, 2018; Zonenshain et al., 1990). Finally, the kinematic and geochronological study of Briggs et al. (2007) suggested that the EZ corresponds to a Permian south-vergent thrust bringing deep metamorphic rocks above unmetamorphosed sediments





Figure 2. Simplified geological map of the Chinese Altai and the East Junggar (modified from Broussolle et al., 2018; Liu et al., 2013) with terranes boundaries (thick dashed black curves) synthesized after Windley et al. (2002) and Xiao et al. (2004) and the different traces of the Erqis Zone from the literature (in red lines).

during a prominent regional shortening at ca. 290 and 265 Ma. Strikingly, the location of the EZ differs according to the studies: One is located north of Buerjing city (Briggs et al., 2007; Buslov et al., 2004; Coleman, 1989; Laurent-Charvet et al., 2003), and the second is located south of it (Broussolle et al., 2019; Jiang et al., 2015; P. Li et al., 2017; Xiao et al., 2009).

The East Junggar unit south of the EZ is located in the northeastern side of the Junggar Basin (Figure 1). It contains remnants of the Paleozoic intraoceanic magmatic arcs (viz., the Dulate arc and the Yemaquan arc), accretionary complexes, and ophiolitic mélanges. The Zhaheba ophiolite complex, which extends to the south of the NW-trending Armantai-Ulungur Fault, separates the Dulate arc to the north from the Yemaquan arc to the south (Long et al., 2012; Luo et al., 2017; Xiao et al., 2004; Zhang et al., 2008). The Zhaheba ophiolites are considered to represent the site of an important suture between the two arcs based on the presence of UHP assemblages exhumation dated as Early Permian (Niu et al., 2007; Xiao et al., 2009) leading Xiao et al. (2004) to interpret the Dulate and Yemaquan arcs as two distinct terranes. Numerous Carboniferous to Permian granitoids intruded these Devonian-Carboniferous volcanic and clastic sedimentary rocks (Chen & Jahn, 2004; Liu et al., 2013; Wang et al., 2017). The Permian bimodal magmatism associated with continental volcanic rocks is interpreted to reflect the transition from subduction to collision (Z. Li et al., 2014).

Altogether, the modern structural and petrological studies show that the northern part of the Chinese Altai is represented by the weakly metamorphosed Paleozoic sequences in the west and the high-grade, magma-rich orogenic core to the east both affected by Devonian folding (Broussolle et al., 2019). In contrast, the southern Chinese Altai seems to reflect mainly Permian deformation, magmatism, and metamorphism with their intensity progressively increasing toward the EZ in the south (Jiang et al., 2019). This general pattern can be interpreted in terms of terrane accretion, or, alternatively, it may have resulted from a





(a) Chinese Altai vs. Mongol-Altai Zone (b) East Junggar vs. Trans-Altai Zone

Figure 3. Schematic lithostratigraphic columns for the Chinese Altai compared to the Mongol-Altai Zone and East Junggar compared to the Trans-Altai Zone compiled from Kröner et al. (2010), Liu et al. (2013), Novikov (2013), Soejono et al. (2018), and Broussolle et al. (2019).

metamorphic-magmatic reworking and a complex structural reorganization of the primarily homogeneous accretionary wedge as suggested by Broussolle et al. (2019). The results of the geophysical study presented below shed light on this dilemma.

2.2. Tectonostratigraphy and Detrital Zircon Spectra of the Chinese Altai and East Junggar Sequences Correlated With Adjacent Mongolian Units

The Paleozoic lithostratigraphy of the Chinese Altai begins with a Cambro-Ordovician sequence composed of variably metamorphosed volcaniclastic rocks intercalated with sandstone, siltstone, and shale layers in





Figure 4. Comparison of detrital zircon ages from Devonian-Carboniferous (meta-)sedimentary rocks of East Junggar (Huang et al., 2018; Long et al., 2012; Zhang et al., 2013), Chinese and Mongol-Altai (P. Li et al., 2015; Soejono et al., 2018, and also unpublished data), and the Trans-Altai Zone (Yang et al., 2019).

the north similar to the Mongol-Altai Zone in the east (Broussolle et al., 2019, and references therein; Jiang et al., 2017). It is followed by the unconformable Devonian sequences dominated by volcanic and volcaniclastic rocks, intercalated with marine clastic sediments and limestones, and Lower Carboniferous siliciclastic and volcaniclastic strata in the south, sequences also similar to the Mongol-Altai Zone (Kröner et al., 2010; Soejono et al., 2018). The Paleozoic sequences of the Mongol-Altai Zone are further unconformably covered by continental and lacustrine deposits associated with bimodal volcanics of Permian age (Figure 3a). The comparison of the Paleozoic sequences in the Chinese Altai and the Mongol-Altai thus shows remarkable similarity implying their common stratigraphic evolution.

To the south of the Chinese Altai, the East Junggar rocks range from Silurian to Jurassic in age. The lowermost part of the lithostratigraphic column is composed of the Silurian siltstone and phyllite unconformably overlain by Devonian volcaniclastic rocks, intercalated with sandstone and siltstone (P. Li, Sun, et al., 2016; Liu et al., 2013). The Lower Carboniferous strata mainly consist of tuff and tuffaceous sandstone (P. Li, Sun, et al., 2016; Liu et al., 2013), whereas the Upper Carboniferous-Lower Permian rocks are composed of volcanic and siliciclastic sediments (Liu et al., 2013; Long et al., 2006). The Upper Permian beds and the Triassic sequence, which unconformably overly the Permian strata, are composed of intercalations of sandstone, siltstone, mudstone, and conglomerate indicating deposition in an intracontinental basin environment. Finally, the Jurassic rocks display alluvial and lacustrine-deltaic facies comprising mostly mudstone and shale intercalated with conglomerate and sandstone alternating with coal units (Bian et al., 2010; Novikov, 2013). In comparison, the rocks of the Trans-Altai Zone ranging in age from Silurian to Jurassic (Figure 3b) display similar sequence of basaltic to andesitic rocks and volcano-sedimentary sequences typical of back-arc and oceanic arc environments (Lamb &

Badarch, 2001; P. Li, Sun, et al., 2016; Novikov, 2013; Ruzhentsev et al., 1985) followed by the Carboniferous clastic sedimentary sequence and the Permian-Jurassic typical intracontinental sedimentary deposits. It thus implies that the lithologies of the Dulate and Yemaquan terranes in East Junggar are highly comparable to those observed in the Trans-Altai Zone in southern Mongolia (Nguyen et al., 2018).

The comparison of published detrital zircon age spectra for the Devonian-Carboniferous metasedimentary rocks from the East Junggar (Huang et al., 2018; Long et al., 2012; Zhang et al., 2013), the Chinese and Mongol-Altai (P. Li et al., 2015; Soejono et al., 2017, 2018), and the Trans-Altai Zone (Yang et al., 2019) shows that age populations from all three domains share identical basic features (Figure 4). All these age spectra contain major peaks at ca. 340 and ca. 490 Ma and a broad minor peak in the interval of 1,200–700 Ma. Such a detrital pattern was interpreted as clastic material derived mainly from the northerly Proterozoic Lake Zone and margins of Precambrian Mongolian microcontinents (e.g., Janoušek et al., 2018; Jiang et al., 2017; Soejono et al., 2018). The difference in amplitude of the ca. 340 Ma age peaks is related to the subordinate presence of Carboniferous magmatic rocks in the Chinese and Mongol-Altai. In contrast, the smaller amount of ca. 490 Ma zircons is caused by the more distal position of the East Junggar and the Trans-Altai Zones from the Cambro-Ordovician arc-related sources in the Lake Zone (Janoušek et al., 2017; Soejono et al., 2017; Soejono et al., 2016).

Altogether, a comparison of the Chinese Altai lithostratigraphy with the classical profiles of the Mongol-Altai (Kröner et al., 2010; Markova, 1975; Soejono et al., 2018) shows that they are strikingly similar and in consequence they can be considered to form one system called the Mongol-Altai volcano-sedimentary wedge (MAW) (e.g., Jiang et al., 2017). Similarly, the lithological columns dominated by the island arcs of the East Junggar Paleozoic sequences and those of the Baytag and Baraan terranes in south-western Mongolia (Figure 1) are very similar to each other (Nguyen et al., 2018), suggesting that





Figure 5. (a) Magnetic map reduced to the pole with boundaries of suspect terranes and principal faults superimposed. (b) Isostatic residual anomaly map with Bouguer anomaly map in inset with boundaries of suspect terranes and principal faults superimposed. The anomaly maps are displayed using a linear scale. (c) Topography map from Earth 2014 (Hirt & Rexer, 2015), with the correlation between the isostatic gravity residual anomalies and the topography in inset. The black dotted lines represent the terrane boundaries.

both regions can be merged into a single Devonian-Carboniferous oceanic unit called here the East Junggar-Trans-Altai Zone (EJTA). The resemblance of detrital zircon age spectra from the MAW and EJTA indicates that the clastic material had a common source and provenance before the Permian. This fact implies that all three domains were mutually connected spatially and could not have been separated by an oceanic domain at that time.

The similarities between the geological records of northwestern China and southern Mongolia imply that the results of geophysical studies of Guy, Schulmann, Munschy, et al. (2014) and Guy et al. (2015) can also be correlated with those presented below. Whereas in Mongolia the main problem was solely the correlation between geophysical anomalies and the supposed suspect terranes, in China it is also important to consider the role of the EZ as a giant boundary between the Mongolian and Kazakhstan collages or, at least, as a proper boundary between the Chinese Altai and the East Junggar units. Importantly, based on revised detrital zircon data and the lithostratigraphy analysis of the MAW and EJTA, we can conclude that both units shared a common tectonic history at least from Late Devonian time. These assumptions have a pivotal impact on existing geodynamic models where the EZ has been assumed to play the role of a major terrane boundary.





Figure 6. Spectra and matched filtering results for magnetic anomalies. (a) Calculated and modeled spectra. (b) Magnetic dipole layer of shallow sources at 3.5 km. (c) Magnetic dipole layer of intermediate deep sources at 17 km. (d) Magnetic half-space layer of deep sources at 42 km. The orientations of the lineaments were quantitatively examined using the program PolyLX to calculate the rose diagrams (https://petrol.natur.cuni.cz/~ondro/oldweb/polylx:home).

3. Potential Field Data and Filtering: Methodology and Results

Magnetic and gravity signals are related to the petrophysical properties of the rocks, and therefore, the anomalies of the signal characterize the contrasts of magnetic susceptibility and density. Depending on the scale and the resolution of data, the magnetic anomalies generally characterize structures of the upper and middle crust, whereas gravity anomalies are commonly used to investigate deeper crustal structures. The analysis of potential field data determines the significant crustal structures by undertaking suitable filtering procedures in order to localize the anomalies, the trend of their gradients, and estimate their continuity in depth. Thus, the spectral analysis and the tilt angle are computed to enhance the gradients, extract the interpreted lineaments, and analyze their trends. Pseudo-gravity transformation is applied to detect the common deep sources, and multiscale edge analysis is performed to obtain the strike and dip of the major contacts between lithologies with different density and/or magnetic susceptibility.

3.1. Data Sets

Magnetic anomaly data used for this study were extracted from the Earth Magnetic Anomaly Grid available at a spatial resolution of 2×2 arc minute (EMAG2), which contains satellite and airborne measurements at 4 km altitude above the geoid (Maus et al., 2009). In order to center the anomalies over their sources, a reduction to the north magnetic pole has been applied to the data according to the International Geomagnetic





Figure 7. Spectra and matched filtering results for isostatic residual anomalies. (a) Calculated and modeled spectra. (b) Gravity signal of the density layer containing shallow sources at 4.5 km. (c) Density layer of intermediate deep sources at 20 km. (d) Density half-space layer of deep sources at 44 km.

Reference Field (IGRF) using 67.4° for inclination and 3.7° for declination and the magnitude of the regional magnetic field of 57,716.9 nT. The magnetic anomalies obtained range from -247 to 364 nT (Figure 5a).

The Bouguer gravity anomaly map (Figure 5b, inset) comes from the Earth Global Model 08 (EGM08) available at a spatial resolution of 2.5×2.5 arc minute (Pavlis et al., 2012). It is composed of the full spectrum including the long-wavelength signals, which have to be removed to enhance the density contrasts of the surface lithologies and faults. Consequently, the isostatic residual Bouguer gravity anomaly map has been calculated following the same procedure and parameters of corrections as in Guy, Schulmann, Munschy, et al. (2014). The residual map ranges from -114 to 3 mGal (Figure 5b) and is weakly correlated with the topography (Figure 5c and inset).

3.2. Spectral Analysis

The magnetic and gravity signals can be decomposed into sets of sinusoids, which are related to sources located from shallow to deeper crustal levels. The decomposition of the signal is performed using the matched filtering, which allows an anomaly separation based on the analysis of the Fourier power spectrum of the potential field data (Phillips, 2001; Spector & Grant, 1970; Syberg, 1972). The power spectra of magnetic and gravity data are step by step matched to their respective modeled power spectra (Figures 6a and 7a). The resultant filtered magnetic anomaly maps display short-, intermediate-, and long-wavelength signals respectively produced by shallow (3.5 km), transitional (17 km), and deep (42 km) magnetic sources





Figure 8. (a) Tilt derivative of the magnetic anomalies and the relative main lineaments (white lines). (b) Tilt derivative of the gravity anomalies. The boundaries of suspect terranes are superimposed (black dashed curves), and the principal faults are represented by dark gray curves.

(Figure 6a). The lineaments represent the locations of the crests of the magnetic highs. The rose diagrams related to the trends of the lineaments for each equivalent layer show that from shallow to deep crustal levels the main strike of the lineaments is NW-SE. The results demonstrate in particular a prime continuity in depth for an elongated prominent magnetic high north-west and south of Altay city. However, there is a complete lack of correlation between the strong magnetic gradients and boundaries of the suspect terranes. The isostatic residual anomaly power spectra have been fitted to three equivalent layers attributed to shallow (4.5 km), intermediate (20 km), and deep (44 km) crustal layers (Figure 7a). From shallow to deep equivalent layers, the rose diagrams reveal larger variations in the orientation of the crests of the gravity highs compared to those of the magnetic lineaments. The resulting lineaments are mostly oriented N-S for the shallowest slice (Figure 7b) to mainly NW-SE for the deepest layer (Figures 7c and 7d). In addition, the results reveal a pronounced discrepancy between the different slices because the deepest layer seems to barely share continuity of the gravity anomalies with the shallow and the intermediate equivalent layers.

3.3. Tilt Derivative

In order to complement and cross-check the lineaments defined by the matched filtering, the tilt angle method was performed. As the tilt angle deals with the ratio of the vertical to the total horizontal derivatives, it is relatively insensitive to the depth of the source and should resolve shallow and deep sources equally well. Moreover, it is positive over the sources, crosses through zero at or near the edge of a vertical boundary, if applied on grid reduced to the pole, and is negative outside the source region. Therefore, the obtained map highlights the orientation of the linear tectonic fabric of the basement (Miller & Singh, 1994; Verduzco et al., 2004), and it can be used to constrain the location of the sources (Figures 8a and 8b). Comparing the resulting tilt angle for both magnetic and gravity data with the matched filtering results, the correlation is high between the lineaments identified by the two methods. The magnetic lineaments defined by the tilt angle are strongly aligned NW-SE, whereas the gravity lineaments trend NE-SW, and equally spaced anomalies are in the northern part of the Chinese Altai. In addition, a NW-SE boundary can be identified from the gravity tilt angle results, which separates the northern from the southern Chinese Altai and which does not coincide with the EZ.

3.4. Pseudo-gravity Transformation

Pseudo-gravity converts a magnetic anomaly into a gravity anomaly in the Fourier domain with respect to the Poisson's relation giving the declination (3.7°) and the inclination (67.4°) of the magnetic field (Baranov, 1957; Cordell & Grauch, 1985). To sum up, the pseudo-gravity transformation provides the gravity field that would have been observed, if the density would be proportional to the induced magnetization. This





Figure 9. (a) Pseudo-gravity transformation of the magnetic anomalies. (b) Bouguer gravity anomaly map for direct comparison with the pseudo-gravity transformation. The boundaries of suspect terranes are superimposed (black dashed curves), and the principal faults are represented by dark gray curves.

transformation enhances the anomalies associated with deep magnetic sources such as magnetic granitoids and mafic basement by reducing the intensity of the shallower sources. Comparing the pseudo-gravity with the Bouguer anomaly map (Figures 9a and 9b) enables us to detect common deep sources for the magnetic and gravity anomalies. The results portray a common high for both the pseudo-gravity and the Bouguer gravity anomaly maps in the western and southern parts of the Chinese Altai and an important high in the north of the Junggar Basin, which indicates a common deep sources of these anomalies.

3.5. Multiscale Edge Detection

Multiscale edge analysis is a wavelet transform-based technique that maps curvilinear features, which correspond to the maxima of the total horizontal derivative of the gridded potential field indicating a boundary between units of distinct physical properties at different levels of upward continuation. For each upward continuation, a layer of maxima is obtained that constrains the location and strength of magnetic and gravity gradients at the depth corresponding approximately to the half of the upward continuation. When superimposing the results for the successive upward continuation layers, we obtain a 3-D architecture where the lateral shift of horizontal gradient maxima represents the strike and dip of contacts for the detectable magnetic susceptibility and density contrasts (Archibald et al., 1999; Holden et al., 2000; Hornby et al., 1999; Vallée et al., 2004).

Multiscale edge detection is processed for the analytic signal of the total magnetic intensity (Baranov, 1957; Fedi, 1989) and for the Bouguer anomalies for 10 upward continuations from 2 to 20 km providing information about the location and dips of geological contacts, granitic intrusions, faults, and shear zones from 1 to 10 km depth (e.g., Austin & Blenkinsop, 2008; Godin & Harris, 2014; Vos et al., 2006). The multiscale edge detection method does not give enough relevant results for the deeper part of the crust due to the ratio between the extents of the area versus the low data resolution (Figure 10). However, the obtained results are sufficient to determine the azimuth of the dip direction of the major shallow crustal structures. Where the space between the maxima of the successive sheets is very tight or even they are superimposed, this suggests that it nearly mirrors the vertical dip of the geological contacts. The strikes of the magnetic and gravity contacts follow the same locations and tendencies as the lineaments obtained with the matched filtering and the tilt angle techniques. For both magnetic and gravity data, the multiscale edge results reveal that the major contacts dip toward the NE with some diametrically opposed SW-dipping contacts (Figure 10). One single NW-dipping contact is identified in West Junggar.

4. Summary of Regional Distribution and Orientation of Geophysical Anomalies

The magnetic and gravity lineaments were identified for different crustal depths with the matched filtering results, the tilt angles, and the pseudo-gravity transformation; and the strikes and dips of the contacts





Figure 10. Multiscale edge analysis from the surface to 10 km depth of (a) the analytic signal results computed from the magnetic anomaly map in gray scale and (b) the gravity results computed from the Bouguer gravity map. The thick blue line shows the trend of an axis separating opposite dips of the structures.

between the contrasting sources were detected by the multiscale edge analysis. The distribution and orientation of magnetic and gravity anomalies are compared with the surface geological map in order to evaluate the relationship of geophysical anomalies to deep-seated geological bodies and first-order structures of the Chinese Altai and East Junggar.

4.1. Magnetic Crustal Structures

Among the different Chinese Altai rock types, the Paleozoic sediments correlate with intermediate to negative magnetic anomalies of low amplitude. The Permian high-grade rocks and the Early Permian and Carboniferous granitoids and ultramafic rocks correlate with magnetic highs forming NW/SE-trending zones in the southern Chinese Altai. The intermediate magnetic signals mainly correspond to the Devonian magmatic province in the northeastern Chinese Altai (Figure 11a). The northern part of the Junggar Basin sometimes displays magnetic highs of low-frequency anomalies indicating deep magnetic sources below the sedimentary cover. These magnetic highs in the basin do not coincide with the surface rocks that comprise Mesozoic sediments, which leads to the assumption that part of the deep Paleozoic basement of the Junggar Basin is probably highly magnetized.

The extraction of lineaments from the matched filtering results (Figures 6 and 7) and the tilt angle (Figures 8a and 8b) help us to quantify both geophysical anomaly trends and their relationships to lithologies and tectonic units (Figure 11b). It reveals three principal groups of distinct trends in the Chinese Altai and East Junggar (Figures 11b and 11c): (1) the NW/SE-trending and elongate lineaments are subparallel to the general trend of units in southern Chinese Altai, the northern East Junggar, and the boundary between the two units; (2) the NE-SW short lineaments constitute the subordinate group and are mostly present in the central Chinese Altai dominated by Habahe Group sediments in the NW and a large magmatic complex in the SE; and (3) the N-S short lineaments are parallel to the Fuyun strike-slip fault, and they progressively disappear toward the east and west from the fault.

The pseudo-gravity map reveals that the Bouguer gravity and magnetic anomalies have common deep sources mostly in the southwestern Chinese Altai and West Junggar (Figures 9a and 9b). This long-wavelength signal testifying to a deep magnetic source straddles the EZ, extending into West Junggar and the Junggar Basin, whereas the southeastern part does not have similarities between the Bouguer gravity highs and the pseudo-gravity lows. Thus, the southwestern Chinese Altai and the northeastern Junggar Basin seem to exhibit the characteristics of deep-seated and highly magnetic, probably mafic, basement.

4.2. Gravity Crustal Structures

The Bouguer anomalies reveal one main NE/SW-oriented gradient that divides the gravity map (Figure 5b inset): (1) to the north-east, a broad gravity low correlates with the rocks of the Mongol-Altai, and (2) to





Figure 11. Geophysical structures. (a) Regional magnetic highs correspond to shear zones, and regional magnetic lows to granitic bodies and sedimentary basins. (b) Juxtaposition of the tilt and matched filtering magnetic lineaments from different equivalent layers superimposed on the geological map. (c) Rose diagram of the three-group magnetic lineaments. (d) Regional gravity highs correspond to magmatic provinces, and regional gravity lows to sedimentary basins. (e) Juxtaposition of the tilt and matched filtering gravity lineaments from different equivalent layers superimposed on the geological map. (f) Rose diagram of the three-group gravity lineaments (PolyLX, https://petrol.natur.cuni.cz/~ondro/oldweb/polylx:home).

the south-west, a prominent gravity high corresponds to the East and West Junggar and to the Junggar Basin. The Chinese Altai rather corresponds to intermediate gravity signals as it is at the transition between these two large anomalies (Figure 11d). The residual gravity anomaly map highlights gravity highs associated with the granitic bodies in the Chinese Altai and with the volcanic sequences in East Junggar. Intermediate gravity anomalies are associated with the metasediments of the Habahe Group, and gravity lows are connected with the Junggar sedimentary basin (Figure 11d). The EZ has a rather hypothetical gravity signature, whereas the Fuyun Fault can be delineated by the gravity signal that displays an offset of anomalies along its trace.

The matched filtering and the tilt angle results reveal one major lineament and four principal groups of distinct trends over the Chinese Altai and East Junggar (Figures 11e and 11f). The major lineament is mostly observed on the long-wavelength matched filtering map (Figure 7d), where it is located at the transition between the gravity low in the NE (the Mongol-Altai) and the gravity high in the SW (Junggar Basin). This main lineament together with a group of the NW/SE-oriented lineaments is subparallel to the typical trend of geological units forming the Chinese Altai. These lineaments are dominant in the western Chinese Altai and spread over the Junggar Basin, but to a much lesser extent than the magnetic lineaments. The short and intermediate long NE-SW lineaments are mostly located in the central and northern Chinese Altai where they constitute the most important group. They are also developed in the East Junggar where they form an irregular pattern together with NW/SE-trending high-frequency anomalies (Figures 11d and 11e). Like the magnetic lineaments, the N-S gravity lineaments are clustered around the subparallel



strike-slip Fuyun Fault. Finally, the N-S lineaments, which delineate marked offsets of the gravity signal, intersect the Chinese Altai and the Junggar units and are regularly spaced and parallel to the Fuyun Fault.

5. Discussion

Following sections first address the relevance of the terrane boundaries in the Chinese Altai and East Junggar, the likely sources of the magnetic and gravity anomalies, and the significance of the weak signal of the EZ. We further discuss geophysical data in the studied domain together with the geological record of both the MAW and EJTA. Finally, we propose a plausible geodynamic scenario for the Devonian and Permian orogens that shaped the southern tract of the Mongolian collage.

5.1. Terranes Correlated With Geophysical Signal

As in most accretionary systems, the Chinese Altai and East Junggar were divided by Windley et al. (2002) and Xiao et al. (2004, 2008) into terranes accreted above a series of parallel subduction zones. These accretionary processes ended along a huge suture in the Late Carboniferous-Early Permian (Briggs et al., 2007; Coleman, 1989) and subsequently reworked by the giant EZ in Permian times. However, the analysis of the magnetic and the gravity anomaly maps (Figure 11) does not exhibit any similarities between the geophysical domains and the geologically defined terranes. In contrast, the Chinese Altai displays a homogeneous intermediate to high Bouguer gravity signal and could be divided into two domains along a NW/SE-oriented lineament. Also, the potential field anomalies and their data filtering demonstrate the absence of prominent deep-seated discontinuities at depth that could be identified as sutures or vertical boundaries between distinct terranes defined by Windley et al. (2002) and Xiao et al. (2004, 2008). Similar conclusions can be made for both gravity and magnetic anomalies of East Junggar where, for instance, the main NW/SE-trending magnetic high is located some 15–20 km to the south from the field occurrence of the Zhaheba ophiolites and the supposed suture zone between the Dulate and Yemaquan arcs/terranes (Niu et al., 2007; Xiao et al., 2009).

In conclusion, the absence of correlation between individual geologically defined terranes and geophysical signals implies other sources for the geophysical anomalies than simple lithological contrasts. It also implies that both the Chinese Altai and East Junggar can be considered rather as two tectonic zones and not as a mosaic of terranes. Broussolle et al. (2019) proposed that the complex architecture of the Chinese Altai can be due to the metamorphic and magmatic reworking of a rather lithologically homogeneous Cambro-Ordovician accretionary wedge. These authors also suggested that orthogonal Devonian and Permian upright folds created the vertical boundaries between variably exhumed metamorphic and magmatic edifice of the Chinese Altai interpreted previously as fault boundaries that divide individual suspect terranes. Therefore, an attempt is made to correlate the structural, magmatic, and metamorphic zones with geophysical data to determine the likely sources of the magnetic and gravity anomalies in various sectors of the Chinese Altai and East Junggar.

5.2. Likely Sources of Magnetic and Gravity Anomalies

Synthesizing previous structural studies (Broussolle et al., 2018; Jiang et al., 2015; P. Li et al., 2015; P. Li, Sun, et al., 2016; Qu & Zhang, 1994; Wei et al., 2007; Zhang et al., 2015), Broussolle et al. (2019) came to the conclusion that three Paleozoic deformation phases affected the Chinese Altai rocks. Originally horizontal metamorphic fabric S1 associated with extensive Early to Mid-Devonian syntectonic magmatism was deformed by upright NE/SW-oriented F2 folds of Late Devonian age cored by migmatites and granites (Jiang et al., 2015, 2019). Then the whole edifice was reworked by Permian upright NW-SE F3 folds and steep deformation/cleavage zones transposing all previous structures. Structural maps of key areas show a change in the distribution, the degree of preservation, and the intensity of Devonian and Permian orogenic fabrics (Figure 12). In the north (Figure 12a), the subhorizontal S1 foliation is gently folded by open to close NE/SW-trending F2 folds. Going to the south, this fabric was rotated into a NW-SE direction by Permian D3 shortening. Farther south-east (Figure 12b), the Devonian structural pattern was replaced by a dominant Permian NW-SE orogenic trend. The area SW of Altay city shows relics of irregularly preserved S1 foliation folded by upright F2 folds that are extensively refolded by F3 folds and transposed by S3 fabrics (Figure 12b). South-east of Altay city (Figure 12c), the D3 deformation becomes dominant leading to extrusion of Early Permian granulites and migmatites along NW/SE-striking tabular zone (Broussolle et al., 2018). Here, the





Figure 12. Structural evolution of the planar fabrics from the north to the south of the Chinese Altai. (a) The Habahe Group, north of Buerjin (modified from Xinjiang, BGMR, 1966). (b) Contacts between the Habahe Group and the Altai Formation, north of Altay city (modified from Jiang et al., 2019). (c) The Kalasu area and the Altai Formation (modified from Broussolle et al., 2018). (d) The Fuyun area and the Erqis Complex (modified from P. Li et al., 2017).

Devonian fabrics are preserved solely in low-grade Ordovician and Devonian metasediments rimming the Permian high-grade rocks. Finally, the southernmost area, west of Fuyun city (Figure 12d), is characterized by NW/SE-oriented subvertical S3 fabric suggesting complete transposition of all the previous structures (P. Li et al., 2017).

The correlation of magnetic and structural data shows that the magnetic highs reveal mainly a NW-SE trend typical of Permian structures (Figures 11 and 12). In particular, the prominent and elongated magnetic high NW to SE of Altay city shows a good continuity at depth (Figures 6a and 8a) and correlates with a large-scale





Figure 13. Magnetite minerals in staurolite (st)-garnet (g) and sillimanite (sill)-bearing paragneiss rocks of Permian age. mt = magnetite; bi = biotite; chl = chlorite; pl = plagioclase. The inset displays the location of the sample in the prominent magnetic high.

Permian vertical and tabular deformation zone (Figures 12b and 12c) that is associated with extrusion of partially molten lower crust (Broussolle et al., 2018; Jiang et al., 2019). This deformation zone is composed of granulites and migmatites (Figure 13) where the decomposition of Fe-rich biotite and the formation of magnetite imposed high magnetic susceptibility of these rocks (Martelat et al., 2014). In contrast, the intermediate magnetic signal of Devonian arc-type granitoids that dominate the Central Altai terrane can be due to the presence of paramagnetic biotite or hornblende (Bouchez, 2000). In general, the NW/SE-oriented magnetic lineaments are more widespread in East Junggar than in the Chinese Altai (Figure 11). These anomalies are parallel to zones of exhumed ophiolites (e.g., Zhaheba), which are typically characterized by a high magnetic susceptibility. On the other hand, the second important group of magnetic lineaments is oriented NE-SW and can be correlated with the strike of Devonian structures (Figure 12).

The Chinese Altai is located at a continental-scale transition zone between a broad gravity high in the western CAOB and a gravity low in the east. The strong NE/SW-trending gradient observed on the Bouguer anomaly map and the long-wavelength anomalies from the deep source layer deduced from the matched filtering imply that this density contrast is located at the Moho rather than in the crust. This gradient is modeled as a change in the crustal thickness from a 39 km thick crust of the Junggar domain to a 54 km thick crust constituting the modern Altai intracontinental orogen (Guy et al., 2017). The isostatic residual anomaly map shows a moderate gravity high (+20 mGal) geographically matching the vast region referred to as the "Central Altai terrane," surrounded by a region of gravity lows (-70 mGal) corresponding to the "North-West Altaishan and Qiongkuer-Abagong" terranes. In addition, the matched filtering results for shallow and intermediate sources (Figures 7b and 7c) show more or less regularly distributed NE/SW-trending anomalies subparallel to hinges of regional Devonian antiforms cored by migmatites and granites. These anomalies may result from juxtaposition of metamorphic rocks of different metamorphic grades that are characterized by contrasting densities (Guy et al., 2015; Jiang et al., 2016; Smithson, 1971; Williams & Betts, 2007). Because the Chinese Altai is formed of a monotonous volcano-sedimentary series, it contains lower and higher modal amounts of high-density minerals in weakly and highly metamorphosed rocks, respectively, that control the possible gravity contrasts observed in our study. Therefore, it can be expected that high-grade metamorphic rocks display gravity highs as they contain larger modal amounts





Figure 14. Diagram summarizing the patterns of magnetic and gravity highs according to the level in the crust and the topography of the Moho in order to demonstrate the ambiguous signal of the Erqis Zone.

of dense minerals compared to low-grade rocks. In conclusion, the Central Altai terrane forms a giant metamorphic dome, well visible in metamorphic maps (e.g., Broussolle et al., 2019) surrounded by low-grade rocks folded by Devonian NE/SW-trending folds cored by high-grade rocks (Figure 12). The NE/SW-trending anomalies are less developed in East Junggar, possibly because they are covered by thick and unconformable Carboniferous and Permian deposits (Figures 2 and 3). Here, some NW/SE-oriented gravity lineaments are also present and can be interpreted as a result of Permian-Triassic deformation (Figure 11).

5.3. The Erqis Zone, a Cryptic Tectonic Lineament

The fundamental issue discussed in this section is whether or not the prominent geophysical features described in this paper are related to the EZ, which is considered to represent a suture zone between the East Junggar and the Chinese Altai (Coleman, 1989; Xiao et al., 2004, 2018). Resolution of this problem is of paramount importance for any geodynamic model that relates the tectonic affinities of the Kazakhstan and Mongolian collages.

The Erqis "fault-suture-shear" zone with a supposed length of 1,000 km (e.g., Buslov et al., 2004; Şengör et al., 1993) and mylonites with a local width up to 10 km (Briggs et al., 2007; Windley et al., 2002) should extend from China to Kazakhstan (Figure 1). Its assumed steep dip and depth range (Wang et al., 2003; Zhao et al., 2003) together with the substantial difference between the felsic rocks of the MAW in the north and the mafic rocks of the EJTA in the south should lead to prominent density and magnetic susceptibility contrasts (e.g., Hynes & Rivers, 2010; Thomas & Tanner, 1975). However, seismic reflection and seismic refraction profiles (Zhao et al., 2003, and Wang et al., 2003, respectively) started in the foothills of the Chinese Altai mountain range, and thus, the EZ was located at the border of these seismic lines. This implies that the edge effects had a strong influence on the assigned subvertical dip of the contacts of the two units and the thickness of the layers that are probably not representative. For example, the EZ extends down to the mantle in the model of Zhao et al. (2003), whereas it reaches only the middle crustal level in the model of Wang et al. (2003).





Figure 15. Correlation of the magnetic and gravity signals with the geological structures. (a) Permian HT-LP extrusion zone, Permian NE-SW shortening, and Zhaheba ophiolites highlighted by magnetic highs. (b) Underthrusting of the East Junggar, Devonian NW-SE, and Permian NE-SW shortenings highlighted by gravity highs and lows. The arrows represent the dips revealed by the multiscale edge analysis.

A crucial point enhanced by the matched filtering of gravity and magnetic data is that the EZ does not form a primary, deep-seated discontinuity across all crustal levels (Figures 6 and 7). Importantly, positive pseudo-gravity values extend across the EZ indicating a magnetic source in depth, whereas the Bouguer anomaly map shows that the gravity highs cover both the East Junggar and the major part of the Chinese Altai (Figures 9a, 9b, and 14). This common magnetic and gravity source in depth can be interpreted as the expression of high susceptibility and density mafic rocks of the Junggar basement located beneath the Chinese Altai rocks. The dominantly mafic composition of the East Junggar basement is confirmed by igneous petrology studies (Chen & Jahn, 2004; Song et al., 2019) and by a seismic profile (Wang et al., 2003). In contrast, the residual magnetic anomaly and the isostatic residual anomaly maps (showing upper part of the crust; Figure 14) do not yield any signal that could be correlated with the larger signal trend in depth. This discrepancy between upper and deep crustal signal trends indicates that the origin of the strong gradient north of the EZ is located in the deep crust, probably reaching the Moho depth. It is therefore possible that the observed gradient is due to important thickening of the Chinese Altai crust and the formation of an unusually thick orogenic root during Cenozoic convergence (Guy et al., 2017). In both cases, the

surface traces of the EZ portrayed in Figure 14 are probably an unsuccessful candidate for contact between the two crustal domains.

5.4. Tectonic Interpretation of Geophysical Data

A strong gravity gradient located in the interior of the Chinese Altai represents a zone of crustal-scale importance (Figures 11 and 14). Here, both deep crustal gravity and upper crustal magnetic anomalies match well with NW/SE-trending vertical orogenic fabrics in the southern Chinese Altai (Figure 11). This wide zone matches well with both the main gravity gradient and the principal magnetic lineament in the Chinese Altai (Figure 14), and it may represent a deep crustal expression of Junggar crust underthrust beneath the Chinese Altai (Figure 15). The tabular zone of vertically extruded UHT granulites south of Altay city (Broussolle et al., 2018, 2019; Jiang et al., 2019) is probably only a surface trace of this important tectonic boundary located deep in the crust. The central Chinese Altai also represents a boundary between NW-oriented dips of magnetic and gravity anomalies in the south (white arrows in Figure 10) and those dipping to the SW in the north (green arrows in Figure 10) that could be interpreted in terms of regional-scale extrusion of deep Chinese Altai crust above the Junggar basement in the south and the metamorphic-magmatic dome in the north (Figure 15). Altogether, the above discussed geophysical features may be interpreted as a result of (1) Permian underthrusting of the Junggar crust beneath the Chinese Altai that generated the extrusion of hot granulites and (2) an important reactivation of this Paleozoic structure during Cenozoic times leading to important thickening of the Altai crust.

In East Junggar, magnetic maps show the locations of geologically defined ophiolitic mélanges (e.g., Zhaheba ophiolite) that are located north of the main magnetic lineament (Figure 14). The form of these anomalies and the close association with ophiolitic occurrences closely resemble to those reported in the Mongolia part of EJTA (Guy et al., 2015; Guy, Schulmann, Munschy, et al., 2014) where both positive gravity and magnetic anomalies were interpreted as important Permian deformation zones. Multiscale edge maps further show their constant NE-oriented dips of angles of $\sim 25^{\circ}$ to 40° in this area (white arrows in Figure 10). These data can be interpreted as reflecting the presence of south-vergent thrust zones of Permian age that disrupt the Junggar basement but also as the shape of the moderately north-dipping Junggar basement (Figure 15).

5.5. Geodynamic Implications

The combination of geology and geophysics provides new insights into the geodynamic reconstruction of the Chinese Altai and the adjacent East Junggar. In the northern Chinese Altai, the alternation of NE-SW trending gravity highs and lows correlates with the region affected by Late Devonian to Early Carboniferous upright folds and crustal-scale domes (Figures 11 and 12). This trend of gravity anomalies depicted in the residual map cross-cuts the boundary between the Chinese Altai and East Junggar (Figures 11 and 14), implying that these two domains were deformed together in Devonian times. In contrast, the distribution of the NW-SE magnetic and gravity lineaments spatially coincides with the high-strain Permian HT-LP deformation zones in the Chinese Altai and with the ophiolitic zones in East Junggar. Therefore, both geophysical and structural data show a complex interplay between zones of Devonian and Permian deformation that straddle the boundary between the Chinese Altai and East Junggar.

The geological and detrital zircon age data (Figure 4) indicate a joint tectonic evolution of the EJTA and MAW since the Late Devonian. These units formed, together with Mongolian microcontinents, a ribbon-like structure surrounded by oceanic domains (Figure 16a). The two domains were affected by Late Devonian deformation responsible for imbrication of the oceanic basement of EJTA (Guy, Schulmann, Clauer, et al., 2014; Lehmann et al., 2010) and for doming and folding of the MAW (Broussolle et al., 2015; Jiang et al., 2015; Lehmann et al., 2010). Subsequently, the whole system together with the Siberian craton underwent ~90° clockwise rotation (Cocks & Torsvik, 2007; Xiao et al., 2018) to reach the Late Carboniferous position portrayed in Figure 16a. In that way, all compressive Devonian fabrics, simultaneously developed in both the EJTA and the MAW, were oriented approximately N-S in current coordinates.

Lehmann et al. (2010) and Edel et al. (2014) proposed that this linear system was affected by large-scale N-S shortening and oroclinal buckling related to the northward drift of the North China and Tarim cratons. The





Figure 16. Schematic geodynamic evolution of the CAOB related to the Chinese Altai and East Junggar. (a) Late Devonian-Early Carboniferous formation of the arc and back-arc system on the western side of the Baydrag Zavkhan Precambrian continental ribbon. (b) Permian convergence leading to orthogonal Devonian and Permian-oriented fabrics and formation of the Mongolian orocline.

late stages of folding were associated with the formation of large-scale deformation zones of Permo-Triassic age subparallel to the axial plane of the megafold, in principle similar to axial plane cleavage (Guy, Schulmann, Clauer, et al., 2014; Lehmann et al., 2010). The magnetic and gravity data filtering performed in the Mongolian part of EJTA further show that these zones are deeply rooted (Guy et al., 2015; Guy, Schulmann, Munschy, et al., 2014). As in Mongolia, we suggest that the prominent NW-SE magnetic highs, developed in both East Junggar and the Chinese Altai, represent the same type of deformation zones (Figure 16b). The main expression of this giant collisional event is a partial underthrusting of East Junggar beneath the Chinese Altai associated with the extrusion of Early Permian HT-LP granulites. In contrast to southern Mongolia, which represents one limb of the orocline, the studied sector is located close to the orocline's hinge, where deep crustal NE/SW-trending Permian deformation zones formed together with N-S reactivation of the MAW-EJTA boundary.

6. Conclusions

The combination of potential field analysis with the lithostratigraphy and structural geology demonstrates the absence of terranes in the Chinese Alai and East Junggar since explicit geophysical gradients along their presumed boundaries are lacking. Overall, the magnetic highs coincide with the NW/SE-oriented Permian



deformation zones, whereas the alternation of gravity highs and lows in the Chinese Altai reflects the Late Devonian to Early Carboniferous NE-SW upright folds and crustal-scale domes.

The Erqis Zone, which separates the Chinese Altai and the East Junggar, does not correlate with any deep-seated discontinuity, while the most prominent geophysical gradient is located in the Chinese Altai north of crustal-scale gravity high coinciding with the East Junggar dense mafic lower crust. The nature of this mafic crust is confirmed by previous magmatic studies and by existing seismic data. Also, major gravity gradient and prominent magnetic high are located at the tip of the dense Junggar lower crust ca. 50 km north of the Erqis Zone. These geophysical lineaments coincide with Permian HT-LP granulitic zone, which forms a boundary between north- and south-dipping gravity and magnetic anomalies that are interpreted as reflecting quasi-symmetrical extrusion of the Chinese Altai crust north of the deeply buried East Junggar indentor.

Finally, the proposed new geodynamic model involves (1) accretionary stage characterized by Late Devonian joint evolution of the Chinese Altai and East Junggar characterized by N-S trending orogenic fabrics and (2) Early Permian oroclinal bending associated with underthrusting of the dense Junggar basement beneath the Chinese Altai and the development of NW/SE-trending deformation zones in both units.

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