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Cambrian mafic and grani ic in r ion in he Ma ar-Tian h ihai errane, We K nl n Orogenic Bel : Con rain on he bd c ion orien a ion of he Pro o-Te h Ocean

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A B S T R A C T

The We K nl n Orogenic Bel (WKOB) carrie ke informa ion abo he e ol ion of he Pro o-Te h Ocean. In order o ha e a be er nder anding of he earl Paleo oic ec onic e ol ion of he WKOB and o nra el he proce of he Tarim a emblage o Gond ana, e repor field ob er a ion , pe rograph , age , chemical and Sr-Nd-Hf i o opic compo i ion of he ne l iden ified Cambrian mafic and grani ic in r ion in he Ma ar Terrane-Tian h ihai errane (MZT-TSHT) a he in erior of he WKOB. O r ircon U–Pb da ing re eal ha he mafic and grani ic rock in Tian h ihai Terrane (TSHT) emplaced a ca. 530 Ma, and ha he mafic rock in he Ma ar Terrane (MZT) emplaced a ca. 500–490 Ma. Whole-rock major and race elemen geochemi r define a holeii ic igna re for he e mafic rock . I o opicall , he TSHT mafic rock ha e deple ed Nd i o ope compo i ion i h ini ial $\varepsilon_{Nd}(\ )$ i o ope ranging from 2.74 o 3.60, herea he MZT mafic rock e hibi enriched hole-rock Nd i o ope compo i ion i h $\varepsilon_{Nd}(\ )$ al e ranging from −12.90 o −9.71. The di inc chemical and i o opic igna re arg e ha he Cambrian mafic rock in he TSHT ere deri ed from a deple ed man le o rce in an ini ial bd c ion e ing, herea he mafic rock from MZT ere deri ed from an enriched b-con inen al li ho pheric man le o rce in an arc e ing. The Cambrian grani e in he TSHT ho pical frac iona ed I- pe grani e elemen al igna re , in line i h heir Nd-Sr-Hf i o ope compo i ion . The e Cambrian grani e ere mo likel genera ed b par ial mel ing of Me opro ero oic (0.9–1.3 Ga) cr al o rce d e o nder-pla ing of he coe al mafic magma. O r re l in combina ion i h pre io die gge ha he Cambrian mafic and grani ic rock in he MZT-TSHT ere genera ed b he o h ard bd c ion of he Pro o-Te h Ocean ini ia ed a ca. 530 Ma. The long- erm o h ard bd c ion led o he forma ion of he ma i e earl Paleo oic accre ionar edge in WKOB. The Pro o-Te h Ocean finall clo ed a ca. 440 Ma a demon ra ed b he amphiboli e facie me amorphi m of he accre ionar comple and he middle o la e De onian mola e nconformabl o erl ing he accre ionar comple . Thi proce ca ed he block in Ea A ia, incl ding he Tarim, Qaidam and Nor h Qilian, Yang e and Indochina, o dock a he nor hern fringe of he Ea ern Gond ana.

1. Introduction

The micro-con inen di rib ed in Ea ern A ia, incl ding he Tarim, Qaidam, Qilian, So h China, Nor h China and Indochina, ere belie ed o ha e been a emblaged o Ea ern Gond ana in he earl Paleo oic d e o he clo re of he Pro o-Te h Ocean di rib ed along he We ern K nl n, Al n, Nor h Qilian, Nor h Qinling and he Ca ha ia (Pan and Wang, 1994; Ma e e al., 1996; Pan, 1996; Ma ern and Schneider, 2000; Xiao e al., 2002a, 2005; Zhang e al., 2004; Li e al., 2018; Zhao e al., 2018). A one of he major ec onic ni of he Tibe an Pla ea and he cen ral orogenic bel in China (*i.e.,* he We K nl n-Ea K nl n-Qilian-Qinling-Dabie-S l orogen, ee Jiang e al., 1992), he We K nl n Orogenic Bel (WKOB) pla a ke role for o r nder anding of he e ol ion of he Pro o- o Paleo-Te h Ocean. Al ho gh man die ha e been carried o on hi orogenic bel , man i e i h regard o i earl Paleo oic ec onic e ol ion remain nclear, ch a he bd c ion orien a ion, he ec onic fea re of he Precambrian

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errane and he clo ing proce of he Pro o-Te h Ocean, and he her or no he Tarim block a emblaged o he Ea ern Gond ana (e.g., D cea e al., 2003; Jiang e al., 2002, 2008, 2013; Ma e e al., 1996; Ma ern and Schneider, 2000; Pan, 1990; Pan and Wang, 1994; Wang e al., 2001, 2002; Wang, 2004; Xiao e al., 1998, 2002a, b, 2005; Yang e al., 1996; Yin and Harri on, 2000; Y an e al., 2002, 2004, 2005; Zhang e al., 2006, 2007). E peciall he bd c ion polari of he Pro o-Te h Ocean i nder deba e . Some geologi fa ored he nor h ard bd c ion (Wang, 2004; Xiao e al., 2000), and he Paleo oic K di-Qiman e Ophioli e a con idered a he remnan of he back-arc ba in of he Pro o-Te h Ocean (Wang e al., 2002; Wang, 2004). Ano her chool of idea gge ed he o h ard bd c ion polari of he Pro o-Te h Ocean benea h he So h K nl n Terrane (SKT), hich led o he amalgama ion be een he Nor h K nl n Terrane (NKT) and SKT in earl Paleo oic (Jiang e al., 2002; Ma ern and Schneider, 2000; Zhang e al., 2018a, b, c, d; Li e al., 2018). In addi ion o he abo e nor h or o h bd c ion orien a ion , ome orker propo ed a do ble- ided bd c ion of he Pro o-Te h Ocean model (Xiao e al., 2002a).

The model a ocia ed i h he bd c ion polari of Pro o-Te h Ocean ere in oked on he follo ing prereq i i e : (1) he SKT a a Precambrian micro-con inen , herefore he arc-rela ed grani e can be formed and (2) he Paleo oic magma ic rock in he WKOB rend o be o nger from nor h o o h and (3) he magma ic rock in he Tian h ihai Terrane (TSHT) are all emplaced d ring Me o oic and no Paleo oic magma i m occ rred. Mo orker con ider ha he Kang i a Fa l , he bo ndar be- een he SKT and TSHT, i he re one re l ed from he clo re of a branch of he Paleo-Te h Ocean (D cea e al., 2003; Jiang e al., 2013; R e e al., 2017), hile o her claimed ha i i ei her a n-accre ion fa l or a po -accre ion fa l (Xiao e al., 2002a, b, 2005; Wang, 2004). Ho e er, o r recen ork re eal ha he main par of he SKT, *i.e.,* he Sai la Gro p, a a Paleo oic accre ionar comple hich ma be re l ed from he o h ard bd c ion of he Pro o-Te h Ocean (Zhang e al., 2018c), and he onl confirmed Precambrian ba emen in he WKOB ere he Archean Ma ar Terrane (MZT, Fig.1a, Zhang e al., 2018a) and he Neopro ero oic TSHT (Fig.1a, Zhang e al., 2018c). More impor- an l , he Earl Paleo oic igneo rock , incl ding doleri e , gab- bro and grani e ere iden ified in he confirmed Precambrian ba emen , *i.e.,* he Ma ar Terrane-Tian h ihai Terrane (MZT-TSHT). The e ne l iden ified Earl Cambrian magma ic rock in he MZT-TSHT pro ide ne in igh for a more reliable recon r c ion of he Paleo oic ec ono-magma i m e ol ion hi or of he WKOB. In hi con rib ion, e repor field ob er a ion , age , and geochemi r of he ne l iden ified Earl Paleo oic doleri e/gab- bro and grani ic in r ion in he Archean MZT and cen ral par of he TSHT, in order o con rain he ec onic igna re of he NE Pamir and WKOB and o be er nder and he ec onic e ol ion of he Pro o-Te h Ocean and a emblage proce be een he Tarim and Ea ern Gond ana.

2. Regional geology and petrography

The WKOB, adjoin he Tarim Ba in o he nor h, he Tibe an Pla ea o he o h, and he Pamir Pla ea o he e , i off e from Ea K nl n Orogen and Songpan-Gan i Terrane b he Al n ini ral rike- lip fa l o he ea (Fig. 1a, Gibbon e al., 2015; Yin and Harri on, 2000). Tec onicall , he WKOB can be di ided in o he ea ern and e ern ec ion. The e ern ec ion, generall kno n a he Pamir alien , ha been bdi ided in o hree ec onic ni , *i.e.,* he Nor hern Pamir, Cen ral Pamir, and So hern Pamir (Robin on e al., 2007, 2012; Sch ab e al., 2004). The 1/250000 mapping and o r ema ic geochronological die in hi area demon ra ed ha he main par of he NE Pamir (*i.e.,* Ta hikorgan Terrane (TSKT) ho n in Fig. 1a) a compo ed of a Cambrian olcanic- edimen ar eq ence, locall kno n a he B l nk ole Gro p (BKG), ra her han a Tria ic accre ionar comple (e.g., Robin on e al., 2012). A i o hern margin, he BKG hr on o he ne l iden ified Archean MZT (Fig. 1a, Ji e al., 2011; Zhang e al., 2018b).

The ea ern ec ion of he WKOB can be bdi ided in o hree main ec onic ni (Fig. 1a), *i.e.,* he NKT, he SKT and he TSHT, b he Paleo oic K di-Qiman e S re (KQS), Ma ar-Kang i a Fa l (MKF) and Hong hanh -Qiaoer ian han S re (HQS), re pec i el (Ma ern and Schneider, 2000; Xiao e al., 2005). The NKT, an plif ed errane of Tarim Block, compo ed of a pre-Nanh anian me amorpho ed and deformed ba emen and nconformabl co ered b Nanh a-Cambrian carbona e-cla ic- illi e eq ence (Zhang e al., 2007, 2016). The main par of SKT, *i.e.,* he Sai la Gro p, a a me amorpho ed Cambrian o earl Ordo ician accre ionar edge and re emble he BKG in rock a emblage, age , me amorphi m grade and deforma ion fea re (Fig. 1a, Zhang e al., 2018c, d). Th , he BKG and he Sai la Gro p compo e a ma i e earl Paleo oic accre ionar edge di rib ed be een he Tarim and he MZT-TSHT (Fig. 1a). The TSHT i idel co ered b glacier depo i and kno ledge of i geolog i highl incomple e d e o geographic remo ene (C i e al., 2006). Some cholar gge ed ha hi errane i eq i alen o he Songpan-Gan i block of Tibe an Pla ea , hich collided i h SKT d ring he Earl Me o oic (Xiao e al., 2005; Li e al., 2015). The Neo- pro ero oic Tian h ihai Gro p (o nge de ri al ircon age peak a ˛ 743 Ma, Zhang e al., 2018c), a he onl Precambrian eq ence of he TSHT, compo ed of me a-gre acke and lime one and i in fa l or nconformable con ac i h he la e Paleo oic o earl Me o oic accre ionar edge (Zhang e al., 2018c). The hick mono ono and par l me amorpho ed cce ion of cla ic marine depo i ho fl ch igna re (Ma ern and Schneider, 2000).

The Earl Paleo oic and Me o oic magma ic rock a ocia ed i h he e ol ion of he Pro o- and Paleo-Te h Ocean are ide pread in he WKOB. Pre io die mo l foc ed on he igneo rock and ome ke geological ni ch a he ophioli e along he Xinjiang-Tibe road and he China-Paki an road d e o he diffic l acce ibili o mo area of he WKOB (e.g., Ma ern and Schneider, 2000; Wang e al., 2002, 2017; Yang e al., 1996; Zhang e al., 2004, 2005, 2016; Li e al., 2015; Jiang e al., 2013). The e die re eal ha he Earl Paleo oic magma ic rock in he WKOB are di rib ed mainl in he SKT and bordina el in he NKT, hile he Me o oic magma ic rock in he WKOB are emplaced mainl along he o hern par of he SKT and he nor hern mar in of he TSHT (Fig. 1a). The Earl Paleo oic grani oid ere emplaced in he SKT d ring 510—400 Ma (Jiang e al., 2002, 2008; Zhang e al., 2018a, 2018b). Geochemicall , he earl Paleo- oic grani e in SKT can be defined a o di inc pha e and pe , *i.e.,* he 510—450 Ma I— pe grani e and he 430-400 Ma high Ba—Sr and A— pe grani e (Ye e al., 2008; Y an e al., 2002, 2005). In combina ion of he ca.440 Ma amphiboli e-facie me a- morphi m of he SKT, he accre ion be een Tarim and SKT ere fini hed a ca.440 Ma (Zhang e al., 2018c).

The MZT i loca ed a he o hea ern margin of he NE Pamir (Fig. 1a), here he Archean ba emen in he WKOB a iden ified (Ji e al., 2011; Zhang e al., 2018b). The Neoarchean eq ence a in r ded b di er e pe of in r ion , incl ding he Neo- pro ero oic rondhjemi e- onali e-granodiori e and Cambrian doleri e-gabbro and Me o oic grani e (Fig. 1b, Zhang e al., 2018b; hi d). To he nor h of hi errane i he Cambrian accre ionar edge (*i.e.,* he BKG, Zhang e al., 2018a) and a i o hea ern ide, i a in r ded b he Me o oic grani e . The doleri e-gabbro are mo l di rib ed a he o h e ern ide of he MZT, ho n a ock and d ke in he field. The ock o crop a o al in form

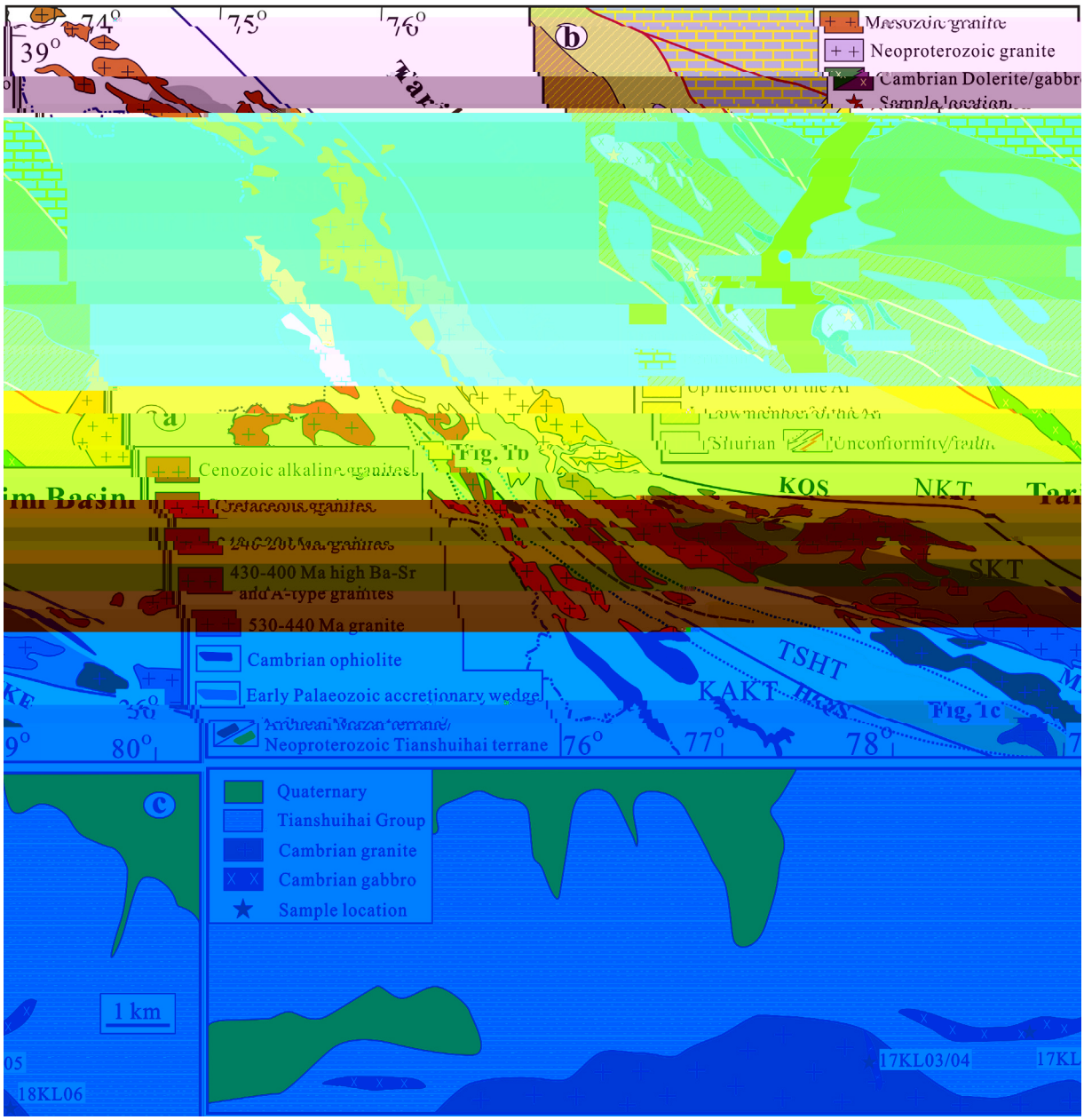

Fig. 1. (a) Simplified ec onic map of he We ern K nl n Orogenic Bel (WKOB), ho ing he major errane and rela ed grani e pl on (Modified from Zhang e al., 2018d). The o-called ba emen of TSKT and SKT, locall kno n a he B l nk ole Gro p and Sai la Gro p, are an earl Paleo oic accre ionar edge. NKT—Nor hern K nl n errane; SKT—So hern K nl n errane; TSKT—Ta hikorgan errane; TSHT —Tian h ihai errane; MZT—Ma ar Terrane; KQS—K di-Qiman e S re; MKF—Ma ar-Kang i a Fa l ; HQS—Hong hanh -Qiaoer ian han S re. (b) Geological map of he Cambrian mafic in r i e rock in he Ma ar errane. (c) Geological map of he Cambrian magma ic rock in he Tian h ihai errane.

i h e eral q are kilome er . The d ke mo l rike in NW and are e eral h ndred me er o more han 1 km long and e eral o h ndred me er ide (Fig. 1b).

The TSHT i a NW-SE rending bel , loca ed o he o h of Kang i a Fa l (Fig. 1a). Magma ic rock in he TSHT ere emplaced mainl d ring Tria ic-J ra ic (240-195 Ma) and b-ordina el d ring he Earl Cambrian (Fig. 1a, H e al., 2016 and hi d). The Earl Cambrian doleri e-gabbro in hi con rib - ion are di rib ed o h o he Dahongli an iron depo i di ric , cen ral par of he TSHT (Fig. 1c, H e al., 2016). The doleri e-gabbro occ r a d ke in he field, rike in EW and are h ndred me er o e eral kilome er long and e eral o do en of me er ide (Fig. 1c). Zircon LA-ICPMS da ing of a gabbro ample near he ample loca ion of hi con rib ion ielded age of 532.3 ± 3.1 Ma (H e al., 2016).

The doleri e /gabbro and grani e ere collec ed a he MZT (Fig. 1b) and cen ral par of TSHT (Fig. 1c). The doleri e/gabbro ample ere al ered o ariable degree a iden ified in he hin ec ion and he elec ronic probe anal e (ee de ail in ec ion 4.2), ch a replacemen of clinop ro ene b hornblende and erici i a ion of he plagiocla e. The gabbro ample con i of p - ro ene (all replaced b he hornblende, ho ing a p ro ene p e domorph) and plagiocla e (Fig. 2a), and con i mainl of bro n hornblende (40—60%), erici i ed plagiocla e (40—50%) and minor Ti—Fe o ide. The doleri e are compo ed mainl of horn-blende (50—65%), erici i ed plagiocla e (30—50%). The grani e are rela i el fre h i h ligh erici i a ion of he plagiocla e (Fig. 2b). The are compo ed mainl of K-feld par (50—55%), plagiocla e

(10–15%), q ar (30–35%) and minor econdar erici e, i h acce or mineral of ircon and apa i e.

3. Analytical procedures

Zircon epara ion a carried o ing andard cr hing, ie ing, and hea liq id and magne ic epara ion echniq e. Repre en a i e ircon ere hen mo n ed on a do ble- ided ape b hand-picking nder a binoc lar micro cope. Zircon da ing of hree ample a carried o a Tianjin In i e of Geolog and Mineral Re o rce (TJIGMR), Chine e Geolog S r e (CGS), here a Nep ne MC-ICPMS co pled i h a 193 nm e cimer la er abla ion em a ed o de ermine ircon U–Pb age . The de ailed anal ical proced re are imilar o ho e of Geng e al. (2011). Zircon da ing of a gabbro ample from MZT a cond c ed on a SHRIMP-II in r men a Beijing SHRIMP Cen re (Na ional Science and Technolog Infra r c re), ing he andard opera ing condi ion (William , 1998). I oplo (L d ig, 2003) a ed for da a proce ing. Zircon U–Pb i o opic da a a li ed in Table S1 and S2.

Mineral compo i ion ere de ermined on hin- ec ion ing an a oma ed JEOL 8800 elec ron microprobe eq ipped i h 5 a eleng h pec rome er a G ang ho In i e of Geochemi r , Chine e Academ of Science . The opera ing condi ion d ring anal e are 15 keV accelera ing ol age and 15 nA beam c rren i h 20 co n ing ime. The anal ical preci ion i be er han 5%. The anal ical re l of hornblende ere li ed in Table S3.

Major-elemen o ide ere ob ained ing Rigak ZSX100e X-ra fl ore cence (XRF) on f ed gla bead a he Nanjing In i e of Geolog and Mineral Re o rce (NJIGMR), CGS, follo ing anal ical proced re imilar o ho e of Li e al. (2006). Anal ical preci ion a be er han 5%. Trace elemen ere anal ed ing a PE Elan 600 ICP-MS a he In i e of Geochemi r , Chine e Academ of Science, follo ing proced re imilar o ho e de cribed b Li e al. (2006)

18KL06 ield ariable U (720–3065 ppm) and Pb (66–283 ppm) con en and ho rela i el high $^{232}Th/^{238}U$ ra io (0.27–1.80, Table S2), imilar o pical magma ic ircon . All he 29 anal e ield concordan $^{206}Pb/^{238}U$ age and $^{207}Pb/^{235}U$ age and form a igh cl er on he concordia diagram i h a eigh ed mean $^{206}Pb/^{238}U$ age of 532.7 ± 2.5 Ma (Fig. 3d, MSWD = 0.24).

4.2. Mineral geochemistry

A o al of 33 anal e ere carried on he hornblende from MZT gabbroic diori e (2016KL17B and 15D071H5). The re l ho rela i el high Si (7.33–7.93) and Ca (1.77–2.03) apf (a om per form la ni) and belong o calcic amphiboli e according o he cla ifica ion cheme of Leake e al. (1997). The ha e lo $(Na + K)_A$ (occ panc of Na + K in A- i e, le han 0.5), and are mainl ac inoli e and magne iohornblende (Fig. 4a). Their $(Na + K)_A$ and $^{[IV]}Al$ (occ panc Al in e rahedral i e) harpl decrea e i h decrea ing TiO_2 (Fig. 4b, c), imilar o he econdar rend of amphibole from he Iberian appini e (Molina e al., 2009).

4.3. Whole-rock elemental geochemistry

The MZT doleri ic/gabbroic ample ha e large range of SiO_2 (47.88–55.36%), Al_2O_3 (11.48–15.58%), CaO (6.02–14.74%), MgO (2.73–10.78%) and $Fe_2O_3^T$ (9.88–13.39%). Their Na_2O (0.74–5.16%) con en are generall higher han K_2O (0.21–1.30%). D e o ari- able h dro hermal al era ion, e e he immobile incompa ible elemen o cla if he rock pe and o decipher heir geochemical igna re . On he Nb/Y er Zr/TiO_2 plo (Fig. 5a), all he ample plo i hin he b-alkaline ba al field. On he AFM diagram, he define a pical holeii ic rend (Fig. 5b). Their $Mg^{\#}$ range from 35 o 65 d e o cr al frac iona ion and/or cr al con amina ion (ee follo ing di c ion). On he Harker diagram (Fig. 6), SiO_2, TiO_2, P_2O_5, o al REE increa e hile Cr and Ni decrea e i h decrea ing Mg#, herea Al_2O_3, $Fe_2O_3^T$, Na_2O, CaO and Zr are no correla ed i h $Mg^{\#}$. On he chondri e-normali ed REE plo , he di pla enriched LREE pa ern i h rela i el con an $(La/Yb)_N$ (2.67–6.87) ra io (Fig. 7a). Mo MZT mafic ample lack ignifican E anomalie (E /E * = 0.81–1.17). Normali ed o primi i e man le, all ample ho arc-like pa ern i h ariable enrichmen in incompa ible race elemen and ignifican Nb–Ta ro gh (Nb/La = 0.30–0.44) and ariable nega i e P anomalie (Fig. 7b).

The TSHT mafic in r ion e hibi rela i el niform SiO_2 (46.82–49.68%) and ar ing Al_2O_3 (14.67–18.16%), CaO (5.47–11.20%), MgO (5.84–10.20%) and $Fe_2O_3^T$ (8.20–11.69%). The are odi m-rich (2.12–4.29%, Na_2O) rela i e o K_2O (0.23–2.99%). The TSHT mafic rock ha e ariable Ni (12–156 ppm) and Cr (7–448 ppm) con en (S pplemen ar Table 3). All ample plo i hin b-alkaline ba al field on he Nb/Y er Zr/TiO_2 plo (Fig. 5a). On he AFM diagram (Fig. 5b), he define a pical holeii ic igna re. On he Harker diagram (Fig. 6), he Na_2O, TiO_2, P_2O_5, Zr and o al REE increa e hile Cr, Ni and CaO decrea e i h decrea ing $Mg^{\#}$ and SiO_2, Al_2O_3 remain con an . The TSHT mafic in r ion ha e ariable o al REE ab ndance (70.68–225.08 ppm). The di pla enriched LREE pa ern i h $(La/Yb)_N$ ra io ranging from 4.71 o 17.4 on he chondri e-normali ed REE diagram (Fig. 7c). Mo TSHT mafic ample ho ligh l nega i e o po i i e E anomalie (E /E * = 0.95–1.29). All ample

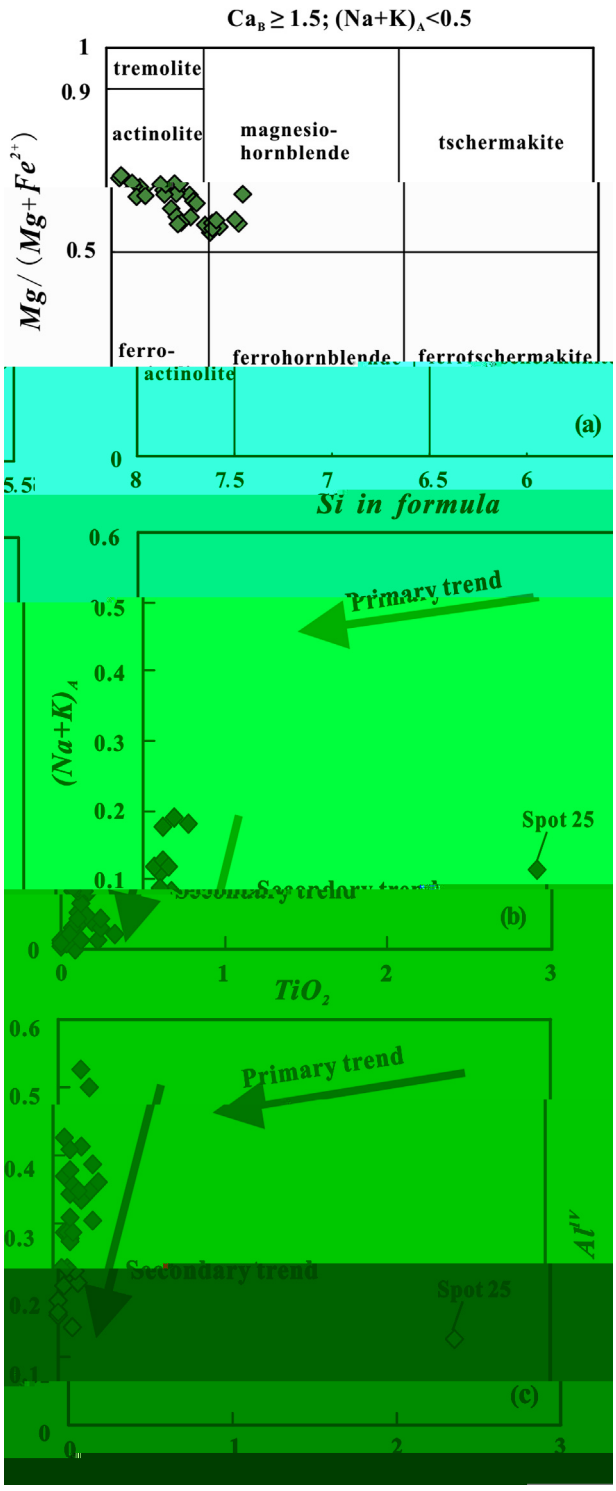

Fig. 4. (a) Cla ifica ion of hornblende (Leake e al., 1997); (b) TiO_2 (%) *vs.* Al ^{IV} and (c) TiO_2 (%) *vs.* $(Na + K)_A$ diagram of he hornblende ho ing he econdar rend .

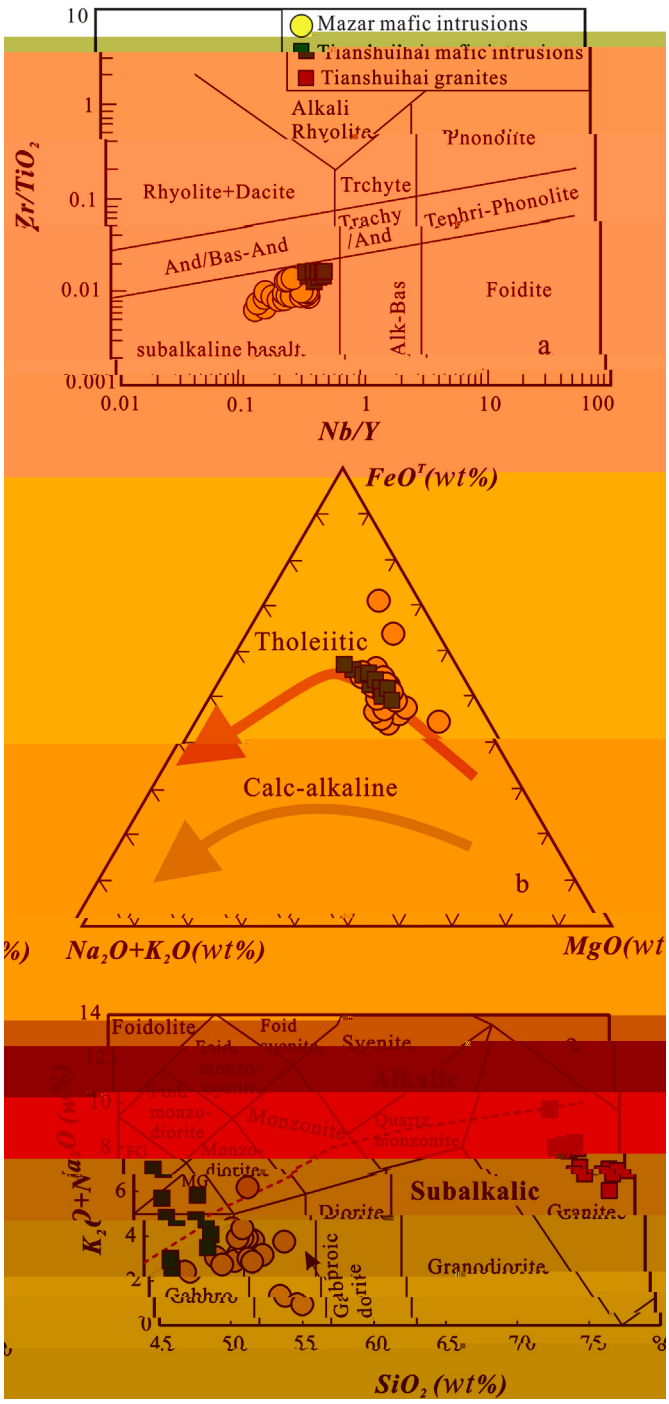

Fig. 5. (a) Nb/Y *vs.* Zr/TiO_2 cla ifica ion, (b) AFM and (c) TAS diagram of he doleri e-gabbro and grani e from Ma ar Terrane-Tian h ihai Terrane.

On he TAS diagram (Fig. 5c), he plo in o he field of grani e. The ha e lo con en of Al_2O_3 (11.80–13.85%), TiO_2 (0.05–0.15%), MnO_2 (0.01–0.03%), MgO (0.06–0.52%) and P_2O_5 (0.01–0.02%). Major elemen define heir peral mino igna re i h A/NK ranging from 1.10 o 1.24 and A/CNK ranging from 1.04 o 1.13. The TSHT grani e ha e o al REE ab ndance ranging from 120 o 241 ppm. The e hibi a rela i el fla REE pa ern on he chondri e-normali ed REE diagram (Fig. 7e), i h $(La/Yb)_N$ ra io ranging from 2.61 o 7.19 and highl nega i e E anomalie (E / E * = 0.02–0.09), likel d e o plagiocla e frac iona ion. Normali ed o primi i e man le, all ample ho enrichmen in large ion li hophile elemen ch a Rb, Th, La and deple ion in Ba, Sr, P, Ti and E (Fig. 7f).

4.4. Zircon in situ Lu–Hf isotopic compositions

A o al of 57 in i L –Hf i o opic anal e ere carried on he da ed ircon from o TSHT grani ic ample (17KL04 and 18KL06,

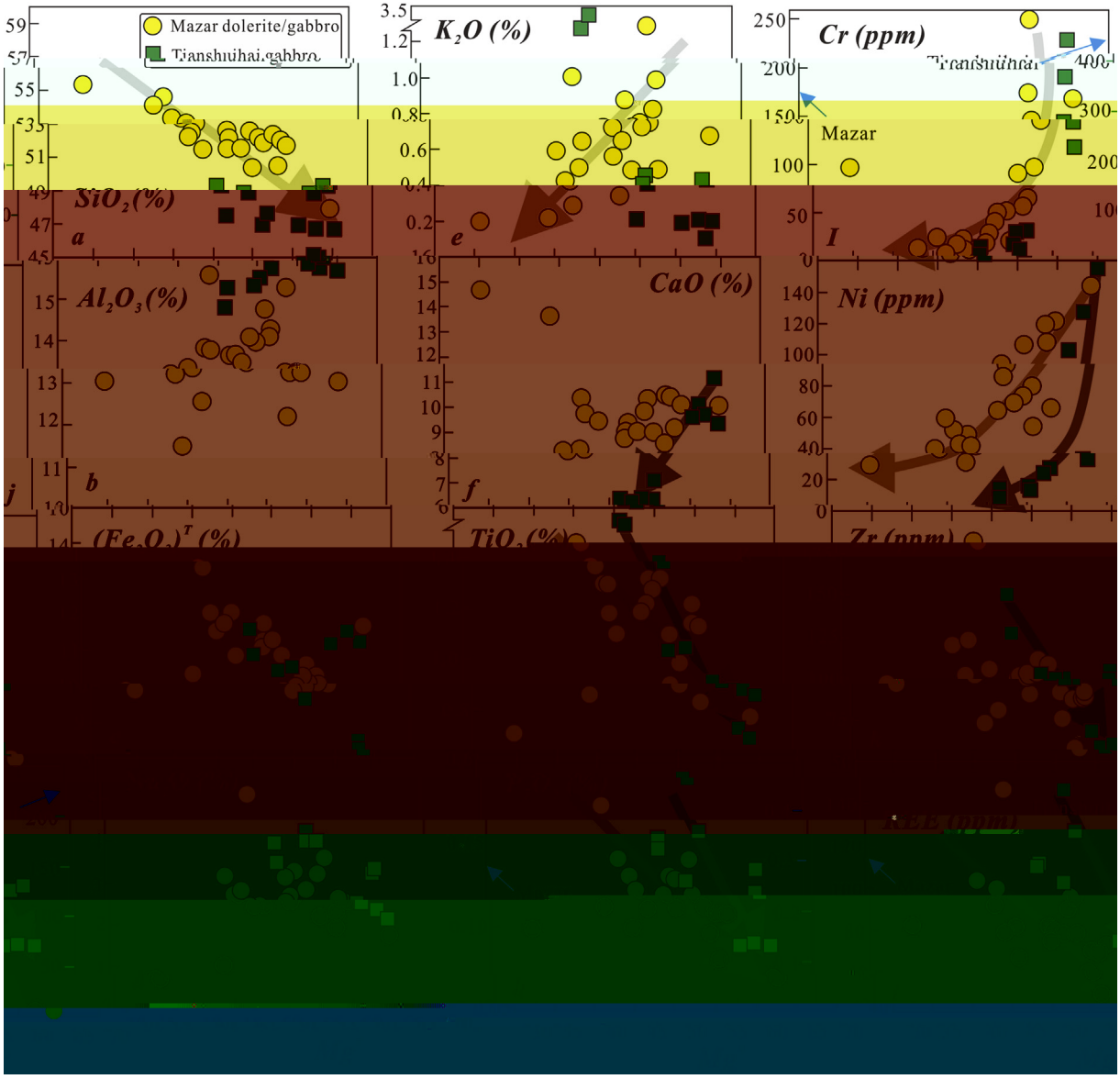

Fig. 6. Harker diagram for he Cambrian mafic in r i e rock from Ma ar- Tian h ihai errane.

Table S5). All anal e ho po i i e ini ial $\varepsilon_{Hf}(\ )$ al e ranging from 2.6 o 9.2 (mo l be een 4 and 8) and e hibi a general Ga ian di rib ion (peak a ˛ 5, Fig. 8a) and Me o-Pro ero oic o age model age (T_{DM2}) ranging from 905 o 1324 Ma (Fig. 8b).

4.5. Sr–Nd isotopic compositions

The MZT doleri e/gabbro ample ha e nega i e $\varepsilon_{Nd}(\ )$ al e (−12.90 − -9.71) and ariable ini ial $^{87}Sr/^{86}Sr$ al e (0.7107–0.71517, Table S6, Fig. 9a). The TSHT mafic rock ha e po i i e $\varepsilon_{Nd}(\ )$ al e ranging from 2.74 o 3.60, and heir ini ial $^{87}Sr/^{86}Sr$ al e ranging from 0.70597 o 0.70847. A for he Cambrian TSHT grani e , he e hibi $\varepsilon_{Nd}(\ )$ al e ranging from −0.39 o 1.08, and ini ial $^{87}Sr/^{86}Sr$ al e ranging from 0.7039 o 0.71229. We no ice he ignifican deco pling be een he hole-rock Nd and Sr i o ope compo i ion for he MZT mafic rock , hich co ld be a cribed o po -emplacemen h dro hermal al era ion (e.g., McC lloch e al., 1981) a demon ra ed b he hin ec ion ob er a ion and he hornblende chemical compo i ion . Th , he Sr i o ope of he MZT mafic rock are n i able for f r her di c ion on he pe rogene i of he e rock . On he $\varepsilon_{Nd}(\ )$. $\varepsilon_{Hf}(\ )$ diagram (Fig. 9b), he TSHT grani e ho broadl co pled hole-rock Nd and ircon Hf i o ope .

5. Discussions

5.1. Petrogenesis of the mafic rocks

5.1.1. Hydrothermal alteration

A indica ed b heir high LOI (mo l higher han 2%), ec-ondar mineral ob er ed in hin ec ion and apparen l ec-ondar rend for he amphibole (Fig. 4b, c), he MZT-TSHT mafic rock nder en ariable degree of al era ion af er emplacemen , hich ma ha e changed he concen ra ion of ome incompa ible elemen d e o heir enhanced mobili . Since Zr i con idered o be immobile d ring lo -grade h dro hermal al era ion and me amorphi m of igneo rock , i ha been ed a a reference for d ing he mobili of o her race elemen (Pearce e al., 1992). We in e iga ed he correla ion be een Zr and o her elemen (fig re no pre en ed). The re l indica e ha TiO_2, Nb, Th, Hf, Y,

Ta and REE correla e ell i h Zr, gge ing rela i e immobili of he e elemen d ring po -emplacemen proce e . Some LILE , ch a Ba, Rb and Sr, ho e er, ho no correla ion i h Zr, indica ing heir mobili . Th , e concl de ha al era ion proce e ha e no ignifican l affec ed high field reng h elemen (HFSE: Th, Nb, Zr, Hf, Ti, Y) and REE . Their aria ion co ld be a cribed o magma ic proce e and can be ed for pe rogene i di c ion .

5.1.2. AFC process

The anal ed mafic rock ha e ariable MgO (2.73–10.78% for MZT and 5.84–10.50% for TSHT), $Mg^{\#}$ (35–65 for MZT and 51–65 for TSHT), Cr (5.88–255 ppm for MZT and 20.0–448 ppm for TSHT), Ni (31.9–145 ppm for MZT and 12.1–156 ppm for TSHT) and o al REE ab ndance (41.5–148 ppm for MZT and 70.7–225 ppm for TSHT), indica ing ha he cr alli ed from e ol ed ra her han primi i e magma , probabl d e o a imila ion and frac ional cr alli a ion (AFC) proce e . A ho n in he Harker diagram (Fig. 6), he e anal ed ample e hibi di inc po i i e correla- ion be een Cr and $Mg^{\#}$ (Fig. 6i), Ni and $Mg^{\#}$ (Fig. 6j), indica ing frac iona ion/c m la ion of oli ine or/and clinop ro ene. The di inc clinop ro ene-plagiocla e con rol rend in he Pearce elemen al ra io diagram (Fig. 10a) confirmed he frac iona ion/ c m la ion of clinop ro ene and plagiocla e. The nega i e correla ion be een Fe_2O_3 and TiO_2 concen ra ion and $Mg^{\#}$ are indica i e of frac ional cr alli a ion/c m la ion of Fe–Ti o ide . AFC proce can prod ce a po i i e correla ion be een ε_{Nd}( ) and $Mg^{\#}$. The ligh l po i i e correla ion be een he ε_{Nd}( ) and $Mg^{\#}$ for he MZT mafic rock arg e for cr al con amina ion before final cr alli a ion 1

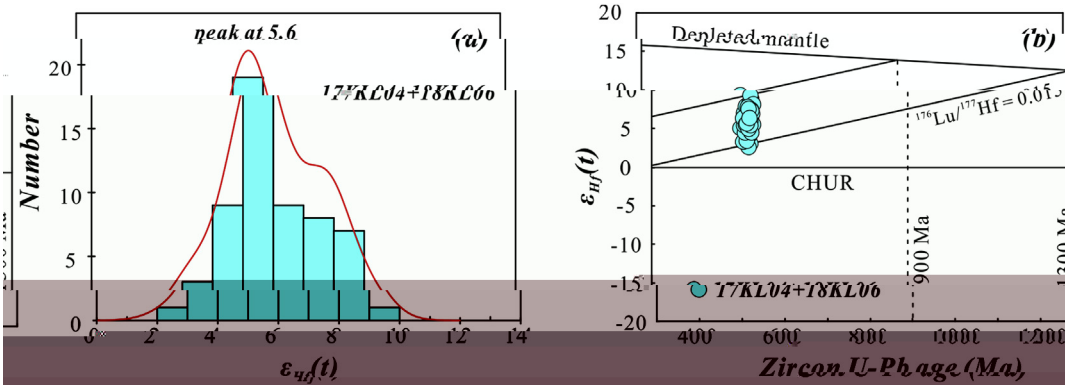

Fig. 8. Zircon $\varepsilon_{Hf}(t)$ pec ra (a) and ircon U–Pb age . $\varepsilon_{Hf}(t)$ diagram (b) of he Cambrian grani ic in r ion from Tian h ihai Terrane.

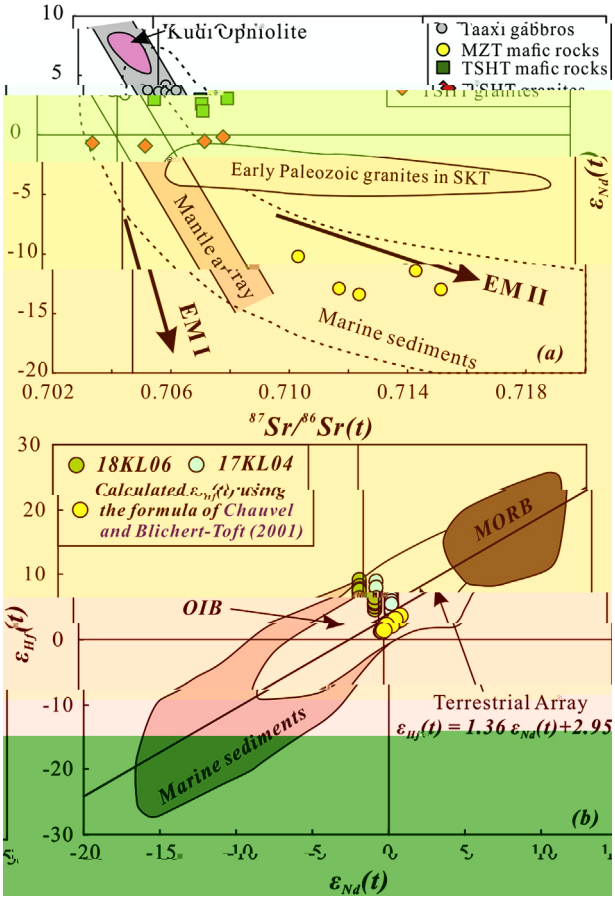

Fig. 9. (a) Whole-rock Sr–Nd i o opic diagram of he Cambrian mafic and grani ic in r ion from Ma ar-Tian h ihai Terrane. The Taa i gabbro are from Zhang e al. (2018d); The So h K nl n Terrane (SKT) grani e are from Zh e al., 2017; Liao e al., 2010, Wang e al. (2017), Li **et al.** (2014); The marine edimen are from Hofmann, 2003; K di Ophioli e are from Pan, 1996. (b) Whole-rock $\varepsilon_{Nd}(t)$. ircon $\varepsilon_{Hf}(t)$ diagram of he Cambrian grani ic in r ion from Tian h ihai Terrane, ho ing co pled Nd–Hf i o opic compo i ion . The erre rial arra and he field for middle ocean ridge ba al (MORB), oceanic i land ba al (OIB) and global edimen are from Ver oo e al., 1999..

be een he $\varepsilon_{Nd}(t)$ and $Mg^{\#}$, indica ing in ignifican cr al con amina ion (Fig. 10b). Cr al con amina ion co ld im l a- neo l decrea e $Mg^{\#}$ and Nb/La ra io hich co ld prod ce a po i i e correla ion be een he $Mg^{\#}$ and Nb/La. Thi concl ion i ppor ed b he ligh po i i e correla ion and no ignifican correla ion be een he $Mg^{\#}$ and Nb/La for he MZT and TSHT mafic rock , re pec i el (Fig. 10c). The $(La/Ta)_N$. $(Th/Ta)_N$ diagram (Fig. 10d) indica e ha he con amina ed componen for he MZT mafic rock a he pper cr .

Therefore, e concl de ha he anal ed mafic ample from TSHT ha e no ndergone ignifican cr al con amina ion, herea ho e Cambrian rock from MZT ha e been con amina ed b he pper cr componen in hi region.

5.1.3. Magma sources

The MZT and TSHT are o di inc Precambrian ba emen in he WKOB, *i.e.,* he Archean MZT (Zhang e al., 2018b) and he Neopro ero oic TSHT (Zhang e al., 2018c). The differen igna re of he Precambrian ba emen for he MZT and TSHT lead o concl de ha he e o errane po e differen Cambrian man le o rce . The mafic rock from he TSHT ha e deple ed hole-rock Nd i o opic compo i ion ($\varepsilon_{Nd}(t) = 2.74$ o 3.60), and e hibi arc-like hole-rock elemen al compo i ion , ch a ig- nifican Nb–Ta ro gh, enrichmen of LREE , LILE and deple ion of HREE and HFSE (Fig. 7, R dnick and Gao, 2003). The deco pling of he deple ed Nd i o ope and he enriched LREE and LILE hare mo fea re of he E-MORB and ome OIB (e.g., Zhang e al., 2018d). S ch fea re can be a cribed o cr al con amina ion (R dnick and Gao, 2003), h bridi a ion of magma o rce b rec cled errigeno edimen or fl id me a oma i m in he b- d c ion one (e.g., Ha ke or h e al., 1993) or cr alli a ion of Ti- bearing mineral (ch a r ile and Ti-bearing amphibole) (e.g., H ang e al., 2010). A men ioned abo e, cr al con amina ion can be r led o . Al ho gh frac iona ion/acc m la ion of Ti-bearing mineral migh ha e occ rred a men ioned abo e, hi a no he ke rea on o genera e he Nb–Ta ro gh of he mafic rock from TSHT, beca e of he po i i e correla ion be een he TiO_2 and Nb/La ra io (fig re no ho n). Th , he man le o rce for he paren magma of he TSHT mafic rock a mo likel me a om- a i ed or enriched b mel or fl id in a bd c ion one (e.g., Ha ke or h e al., 1997). Nb/U and Ta/U ra io are commonl ed o iden if he injec ion of cr al ma erial in o man le o rce or cr al con amina ion (e.g., Hofmann, 1988). The Nb/U and Ta/U ra io of he TSHT mafic rock are 7.1–23.3 and 0.4–1.3, ignifi- can l lo er han ho e of he OIB and MORB (Nb/U~47 and Ta/ U~2.7, Hofmann, 1988). The lo ra io of Nb/U and Ta/U fea re of he TSHT mafic rock arg e for ignifican injec ion of cr al ma- erial in o he deple ed man le o rce for he TSHT mafic rock , hich migh be d e o bd c ion proce e . In ligh of heir deple ed hole-rock Nd i o opic compo i ion , e propo e ha he ere origina ed in he ini ial bd c ing e ing of he o h ard bd c ion of he Pro o-Te h Ocean.

Al ho gh ha ing ndergone pper cr con amina ion, he MZT mafic rock i h ariable $Mg^{\#}$ n mber e hibi imilar Nb/La

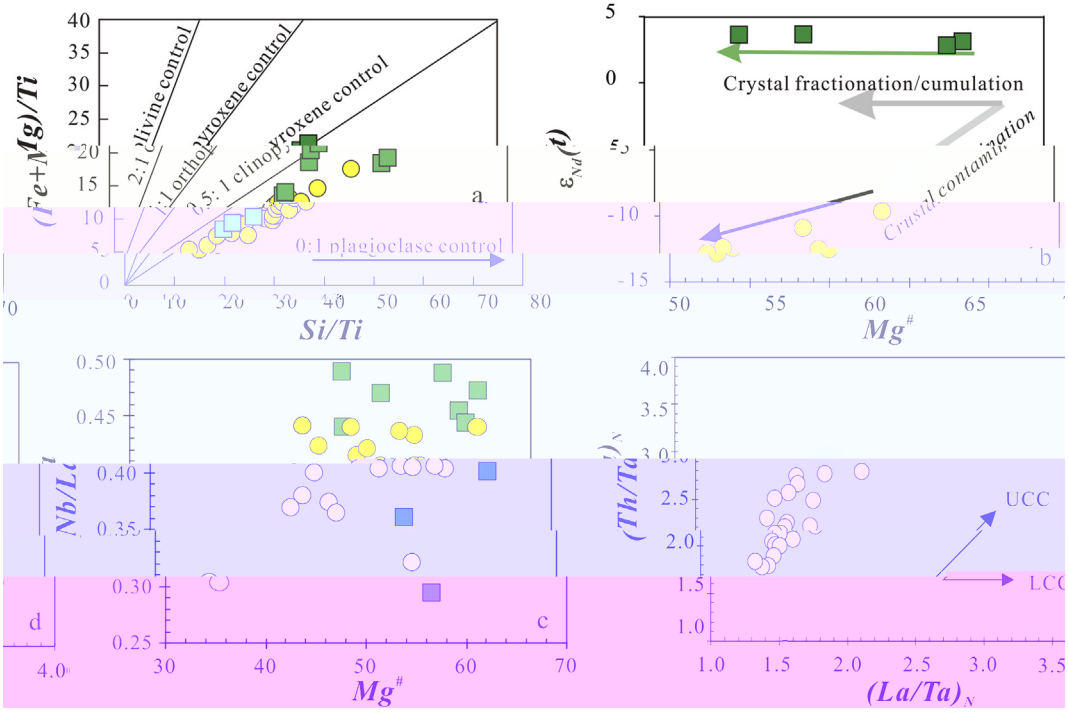

Fig. 10. (a) Si/Ti *vs.* (Mg + Fe)/Ti (molar ra io) diagram of MZT-TSHT mafic rock ho ing acc m la ion of clinop ro ene and plagiocla e; (b) $Mg^{\#}$ *vs.* $\varepsilon_{Nd}(\ )$, (c) $Mg^{\#}$ *vs.* Nb/La and (d) $(La/Ta)_N$ *vs.* $(Th/Ta)_N$ diagram ill ra ing pper con inen al cr con amina ion rend for he MZT mafic rock , and no ignifican con amina ion for he TSHT mafic rock . UCC – pper con inen al cr ; LCC – lo er con inen al cr .

ra io (0.30–0.46). Th , heir incompa ible ra io co ld broadl reflec heir primi i e geochemical igna re . The REE and incompa ible elemen di rib ion pa ern of MZT mafic in r ion broadl e hibi arc ba al igna re ch a heir ignifican Nb–Ta ro gh (Fig. 7), enrichmen of LREE , LILE and deple ion of HREE and HFSE (R dnick and Gao, 2003, Fig. 7). F r hermore, heir HFSE ra io , ch a Th/La and Nb/Th, are al o comparable i h ho e of primi i e arc ba al (Fig. 11, OIB , primi i e arc ba al and a erage con inen al cr are from S n and McDono gh, 1989 and R dnick and Gao, 2003, re pec i el). Among he MZT mafic rock , he ample i h lea nega i e ini ial Nd i o opic compo i ion (−9.71)

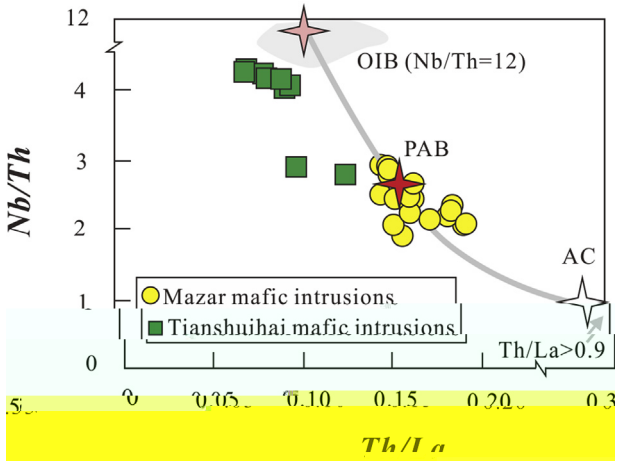

Fig. 11. Th/La *vs.* Nb/Th diagram. The MZT mafic rock cl er aro nd primi i e arc ba al (PAB) and he TSHT mafic rock plo be een oceanic i land ba al (OIB) and PAB. OIB, PAB and a erage con inen al cr (AC) are af er S n and McDono gh (1989), R dnick and Gao (2003), re pec i el .

ha high $Mg^{\#}$ (59), hich arg e for an i o opicall enriched man le o rce for he primar magma of he MZT mafic rock . We ded ce ha he ere deri ed from an enriched b-con inen al li ho-pheric man le (SCLM). A a ma er of fac , he Archean MZT po - e e a long- erm enriched SCLM according o he hole-rock $\varepsilon_{Nd}(\ )$ al e of he Archean mafic olcanic rock (−11.9 o −9.3, recalc la ed o 490 Ma, Ji e al., 2011), hich i con i en ell i h he MZT mafic rock . Par ial mel ing of an ini ial cold SCLM co ld no occ r nle plen of bd c ion-rela ed fl id modified he man le o rce (Ring ood, 1974). Thi ma be rela ed o he con in o l (530–490 Ma) o h ard bd c ion of he Pro o-Te h Ocean.

The TSHT mafic rock e hibi po i i e hole-rock Nd i o opic compo i ion herea he MZT mafic rock di pla m ch more enriched hole-rock Nd i o opic compo i ion ($\varepsilon_{Nd}(\ ) = -12.90$ – -9.71). From he TSHT mafic rock (ca. 530 Ma) o he MZT mafic rock (ca. 490 Ma), he man le o rce of he mafic rock ran - formed from a deple ed man le o an enriched SCLM, hich migh be re l ed from increa ing me a oma i ed degree of he lab bd c ion. Thi concl ion i f r her ppor ed b he rela i el higher Th/Yb ra io a a gi en Nb/Yb for he MZ-TSHT mafic rock . All MZT mafic rock plo in o he field of con inen al arc and ho e TSHT mafic rock plo be een he field of con inen al arc and he man le-arra on he Nb/Yb . Th/Yb diagram (Fig. 12). Comparing i h he binar diagram, he riang lar diagram o ld be infl - enced le b cr al frac iona ion. On he Nb–Zr/4-Y diagram (Fig. 13), he TSHT mafic rock are mo l plo in he field of i hin pla e holeii ic ba al , i h ome hif o i hin pla e alkaline ba al , hile he MZT mafic rock plo in o he field of olcanic arc ba al .

To m p, he Cambrian TSHT mafic rock ere deri ed from a deple ed man le o rce in an ini ial bd c ion e ing, herea he Cambrian MZT mafic rock ere mo likel deri ed from a bd c ion me a oma i ed SCLM edge in an arc e ing.

A a common acce or mineral in magma ic rock , apa i e ha e differen ol bili in differen magma em (e.g., Li e al., 2007). Apa i e ha e er lo ol bili in me al mino o eakl peral mino magma em and cr alli e earl d ring he fraciona ion of magma em, hich re l in a nega i e rela ion hip be een P and SiO_2. While in he rong peral mino magma, he apa i e ho an oppo i e beha ior and lead o a po i i e or remain nchanged a he SiO_2 increa e (Wolf and London, 1994). Thi differen beha ior of apa i e in me al mino o eakl peral mino magma and peral mino magma can be ed o di crimina e I- and S- pe grani e (W e al., 2003). The TSHT grani e e hibi er lo con en of P_2O_5 ($\leq$0.02%, Fig. 14b), indica i e of I- pe grani e affini . In addi ion, all TSHT grani ic ample plo in o I- pe grani e field on he Zr . TiO_2 diagram (Fig. 14c). Therefore, e concl de ha he Cambrian TSHT grani e are highl -frac iona ed I- pe grani e .

The e remel nega i e E anomalie (E /E * = 0.02–0.09) and lo con en of Sr (21.9–71.5 ppm) gge frac ional cr alli aion of plagiocla e. The apparen l nega i e Ba, Sr, P and Ti anomalie in he primi i e-man le-normali ed race elemen and REE aria ion diagram for he TSHT grani e (Fig. 7) indica e frac iona ion of plagiocla e, apa i e and Fe–Ti o ide d ring magma e ol ion. F r hermore, plo of proce iden ifica ion diagram on log Ba . log Rb (Fig. 14d) ield rend of cr al frac iona ion of plagiocla e and K-feld par, hich i con i en i h he nega i e correla ion be een log E and log Ba (Fig. 14e). The TSHT grani e ho lo o al con en of REE (lo o 120 ppm), hich co ld be a cribed o frac ional cr alli a ion of REE-enriched acce or mineral , ch a apa i e and mona i e. The La . $(La/Yb)_N$ diagram (Fig. 14f) re eal ha he REE aria ion in he TSHT grani e ere likel con rolled b cr alli a ion of mona i e and/or allani e.

The TSHT grani e occ r clo el emporall and pa iall rela ed o he TSHT mafic rock , gge ing he former co ld be formed b in en i e frac ional6(.)-4464.5( )(af6.96970TD( )Tj/F11.3088r1.3084.9(b

5.2. Petrogenesis of the TSHT granites

The TSHT grani e ha e e remel high con en of SiO_2 (75.14–79.57%) and highl nega i e E anomalie (E / E * = 0.02–0.09) and are deple ed in Ba, Sr, P in he primi i e man le normali ed diagram (Fig. 7f). The e hibi lo ra io of 1000*Ga/Al (2.23–2.65) and (Na_2O + K_2O)/CaO (5.15–9.45), and lo con en of Zr (96.6–146 ppm) and Zr + Nb + Ce + Y (207–345 ppm), bo h lo er han he lo er limi of he pical A-pe grani e (Collin e al., 1982; Whalen e al., 1987). Mo TSHT grani e plo in o he frac iona ed grani e field on he diagram of Zr + Nb + Ce + Y *vs.* (Na_2O + K_2O)/CaO (Fig. 14a). The e characeri ic of he TSHT grani e re eal ha he are highl frac iona ed grani e , a e idenced b heir lo con en of $Fe_2O_3^T$ and MgO. Unfrac iona ed grani e all ha e rela i el con an ra io of in HFSE elemen , ch a Zr/Hf and Nb/Ta (Green, 1995). While ho e ra io ill decrea e ob io l hen he magma em e periencing in en i e frac iona ion (e.g., Pére -Soba and Villa eca, 2010). The TSHT grani e ho lo ra io of Zr/Hf (22.5–28.9) and Nb/Ta (4.25–7.90) rela i e o pical grani e (38 for Zr/Hf and 17 for Nb/Ta), hich i con i en i h rong differen ia ion.

The TSHT grani e ho rela i el lo con en of Al_2O_3 (11.80–13.85%) and are eakl peral mino (mo l lo er han 1.10), hich i di inc from pical S- pe grani e (Chappell, 1999).

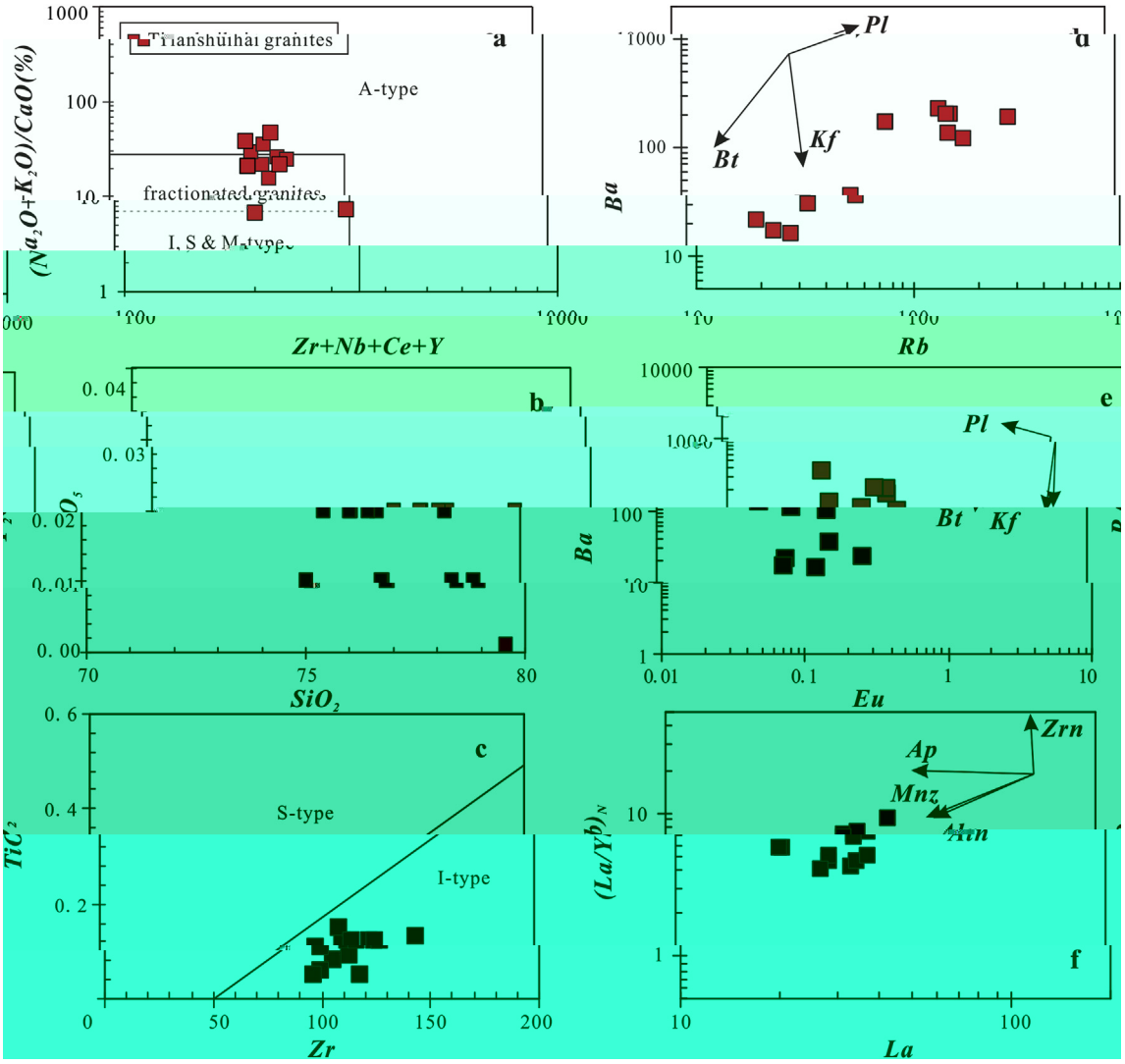

Fig. 14. (a) Zr + Nb + Ce + Y *vs.* $(Na_2O + K_2O)/CaO$, (b) SiO_2 *vs.* P_2O_5 and (c) Zr *vs.* TiO_2 diagram ho ing frac iona ed I- pe grani e igna re for he grani ic rock from Tian h ihai errane. (d) Rb . Ba and (e) E . Ba diagram ho ing cr alli a ion of plagiocla e and (f) La . $(La/Yb)_N$ diagram ho ing cr alli a ion of mon oni e and/or allani e.

The final clo re of he Mo ambiq e Ocean be een Ea Gond ana and We Gond ana a ca. 540–530 Ma formed he Grea Gond ana (Fig. 15a, Collin and Pi are k , 2005; Li e al., 2008), a e idenced b he palaeomagne ic die (Meer and Van der Voo, 1996), ca ing he final docking of India o A ralia-Ea An arc ica along he Pinjarra Orogen (Boger and Miller, 2004; Collin and Pi are k , 2005). Epi odic biopro ince connec ion i h Ea Gond ana d ring he Earl - o mid-Paleo- oic indica ed ha he micro-con inen di rib ed in Ea ern A ia, incl ding he Tarim, Qaidam, Qilian, So h China Block (SCB), Nor h China Block (NCB), Ale , Sib ma and Indochina, ere loca ed nearb A ralia (Fig. 15b, Me calfe, 2011, 2013).

The Archean MZT and la e-Neopro ero oic TSHT are o ne l iden ified Precambrian ba emen in he WKOB (Zhang e al., 2018c, d). Al ho gh he MZT and he TSHT are differen in age, he are all confirmed Precambrian ba emen in he WKOB. Con idering he imilari of he Earl Paleo oic accre ionar comple of BKG and Sai la Gro p (Zhang e al., 2018a, c), di rib- ed o he nor h of he MZT and TSHT, re pec i el , i i q i e po ible ha he MZT and TSHT are a a hole before he earl Cambrian (ca. 530 Ma). Thi concl ion i f r her ppor ed b he paleogeographic e idence o he o hern margin of he Tarim Block (H ang e al., 2011). According o he paleogeographic recon r c ion of Li e al. (2018), e place he MZT-TSHT be een he Tarim and Ea ern Gond ana (Fig. 15b). The MZT po e e he Archean (ca. 2.5 Ga) bimodal me a-igneo rock o erprin ed b ca. 2.0 Ga me amorphi m and Neopro ero oic (ca. 840 Ma) grani ic magma i m (Zhang e al., 2018b), hich hare mo imilari o he Archean Kongling comple in he SCB (Zhang and Zheng, 2013). F r her, he de ri al ircon of he fl ch-like edimen ar e- q ence in he TSHT hared imilar age pec ra o he la e Neo- pro ero oic eq ence from SCB (H e al., 2016; Zhang e al., 2015, 2018c). Precambrian rock a embage , pha e of igneo ac i i ie and me amorphi m of he MZT-TSHT hare mo fea re o ho e of he SCB, hich arg ed ha hi errane a con inen al frag- men de ached from SCB d ring he break p of he Rodinia S - percon inen . The BKG a an earl Cambrian (530–508 Ma, Zhang e al., 2018a) accre ionar edge be een he Tarim and he MZT. The Earl Cambrian (ca. 530 Ma) gabbro hee and ock emplaced in he lo er par of he BKG ere gge ed o be deri ed from a me a oma i ed a heno phere man le o rce in a fore-arc e ing (Zhang e al., 2018d). The ca. ˛ 530 Ma arc-like doleri e/

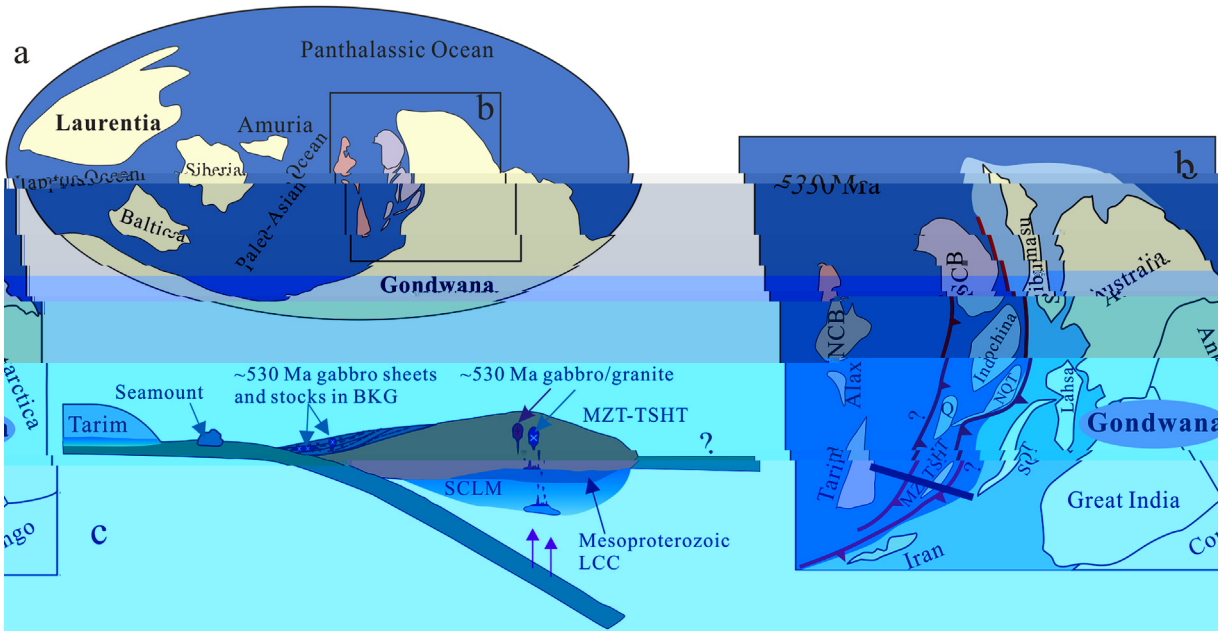

Fig. 15. Earl Cambrian (~530 Ma) global con inen al/micro-con inen al block di rib ion (a) and po ible di rib ion of he block a he nor hern fringe of Gond ana (b, Modified from Li e al., 2018; Me calf e al., 2011, 2013). (c) Car oon model ho ing he forma ion of Cambrian doleri e-gabbro in he MZT-TSHT and he ini ia ion of Pro o-Te h ocean bd c ion a ca. 530 Ma (he hickne of he SCLM and cr i no e ac l caled). BKG—Cambrian B l nk ole Gro p; Q—Qaidam; SCB—So h China Block; NCB—Nor h China Block; SQT—So h Qiang ang; NQT—Nor h Qiang ang; MZT-TSHT—Ma ar Terrane-Tian h ihai Terrane. See de ail in he e .

gabbro in r ion in he TSHT o h o he BKG a coe al i h ho e gabbro hee and ock emplaced in he lo er par of he BKG (Zhang e al., 2018d), hich formed he ini ial magma ic arc of he o h ard bd c ion of he Pro o-Te h Ocean (Fig. 15c). The con in o o h ard bd c ion of he Pro o-Te h Ocean led o he me a oma i m of he SCLM benea h he MZT. Par ial mel ing of he me a oma i ed enriched man le o rce (SCLM) genera ed he mafic in r ion in he MZT.

Vol mino earl Paleo oic grani e emplaced in he SKT and he TSKT d ring 510—400 Ma (Jiang e al., 2002, 2008; Zhang e al., 2018a, 2018b). The e grani e ho ariable geochemical compo- i ion , incl ding he 430 Ma adaki ic rock (Ye e al., 2008; Wang e al., 2017), hich ma be re l ed from par ial mel ing of he hickened lo er cr (Wang e al., 2017). The hickening of he con inen al cr in an orogenic bel can be a cribed o he con inen -con inen colli ion, ch a he Dabie Orogenic Bel and Tibe an Pla ea (Ch ng e al., 2003; Wang e al., 2007), indica ing ha he final colli ion be een he Tarim Block and Ea Gond ana a earlier han 430 Ma. O r re l , co pled i h he occ rrence of ca. 440 Ma amphiboli e-facie me amorphi m of he SKT, doc men ha he accre ion be een Tarim and TSHT a fini hed a ca.440 Ma (Zhang e al., 2018c). The clo re of he Pro o-Te h Ocean led o he final a emblage of he block in he Nor hern Tibe and A ia, incl ding he Tarim, MZT-TSHT, Qaidam, SCB, Indochina, e c., o he nor hern margin of he Ea Gond ana (Me calfe, 2011, 2013).

6. Conclusions

(1) The grani ic in r ion in Tian h ihai Terrane ere emplaced a ca. 530 Ma, coe al i h he doleri e-gabbro in hi area and he gabbro hee and ock emplaced in o he lo er par of he Cambrian accre ionar edge. The doleri e-gabbro from he Ma ar Terrane a emplaced a ca. 500—490 Ma.

(2) The doleri ic/gabbroic in r ion in Tian h ihai Terrane ere deri ed from a deple ed man le o rce in an ini ial bd c ion e ing; herea he mafic in r ion in Ma ar Terrane ere genera ed from a b-con inen al li ho pheric man le o rce in an arc e ing.

(3) A Cambrian magma ic arc, gene icall rela ed o he o h- ard bd c ion of he Pro o-Te h Ocean d ring 530—490 Ma, a de eloped along he Ma ar-Tian h ihai errane. The final clo re of he Pro o-Te h Ocean occ rred a ca. 440 Ma, hich led o he errane along he nor hern margin of he Tibe Pla ea and Ea A ia docked o he Ea Gond ana.

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Appendix A. Supplementary data

S pplemen ar da a o hi ar icle can be fo nd online a h p ://doi.org/10.1016/j.li ho .2019.105226.

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