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Intracontinental subduction: a possible mechanism for the Early Palaeozoic Orogen of SE China.

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Key words : Intracontinental belt, Decollement, Crustal melting, Intracontinental subduction, SE China, Early Paleozoic

Abstract

The Early Palaeozoic Orogen of SE China consists of three litho-tectonic elements, from top to bottom: a sedimentary Upper Unit, a metamorphic Lower Unit and a gneissic basement. The boundaries between these units are flat lying, south directed, ductile decollements. The lower one is coeval with an amphibolite facies metamorphism (M1). The belt is reworked by migmatite-granite domes, high-temperature metamorphism (M2) and granitic plutons related to post-orogenic crustal melting. We date here the syn-M1 ductile shearing at 453±7 Ma by U-Th/Pb

method on monazite. Previous ages, and our new $^{40}Ar/^{39}Ar$ ages of biotites and muscovites show that the metamorphic rocks experienced syn-M2 exhumation from 440 Ma to 400 Ma. The Early Palaeozoic Orogen of SE China is an intracontinental belt in which decollements accommodated the north-directed subduction of the Cathaysian continent. This orogen is an example of intracontinental subduction that was not preceded by oceanic subduction.

Introduction

Continental subduction accounts for high-pressure metamorphism, ductile deformation and melting of crustal rocks. This process is well documented in collision belts where magmatic arc and ophiolitic nappes show that oceanic subduction precedes continental one (e.g. Mattauer, 1986; Escher and Beaumont, 1997; Matte et al., 1997; Guillot et al., 2003, Faure et al., 2008). In intracontinental belts, evidence for an earlier, long lasting, oceanic subduction is lacking. The Central Asia ranges result of intracontinental subduction caused by the indentation of Asia by India after the collision (Mattauer, 1986; Burtman and Molnar, 1993; Avouac et al., 1993; Allen et al., 1999), but these orogens do not expose their deep zones. The Pyrenees or Alice Springs belts are examples of intracontinental orogens where metamorphic or magmatic domains are observed (e.g. Teyssier, 1985; Roure et al., 1989; Hand and Sandiford, 1999). This paper presents structural and geochronological data that allow us to propose an intracontinental subduction model accounting for the formation of the Early Palaeozoic Orogen of SE China.

An outline of the geology of SE China

The South China Block (SCB, Fig. 1A) is one of the continental masses that amalgamated to form Eurasia. It contains several internal belts, such as the Xuefengshan, or the Wuyi-Yunkai Fold Belt (Fig 1A). SCB experienced five main tectonic events since the Proterozoic. The earliest one corresponds to the Neoproterozoic Jinning Belt that welded the Yangtze and Cathaysia Blocks to form the SCB (Guo et al., 1985, 1989; Chen et al., 1991; Xu et al., 1992; Charvet et al.,

1996; Shu and Charvet, 1996). From 830 to 690 Ma, the intracontinental Nanhua rift, characterized by up to 5 km of terrigeneous and volcanic rocks, superimposes upon the Jinning Belt (Li et al., 1999; Wang and Li, 2003). There is no major sedimentary break between late Neoproterozoic and Cambrian rocks, but sharp facies and thickness contrasts are recognized for the Cambrian-Ordovician deposits between the northern and southern domains. The former is represented by ca 4.5 km of carbonate and black shale, whereas the latter consists of more than 8 km of sandstone, siltstone and mudstone. In the southern domain, Silurian deposits are missing, and Devonian conglomerates and sandstone unconformably cover Early Paleozoic series (JBGMR, 1984, HBGMR, 1988; Zhao et al., 1996). Excepting the area that experienced the Early Palaeozoic Orogeny, the Devonian rocks cover the Silurian rocks either in direct continuity or with a slight disconformity. The Devonian-Carboniferous transition is also continuous. Platform sedimentary sedimentation continues in the Permian, Early and Middle Triassic. A Late Triassic regional unconformity argues for the Late Permian to Middle Triassic Indosinian Orogeny (e.g. Huang, 1945; Faure et al. 1996, Shu et al., 2006; Wang et al., 2007; Lin et al., 2008). The Jurassic-Cretaceous Yanshanian event is characterized by NE-SW trending normal or wrench faults that controlled pluton emplacement and continental sedimentation (e.g. Gilder, 1991; Jahn et al., 1990; Faure et al., 1996; Lin et al. 2000; Zhou et al., 2006; Shu et al., 2008). In the study area, the post-Devonian deformation is localized along faults and does not significantly disturb older structures. A discussion of the Indosinian and Yanshanian events is beyond the scope of this paper.

In SE China, the existence of Early Palaeozoic tectonics is documented by the Devonian unconformity, and Late Silurian to Early Devonian granitoids intruding folded Early Palaeozoic rocks (e.g. Grabau, 1924; Huang 1945; Ren et al. 1989; Zhang et al., 1984; Guo et al, 1985). The tectonics of SE China have been variously interpreted, namely i) Triassic collision between the Yangtze and Cathaysia Blocks (Hsu et al., 1990); ii) Andean-type subduction followed by collision (Ma, 2006; Jahn et al., 1990); iii) multiple arc collisions (Guo et al., 1969; Ma, 2006); iv) intracontinental belt (Ren et al., 1969; Charvet et al., 1996; Wang et al., 2007; Shu et

al. 2008). However these models do not provide detail structural information.

The Early Palaeozoic Orogen of SE China

The Early Palaeozoic Orogen is exposed from Wuyi to Yunkai in China and in the Song Chai massif of Vietnam (Fig. 1A). In the study area, South of Nanchang, we recognized five units (Fig. 1B).

The Sedimentary Upper Unit consists, from top to bottom, of Middle to Late Ordovician turbidite with slumps, disrupted sandstone beds and pebbly mudstones. Plurimeter-scale limestone lenses scattered within sandstone are likely olistoliths. Dykes or lava flows are absent.

The Metamorphic Lower Unit is composed of micaschist, paragneiss and a small amount of quartzite, amphibolite and marble. The protoliths of these rocks are terrigeneous or volcaniclastic rocks. Detrital zircons in paragneiss with 1000- 700 Ma ages argue for a Neoproterozoic protolith (Wan et al. 2006).

The Paleoproterozoic basement consists of biotite-amphibole gneiss, amphibolite, granitic-gneiss, and porphyritic granite. East of the study area, amphibolite yields SHRIMP U/Pb zircon age of 1766±19 Ma interpreted as the protolith age (Li et al., 2000). Detrital zircons from paragneiss yield U/Pb ages ranging from 3.6 to 2.5 Ga (Yu et al., 2006; Xu et al., 2005).

Metatexites, diatexites and anatectic granitoids developed at the expense of the Lower Unit and Proterozoic basement at the end of the Early Palaeozoic Orogeny (cf. below).

Undeformed biotite granite, two micas leucogranite and porphyritic granodiorite, formed by crustal melting, intrude the Upper and Lower Units (Li et al., 1989; Wang et al., 2007; Zhou et al., 2006).

The Upper Unit is well exposed in the southwestern part of the study area, whereas the Lower Unit, migmatites and basement crop out in the northwestern one (Fig. 1). The bulk architecture of the chain (Fig. 2) shows that the sedimentary Upper Unit overlies the metamorphic Lower Unit that in turn overlies the Proterozoic basement. The Upper Unit-Lower Unit boundary is a widespread flat-lying decollement zone (cf.

below). The contact between the Lower Unit and the Proterozoic basement is poorly exposed, however, near Jianning, the upper part of the Proterozoic gneiss is mylonitized (cf. below). Migmatites and anatectic granites form several domes deforming the Lower Unit. To the North, from Chongren to Cizhou, the foliation dips at high angle to the North. The northern boundary of the belt is the Jiangshan-Shaoxing fault, North of which the Palaeozoic series is continuous and not deformed before the Devonian.

Deformation and metamorphism in the Early Palaeozoic Orogen

Thin skinned tectonics in the sedimentary Upper Unit. In Chongyi-Jian area (Fig. 1), the Late Neoproterozoic to Ordovician series is deformed by E-W to NW-SE trending folds overturned to the S or SW (Fig. 3A). NW-SE trending fracture cleavage develops in Ordovician rocks, and slaty cleavage is common in Cambrian ones (Fig. 4). Bedding-cleavage relationships indicate a southwestern vergence of the folds. High angle thrusts are also observed. Open buckle folds predominate in Ordovician rocks and similar, even isoclinal, folds are found in Cambrian-Sinian rocks. A NE-SW trending stretching lineation marked by reorientation of detrital particles sometimes appears in the slates but associated metamorphism is absent. As a whole, the ductile deformation increases downward.

The decollement zone. North of Xingguo (Fig. 1B), subhorizontal slaty cleavage and N-S to N50E stretching lineation are conspicuous (Figs. 3B, 4). Asymmetric pressure shadows, sigmoidal quartz or feldspar clasts and sericite clots indicate a top-to-the-SW shearing. These structures are coeval with sericite or chlorite metamorphism. Isoclinal folds with axes parallel to the lineation formed during the ductile shearing are also found. This high-strain zone is interpreted here as a ductile decollement along which the horizontal shortening accommodated by folding and thrusting in the sedimentary Upper Unit is transferred.

The synmetamorphic polyphase deformation in the Lower Unit. Micaschist, quartzite and paragneiss that widely develop in the east of the study area exhibit two synkinematic metamorphic assemblages (M1 and M2). The youngest and most

conspicuous M2 event is represented by biotite-garnet-sillimanite-muscovite oriented along the macroscopic foliation. Mica and sillimanite form a N-S to NW-SE trending mineral lineation. According to geological maps (JBGMR, 1984), this foliation defines several 20 to 30 km-scale dome structures. In the centre of the domes, anatectic granite presents a foliation represented by schlierens, mafic enclaves (Fig. 3C) and preferred orientation of mica and feldspar. This foliation is parallel to the one observed in migmatites and metamorphic rocks. Along the mineral lineation, biotite or quartz pressure shadows and sigmoidal micas indicate contrasted kinematics depending on their location in the dome. The southern and northern flanks of the dome exhibit top-to-the S and top-to-the N senses of shear, respectively. In Cizhu area, the migmatitic gneiss is overlain by Neoproterozoic-Cambrian sandstone or black shale of the Upper Unit. The boundary between these two units is a south-dipping detachment fault with a N-S stretching lineation and top-to-the-south kinematic indicators.

In the Nancheng and Chongren areas, evidence for migmatization is absent, but the north-dipping foliation is deformed by north directed extensional shear bands and sigmoidal biotite porphyroblasts indicate a top-to-the-North shearing (Fig. 3E). This post-folial deformation developed at the end of M2 event, as indicated by Ar/Ar dating (cf. below).

Furthermore, relict porphyroblasts of staurolite, kyanite, garnet, and biotite inclusions in garnet (JBGMR, 1984) argue for an early M1 metamorphism. Locally, sillimanite develops at the expense of kyanite. The high temperature M2 event overprints the medium pressure M1one. The pressure-temperature evolution from medium to high-pressure conditions (11-12kb, 550-600°C) to high temperature ones (4-4.4 kb, 570-650°C) has already been determined in the Wuyi area (Zhao and Cawood, 1999). As the M1 assemblages are mostly erased by the M2 event, the M1-related microstructures are rare. Kyanite defines a N-S trending lineation, but the kinematics is unclear. As a hypothesis, we suggest that the syn-M1 lineation is coeval with the lineation observed in the decollement zones. The thermo-barometric estimates proposed by Zhao and Cawood (1999) and our own dating (cf. below) are used to

construct a P-T-t path for the Lower Unit (Fig. 4).

Deformation of the Proterozoic basement. A few hundred of meters below the contact with the Metamorphic Lower Unit, the basement gneiss is penetratively foliated and contains a N-S trending mineral lineation marked by biotite clots and amphibole needles (Fig. 3D). Quartz and feldspar form elongated ribbons alternating with mafic minerals. Asymmetric K-feldspar porphyroclasts indicate a top-to-the-S sense of shear.

Geochronological constraints

Available radiometric dating and our new data allow us to settle the timing of the main events of the Early Palaeozoic Orogeny. The post-tectonic granitoids between Jingganshan and Chongyi yield U/Pb zircon ages of 387± 4 Ma, 397+/- 4 Ma and 434±5Ma (JGGMR, 1984; Li et al., 1989; Li, 1994; Shen et al. 2008). The M2 metamorphism and coeval anatexis is estimated around 450-420 Ma from U/Pb zircon ages of Cizhu (432±4 Ma), Lichuan (444±4 Ma), and granites east of the study area (447±2 Ma, Wan et al., 2007; Chen et al., 2008; Shu, unpublished). The Cizhu anatectic granite, coeval with the M2 event, yields a muscovite $^{40}Ar/^{39}Ar$ age at 421±8 Ma (Shu et al., 1999).

Presently, the M1 metamorphism is undated, therefore, in order to place time constraints on the early metamorphic event, monazite was dated by the chemical U-Th/Pb method (Cocherie and Albarède, 2001). The analyzed quartz-biotite-garnet micaschist, located near Chongren (Fig. 1), formed during the M1 event. M2 sillimanite is absent. U, Th and Pb contents measured by EPMA in ten monazite grains are plotted in the Th/Pb vs. U/P diagram (Fig. 6). The analytical points define a regression line close to the 453±7 Ma isochron interpreted as the age of the M1 event. $^{40}Ar/^{39}Ar$ laser probe, single grain step-heating dating was carried out on a muscovite-biotite pair from the same sample where those micas are deformed by top-to-the-N shear bands. The analytical procedure is described in Brichau et al. (2007). Data are reported in table 1. Both micas provide relatively concordant age

spectra for a large percentage of the argon released with very few evidence of argon loss or excess argon. Plateau ages of 397±4 Ma and 405±4 Ma have been calculated for biotite and muscovite, respectively (Fig. 7). These ages are interpreted to date final cooling of this micaschist through a temperature window of about 400-300 °C as the unit was progressively exhumed at the end of the M2 event.

Tectonic interpretation and a possible geodynamic evolution model

The above described tectono-metamorphic events are restricted to the South of the Jiangshan-Shaoxing fault (JSF, Fig. 1), North of which, the sedimentary series is continuous from Late Neoproterozoic to Early Triassic, deformed by NE-SW striking upright folds before the Late Triassic unconformity (JBGMR, 1988). Silurian rocks, concordant with Ordovician ones, are covered by Middle Devonian deposits with a disconformity lower than 20°. Therefore, the JSF appears as a major tectonic boundary for the Early Palaeozoic Orogen. Furthermore, Palaeozoic arc-type plutons or volcano-sedimentary rocks are missing.

The metamorphic Lower Unit and the basement are reworked by a high-temperature and melting event. The top-to-the-north kinematics observed in the northern part of the belt coeval with the M2 event, develops during the exhumation of the M1 metamorphic rocks. The Upper and Lower Units cannot be considered as nappes, as younger and less metamorphosed rocks always superimpose upon older ones. Thus, the boundaries between the three elements are decollement zones rather than thrust contacts.

The Jiangshan-Shaoxing Fault does not represent an ophiolitic suture zone, but a tectonic “scar” corresponding to the place where a piece of continental lithosphere of Cathaysia has been subducted to the north below another piece of the same continent (Fig. 8). A tectonic scenario is proposed here (Fig. 8). From the Late Neoproterozoic to Middle Ordovician, the site of the Early Palaeozoic Orogen was occupied by a subsiding trough corresponding to the Nanhua Rift, and to the Early Palaeozoic facies transition.

In the Late Ordovician, ca 460-450 Ma, two main, south-directed, ductile decollement zones accommodate North-South shortening. The upper decollement, devoid of metamorphism, separates the Upper and Lower Units. The lower one separates the metamorphic Lower Unit from the basement. These high strain zones correspond to rheologically weak interfaces such as Neoproterozoic pelites or the contact between the crystalline basement and the overlying sedimentary rocks. The northern boundary of the deformed block is the JSF scar. The synsedimentary structures in the Ordovician turbidite argue for a tectonic instability that might reflect the onset of the deformation.

In Early Silurian, (ca 445-430 Ma), the deep part of the orogen is exhumed coevally with the development of the high temperature M2 metamorphism and anatexis. The detail of temperature rise is not settled yet. The erosion of the belt provided the material for the Silurian sandstone in the northern domain as indicated by NW-directed scour marks (Rong et al., 2003). However, the $^{40}Ar/^{39}Ar$ ages suggest that exhumation continued up to Early Devonian.

Conclusion

The Early Palaeozoic Orogen of SE China lacks ophiolites, magmatic arc, subduction complexes, high-pressure metamorphism, thus it cannot be a collision belt. Conversely, ductile decollements, medium pressure/medium temperature metamorphism, and crustal melting are conspicuous. The structural, metamorphic and sedimentary elements presented here characterize an intracontinental orogen controlled by the northward subduction of Cathaysia. Pre-orogenic sedimentary and structural inheritances play certainly an important role in the localization and initiation of continental subduction (e.g. Cloetingh et al., 2008).

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Figure captions

Figure 1A: Tectonic sketch of the South China Block. JLS: Neoproterozoic Jiulingshan belt; XFS: Triassic Xuefengshan Belt; JSF: Jiangshan-Shaoxing Fault.

1B: Structural map of the Early Palaeozoic Orogen in the study area, south of Nanchang (Jiangxi Province). For clarity, sedimentary series and granitic plutons younger than Early Triassic have been omitted. In the Sedimentary Upper Unit, dotted lines represent bedding trajectories. In the Metamorphic Lower Unit, dotted lines outline dome structures. Boxes show the new radiometric ages given in figures 6 and 7. U/Th/Pb mz : chemical age obtained on monazite (mz), Ar/Ar bi/ms : $^{40}Ar/^{39}Ar$ ages from biotite (bi) and muscovite (ms).

Figure 2: Synthetic cross section (located in figure 1) showing the bulk geometry of the Early Palaeozoic Orogen.

Figure 3: Some tectonics features of the pre-Devonian orogen of SE China in Jiangxi. A: nearly isopach fold in Cambrian sandstone S. of Jinggangshan. B: Stretching lineation in the decollement layer N. of Xingguo. C: anatectic granitoids near Lichuan, the magmatic foliation is defined by biotite schlierens and preferred orientation of biotitic boudins, note also a gneiss xenolith the foliation of which is oblique to the magmatic one. D: Proterozoic gneiss with a conspicuous planar and linear fabric related to the Early Paleozoic tectonics, N. of Jianning. E: Sigmoidal biotite showing a top-to-the-N sense of shear attributed to the late orogenic exhumation, S. of Chongren. This sample is the one dated by $^{40}Ar/^{39}Ar$ (cf. figure 7)

Figure 4: Stereographic plots (Schmidt lower hemisphere projection) of the structural elements related to the Early Palaeozoic orogeny of SE China.
A: poles of bedding (S0) and cleavage (S1) planes in the sedimentary Upper Unit near Chongyi. B: cleavage poles (S1) and strike of stretching lineation in the ductile decollement layer North of Xingguo. C: pole of composite foliation (S1-2) and M2 mineral lineation (L2) mainly represented by sillimanite and biotite around the Cizhou dome.

Figure 5: P-T-t path of the Metamorphic Lower Unit. Time constrains are those provides in this paper (cf. figures 6 and 7), P and T conditions are adapted from Zhao and Cawood, (1999).

Figure 6: U-Th/Pb isochron diagram of monazite from a biotite-garnet micaschist belonging to the metamorphic Lower Unit (location 27°42’20, 115°59’26). Analytical procedure and data reduction are provided in Cocherie and Albarede (2001). The calculated regression line (thick line) is similar to the theoretical isochronon (dashed line). The thick lines represent the error envelopes. The calculated age at the centroid

is 453±7 Ma, which is interpreted as the age of the M1 metamorphism.

Figure 7: Laser probe, single grain step-heating dating of muscovite and biotite from the same biotite garnet micaschist sample belonging to the metamorphic Lower Unit (location 27°42’20, 115°59’26). Plateau ages of 397±4 Ma and 405±4 Ma have been calculated for biotite and muscovite respectively. These ages are interpreted to date final cooling of this micaschist through a temperature window of about 400-300 °C.

Figure 8: A possible geodynamic evolution model of the intracontinental orogen.
A: Early Ordovician reconstruction of the Early Palaeozoic paleogeographic transition from a carbonate platform to terrigeneous trough from North to South. The facies transition zone is independent of the Neoproterozoic collision, but it might represent a potentially weak zone for the development of the Early Paleozoic Orogen. The southern continent, South of the Jinning suture, is Cathaysia. Y: Yangtze Block.
B: Late Ordovician northward continental subduction of the Paleoproterozoic basement of the southern part of Cathaysia, decollement of the Lower Unit, and development of the biotite-garnet-kyanite M1metamorphism. South-directed thrusting and folding with a basal ductile decollement layer deform the Neoproterozoic to Ordovician Sedimentary Upper Unit. The deformation does not propagate North of the Jiangshan-Shaoxing fault (JSF). The Jinning suture, lying to the North of the scar, is not reactivated. Second order decollement layers are located in coal measures or in soft mudstone beds separating quartzite or sandstone strata.
C: Early Silurian (444-430 Ma) completion of the northward continental subduction of Cathaysia. Crustal melting and high temperature M2 metamorphism overprint the M1 event. The exhumation of the chain is accommodated by erosion with northward transport to a Silurian turbiditic basin, doming and detachement faulting.

Table 1. Analytical data of laser probe, single grain step-heating dating of muscovite and biotite from the a biotite garnet micaschist sample.

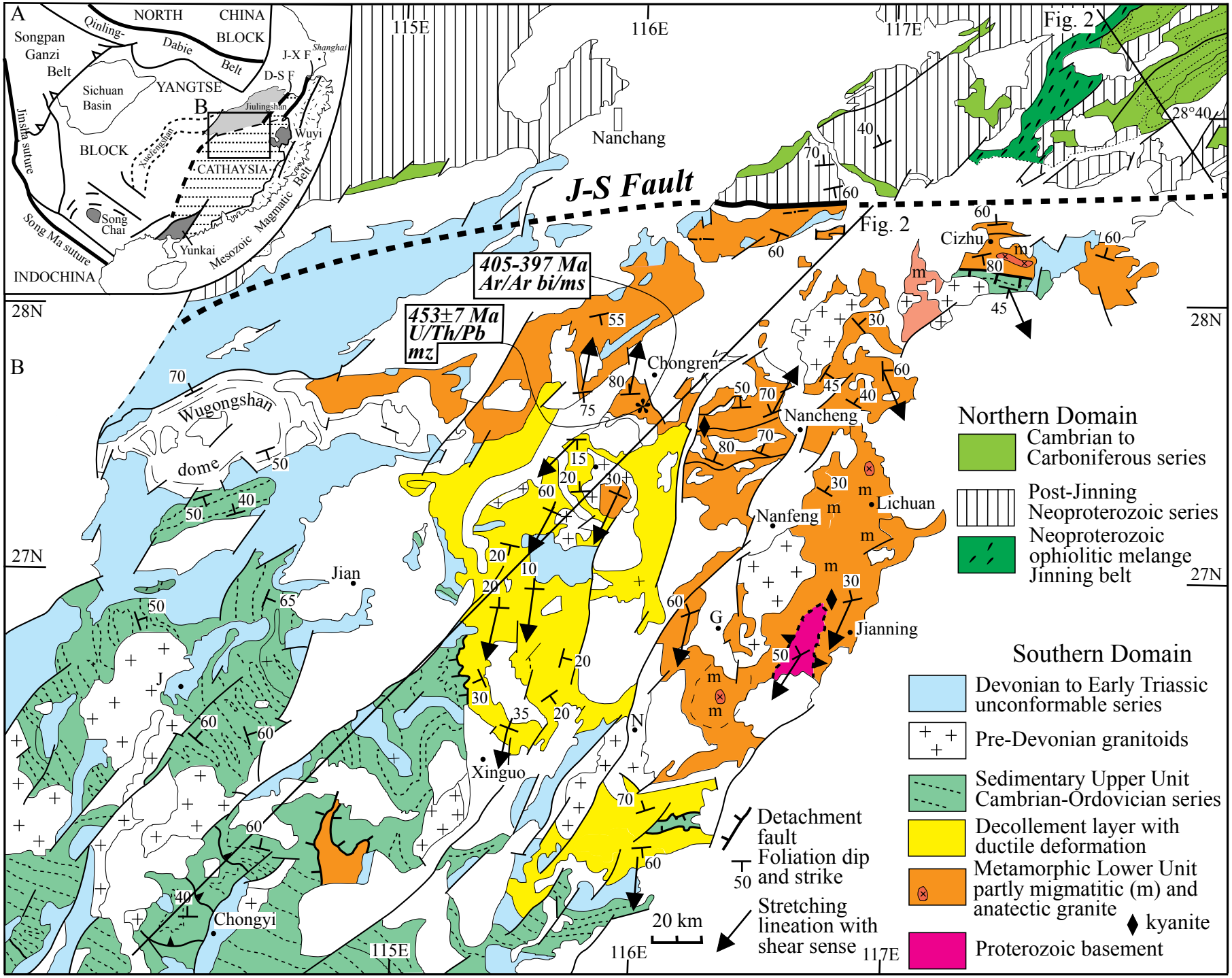
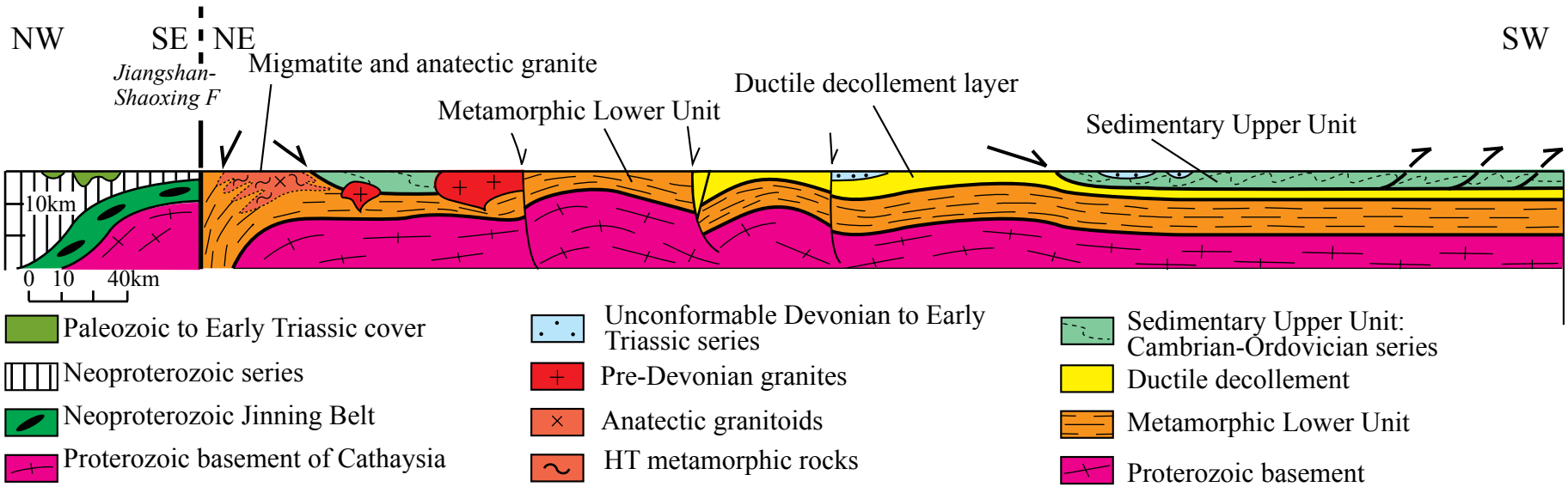

A
NORTH CHINA BLOCK
Qinling-Dabie Belt
Songpan Ganzi Belt
Sichuan Basin
YANGTSE BLOCK
Jinsha suture
Song Ma suture
INDOCHINA
Song Chai
Yunkai
Mesozoic Magmatic Belt
CATHAYSIA
Xuefengshan
Jiulingshan
Wuyi
J-X F
D-S F
Shanghai
B
115E
116E
117E
Fig. 2
28°40
Nanchang
J-S Fault
Fig. 2
Cizhu
405-397 Ma
Ar/Ar bi/ms
453±7 Ma
U/Th/Pb
mz
28N
B
Chongren
Wugongshan
dome
Nancheng
Lichuan
Nanfeng
Jian
27N
Jianning
G
J
N
Xinguo
Chongyi
20 km
Northern Domain
Cambrian to Carboniferous series
Post-Jinning Neoproterozoic series
Neoproterozoic ophiolitic melange Jinning belt
Southern Domain
Devonian to Early Triassic unconformable series
Pre-Devonian granitoids
Sedimentary Upper Unit Cambrian-Ordovician series
Decollement layer with ductile deformation
Metamorphic Lower Unit partly migmatitic (m) and anatectic granite
kyanite
Proterozoic basement
Detachment fault
Foliation dip and strike
Stretching lineation with shear sense

Fig. 1



Paleozoic to Early Triassic cover
Neoproterozoic series
Neoproterozoic Jinning Belt
Proterozoic basement of Cathaysia
Unconformable Devonian to Early Triassic series
Pre-Devonian granites
Anatectic granitoids
HT metamorphic rocks
Sedimentary Upper Unit: Cambrian-Ordovician series
Ductile decollement
Metamorphic Lower Unit
Proterozoic basement

Fig. 3

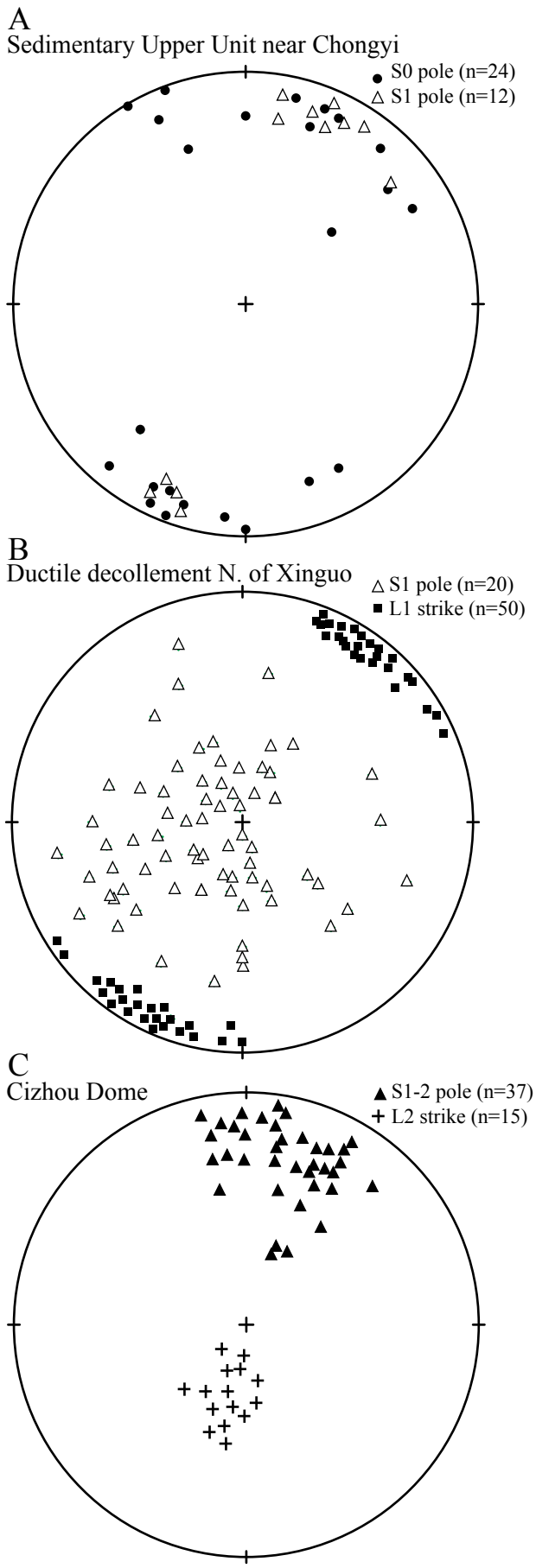
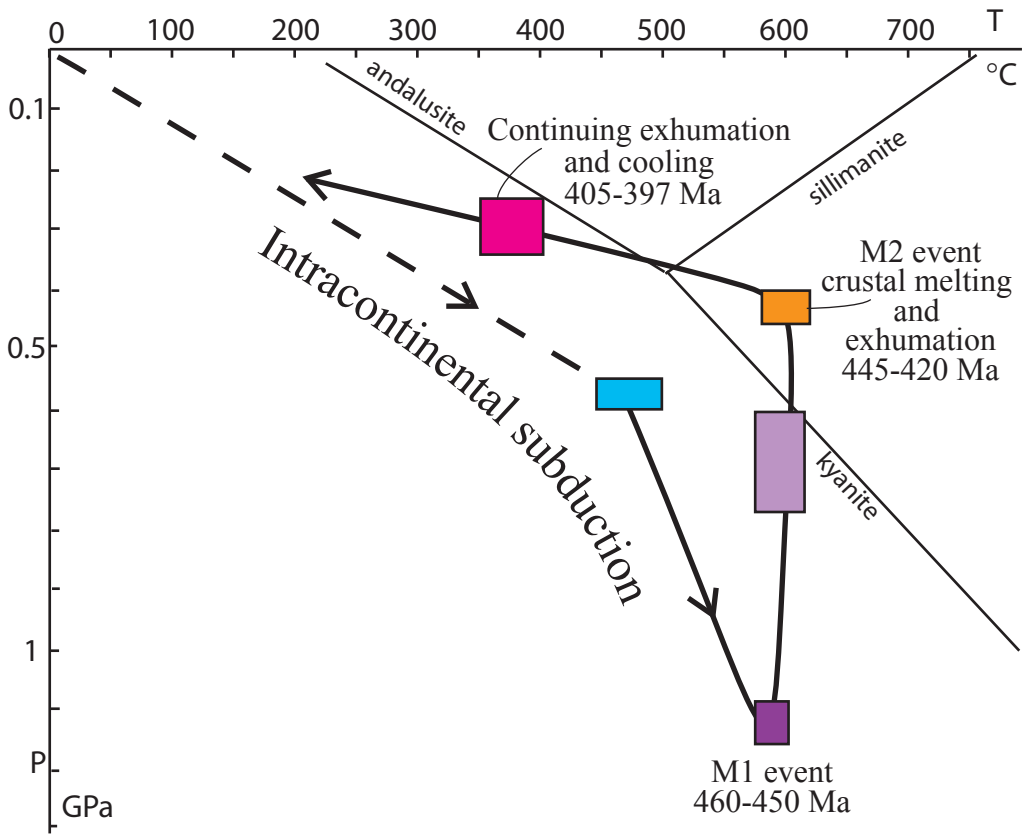

A
Sedimentary Upper Unit near Chongyi
S0 pole (n=24)
S1 pole (n=12)
B
Ductile decollement N. of Xinguo
S1 pole (n=20)
L1 strike (n=50)
C
Cizhou Dome
S1-2 pole (n=37)
L2 strike (n=15)

Fig 4.


0
100
200
300
400
500
600
700
T
°C
0.1
0.5
1
P
GPa
andalusite
sillimanite
kyanite
Continuing exhumation
and cooling
405-397 Ma
M2 event
crustal melting
and
exhumation
445-420 Ma
M1 event
460-450 Ma
Intracontinental subduction

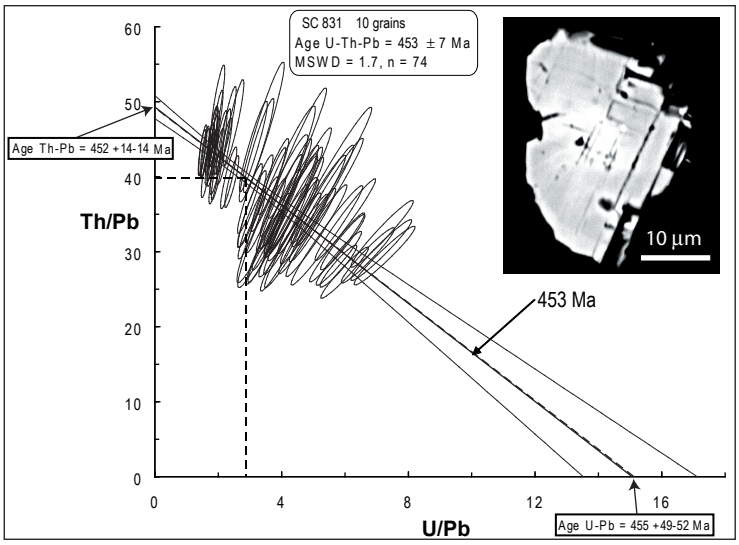
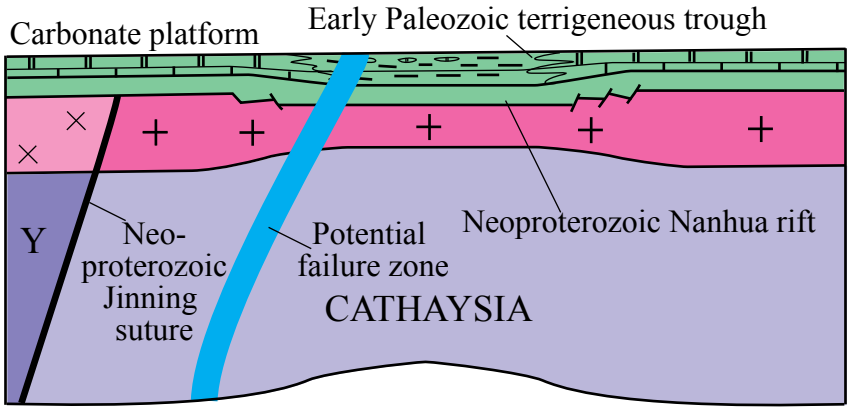
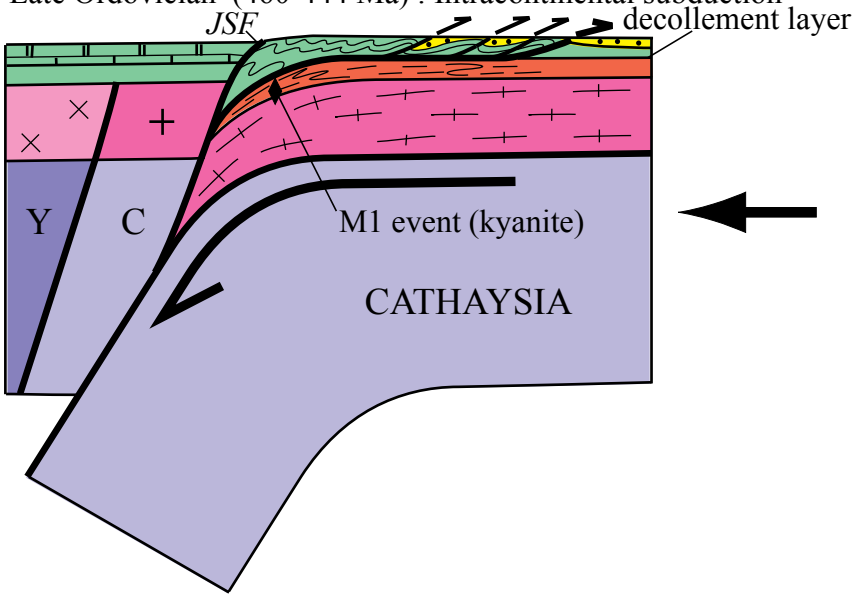
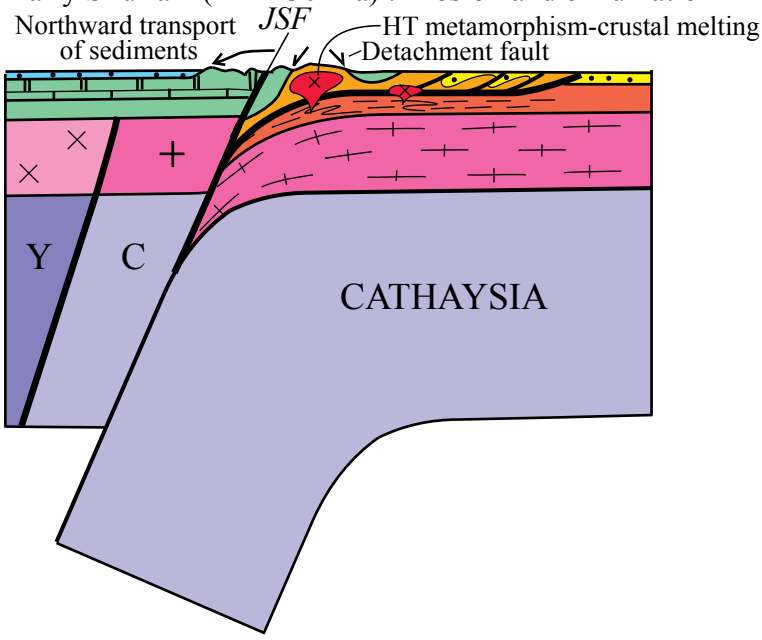

SC 831 10 grains
Age U-Th-Pb = 453 ± 7 Ma
MSWD = 1.7, n = 74
Age Th-Pb = 452 +14-14 Ma
Th/Pb
U/Pb
453 Ma
10 µm
Age U-Pb = 455 +49-52 Ma
0
10
20
30
40
50
60
0
4
8
12
16

Fig. 6

Middle Ordovician ca 470 Ma) : contrasted sedimentation



Late Ordovician (460-444 Ma) : Intracontinental subduction



Early Silurian (444-430 Ma) : Erosion and exhumation