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Comparing the Upper Triassic Deep-sea Flysch of the Shannan Terrane with the Coeval Shallow Shelf Sediments of the Tethys Himalaya, Southern Tibet

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Abstract: The provenance and paleogeography of the Upper Triassic deep-sea flysch Langjiexue Group (LG) of the Shannan Terrane in the northeastern Himalaya orogen, south of Yarlung Zangbo, have been disputed in recent years since its affinity to the Tethys Himalaya was suspected during the early 2000s. Based on the earlier discoveries of the Upper Permian–Triassic basalts and mafic dykes from the LG and of coeval detrital zircons from the Qulonggongba Formation (QF) in shallow shelf sediments of the Tethys Himalaya, the previous viewpoints on the basin and tectonics of the LG have been recently rejected. We compared the two units of the Upper Triassic, and our results reveal a number of differences, discrepancies, and inconsistencies in the debate, raising crucial questions on the postulation and provenance model of the remote Gondwanide Orogen for the LG. It is suggested that more observations and evidence are needed to further improve the paleogeographic understanding and relationship of the two units.

Key words: sedimentology, paleogeography, flysch, shelf sediment, Late Triassic, Shannan Terrane, Tethys, Tibet

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1 Introduction

The Upper Triassic deep-sea flysch, the Langjiexue Group (LG), is widespread in the Shannan area of southeastern Tibet, south of Yarlung Zangbo, recording important evidence of the eastern Gondwana breakup. It has been interpreted either as a deep-sea sediment of the Tethys Himalaya (Yu and Wang, 1990), i.e., in the northern Indian passive margin (e.g., Wang, 1983; Yin and Harrison, 2000; Dunkl et al., 2011), or as an accretionary prism (Zhou et al., 1984; Pan et al., 2010; Wang et al., 2013; Ao et al., 2018) within the mélange belt of the Yarlung Zangbo suture zone to the west of Xigaze (TBGMR, 1993, 1997). However, its affinity with the Tethys Himalaya was suspected by the discovery of southward paleocurrent directions in the Shannan area (Li et al., 2003a; Xu et al., 2009; Zhang et al., 2017), and the disaffinity to the Indian continent was verified by the featured Permian–Triassic (~300–200 Ma) detrital zircon age population (e.g., Li G W et al., 2010, 2014; Webb et al., 2013; Cai et al., 2016; Li X H et al., 2016; Wang et al., 2016), resulting in the proposition of multiple tectonic and paleogeographic models (e.g., Li G W et al., 2010, 2014; Cai et al., 2016; Li X H et al., 2016; Cai et al., 2016; Wang et al., 2016; Zhang et al., 2017; Cao et al., 2018). There are two basic categories of tectonic and paleogeographic models. One proposes that the provenance is not related to the Indian continent (e.g., Li G W et al., 2010, 2014; Cai et al., 2016; Li X H et al., 2016; Wang et al., 2016; Zhang et al., 2017; Li, 2019; Ma et al., 2019; Liu et al., 2020), while the other suggests an affinity of provenance with the Indian continent (Tethys Himalaya. e.g., Cao et al., 2018; Fang et al., 2018; Meng et al., 2019; Zhang et al., 2019).

Surprisingly, the Late Permian–Triassic detrital zircons were newly discovered from three sandstone samples of the Qulonggongba Formation (QF) in shallow shelf sediments of the Tethys Himalaya (Nyalam and Tingri regions, southern Tibet) (Meng et al., 2019). Although only nine detrital zircons (dated as ~260–207 Ma) of the QF have been studied, the authors compared the zircon age population with that of the LG flysch, including the Nieru Formation (Li et al., 2011) of the Shannan Terrane and west to Renbu (Li et al., 2016), southern Tibet, and then proposed that the QF and LG have a provenance similarity and that the deep-sea LG flysch is an in-situ Tethys Himalayan sedimentary sequence rather than part of an exotic block. Meng et al. (2019) agreed and further elucidated the Gondwanide Orogen source model (eastern Australia/East Gondwana) (e.g., Cai et al., 2016; Wang et al., 2016; Cao et al., 2018) and envisaged a new model for the paleogeography and sedimentary evolution for both the QF and LG. These data and interpretations provide new insights into the LG's provenance and paleogeography as well as its tectonic character.

However, the postulation of the LG flysch as an in-situ sedimentary sequence unit appears simplistic and uncritical as a number of discrepancies and/or inconsistencies remain, which were left unaddressed by

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earlier authors. Therefore, here we raise crucial questions that allow us to argue against the validity of the new postulation. To clarify the relationship or unrelatedness of the two units, we briefly contrast them in terms of tectonic nature, chronology, paleogeography, provenance, and sedimentology.

2 Tectonic and Metamorphic Considerations

Though it was acknowledged that the "LG is everywhere in fault contact with Tethys Himalayan strata", the LG flysch was suggested to represent an in-situ stratigraphic unit in the Tethys Himalaya (Meng et al., 2019). One aspect we need to make clear is that the LG is confined by the Great Counter Thrust in the north (e.g., Gansser, 1964; Yin et al., 1999; Murphy and Yin, 2003; Dong et al., 2016) and by the Qiongduojiang–Zara Fault and/or the Rinbung–Zhamda–Lhunze Fault in the south (e.g., Pan et al., 2004; Pan and Wang, 2010). Obviously, there are no Tethys Himalayan strata in fault contact with the LG in the north. Secondly, these kinds of large and deep (lithospheric scale) faults do not confine the Upper Triassic (i.e., QF) in the Tethys Himalaya even though numerous small-scale faults occur within the Himalayan thrust sheets (e.g., Murphy and Yin, 2003).

Besides the discrepancy of the fault contact relationship, the two units also differ in their deformation and metamorphism. The tight deformational style and commonly overturned strata of the LG differ greatly from the wide and ramp deformation style of the QF in the Tethys Himalaya (e.g., Webb et al., 2013; Fang et al., 2018). Also, most of the LG is composed of slate to schist metamorphic rocks, whereas the QF is purely sedimentary and non-metamorphic (e.g., Wang, 1983; Yu and Wang, 1990; Li et al., 2003a; Dunkl et al., 2011; Zhang et al., 2015; Meng et al., 2019).

Supposing that tectonism and metamorphism had been involved during the Indian-Asian Cenozoic collision, the differences of deep thrusts and tight deformation cannot preclude that the LG belongs to the in-situ Tethys Himalaya sedimentary sequence. However, deformation and metamorphism of the LG might have occurred early within the Cretaceous, as indicated by the Early Cretaceous dyke emplacement (Dunkl et al., 2011) while drifting towards Asia (Li et al., 2016).

The thrust contact together with the tightly deformed and metamorphic strata rather indicate that the LG is an independent terrane of the Tethys Himalaya and differs from the QF in both tectonic and stratigraphic nature. This discrepancy may suggest that the LG flysch was deposited at a considerable distance from the QF, likely ruling out that the LG is an in-situ or autochthonous unit of the Tethys Himalaya. It is more probable that the LG flysch is exotic within the Tethys Himalaya sequence, particularly when various other aspects (below) are considered as well.

3 Age Range

The QF and LG partly share the age of the Late Triassic, but both units have different age ranges. As Meng et al. (2019) cited, the QF has previously been assigned to the early Norian (Late Triassic) (Jadoul et al., 1998), even though it was later assigned to the middle or late Norian based on ammonite zones (e.g., Shi, 2001; Zou et al., 2006). Bivalve zones of the family Halobiidae (e.g., genera *Daonella* and *Halobia* and relevant species) and the family Monotidae (e.g., *Monotis*) indicate that the LG age is the early Carnian through the latest Norian (McRoberts, 2010) (for detailed summary see Li et al., 2011), possibly even as old as the Ladinian (mid-Triassic) because of the presence of *Daonella* (McRoberts, 2010).

The above age determination demonstrates that the LG is at least 7 Myr (Carnian, 235–228 Ma) older than the QF and even likely more than 15–20 Myr range considering that the LG is over 2,000 m (Zhang et al., 2015, 2017) thicker than the QF and that the QF represents half (10 Myr) or 1/3 (~7 Myr) of the Norian time range. These different age ranges raise the question of whether Meng at al. (2019) indeed compared "coeval" strata, especially since no details on the similar age were presented. Thus, we wonder whether their claim of having compared strata of coeval age is actually tenable and valid.

4 Lateral Paleogeographic and Transportation Distances

4.1 Biota and paleobiogeography

Fossils of the LG are dominantly planktonic bivalves and ammonites, and benthic fossils are almost absent. Bivalves are represented by the genera *Holobia, Monotis, Daonella, Posidonia, Entolium,* etc., and ammonites by *Tropites, Parajuvarites, Tibatites, Indojuvarites*, *Juvarites*, etc. (for detailed summary see Li et al., 2011).

The QF contains both benthic and planktonic biota, including brachiopods, bivalves, cephalopods, conodonts, ostracods, and sporopollens (e.g., Yin et al., 1974, Rao et al., 1987; Jadoul et al., 1998; Shi, 2001; Zhu et al., 2005; Zou et al., 2006). Among the biota, bivalves are dominated by benthic forms such as *Indopecten, Burmesia, Myophoriopis, Pichleria*, and others (e.g., Yin et al., 1974; Rao et al., 1987; Zhu et al., 2005; Zou et al., 2006). It is also characterized by ammonites such as *Indojuvarites, Cyrtopleurites, Pinococeras, Nodotibetite, Metacarnites,* etc. (e.g., Yin et al., 1974; Rao et al., 1987; Jadoul et al., 1998; Zou et al., 2006).

The different fossil compositions reflect not only the difference in stratigraphic age but also the different paleoecologies and paleobiogeographies for the two lithostratigraphic units. The bivalve *Holobia* of the LG was widespread in global deep-sea sediments (McRoberts, 2010) and is comparable with those of the coeval flysch of the Caodi Group in the Songpan–Ganzi Fold Belt of western Sichuan (e.g., Yin et al., 1992). The above-mentioned contrasting biota and their different paleobiogeographic implications dictate that the LG and QF were deposited at great lateral paleogeographic distance.

4.2 Sedimentary facies

As described in their publication (Meng et al., 2019: fig. 2), the QF is composed of dark and greenish-gray shales/mudrocks with intercalations of thin- to medium-bedded siltstones and fine sandstones, of which variable cross-bedding structures are associated with some horizontal lamination and phosphate nodules. Particularly, hummocky cross-bedding, in line with lithology and benthic fossils, indicate a shallow marine, shelfal depositional environment (e.g., Yu and Wang, 1990; Jadoul et al., 1998; Zhu et al., 2005; Meng et al., 2019).

The LG differs greatly from the QF in lithofacies as it consists mostly of slates, (meta-)siltstone and sandstones with abundant Bouma sequences, tractional cross-bedding, and flute casts formed in a sand- and mud-dominated deep -sea submarine fan system (e.g., Li et al., 2003a; Zhang et al., 2015, 2017). A large number of paleocurrent indicators, ZTR heavy mineral indices, and grain size changes are in support of the submarine fan interpretation (Li et al., 2003b; Zhang et al., 2017). Evidently, the QF and LG are quite different in lithology, sedimentary structures, and sedimentary environments, also indicating their distinct paleogeographic distance from one another.

4.3 Zircon granulometry and transport distance

Shape and size of detrital zircons have been used to characterize transport distance (e.g., Byerly et al., 1975; Garzanti et al., 2008, 2015; Markwitz and Kirkland, 2018). The length/width ratio is a common parameter to analyze hydraulic behavior and environment (e.g., Garzanti et al., 2008, 2009, 2015; Markwitz and Kirkland, 2018). Importantly, grain shape and age distributions of both magmatic and detrital populations have no significant effect on hydraulic sorting, and transport of zircon grains from magmatic sources to final sedimentary sink is more affected by length rather than width (Markwitz and Kirkland, 2018). These criteria enable us to apply the length/width ratio and roundness in transport distance analysis.

We randomly selected a sample (TL10-04zk: Fig. 1) from a sandstone of the LG to simply calculate the length/width ratios and to observe the roundness of the detrital zircons. The results show that the length/width ratios are >3/1, 3/1–1/1, <1/1 corresponding to about 38%, 43% and 19%, while the sub-angular and sub-rounded zircon grain ratios are ~52% and ~48%, respectively. Supposing that the zircon morphology was not altered by chemical and petrogenetic processes as well as selective preservation (Garzanti et al., 2015; Markwitz and Kirkland, 2018), the data suggest that a proximal to moderate transport of the detrital zircons did ensue. This means that it is very difficult to explain how the zircons could have been transported for thousands of kilometers from the remote Gondwanide Orogen (eastern Australia). Particularly, all the 17 zircons dated as 259–227 Ma have >2/1 length/width ratios and sub-angular grains (marked in bold print, Fig. 1), indicative of proximal transport. Although the nine detrital zircons in figure 7 of Meng et al. (2019) have length/width ratios of less than <2/1, they display sub-angular roundness, suggesting a proximal to moderate transport distance besides a mafic origin, instead of a distal transport and felsic origin.

The latest study on zircon morphology illustrates that zircon grains with ages >300 Ma from the LG are dominated by preweathered and weathered surfaces as well as fairly rounded to completely rounded scales, and those with 300–200 Ma grains are characterized by (sub-) angularity, fresh surfaces, and completely unrounded to poorly rounded scales (Ma et al., 2019). Clearly, zircons with ages >300 Ma and a high degree of polycyclicity, are not useful in determining the precise provenance, but those of the young population indicate a proximal provenance.

5 Provenance

It seems sensible that clastics of the QF, with the other Triassic and Paleozoic successions on the northern Indian passive margin, derived from the Indian continental crystalline basement even though felsic volcanic rock fragments and 260–207 Ma detrital zircons were found in the QF sandstones (Meng et al., 2019). However, the provenance of the LG has been viewed controversially. Zheng and Zhang (1988) first assumed northern sources based on the southward decrease of grain size, and this idea was later supported by mainly southward paleocurrents in the Qiongjie and Zha’nang (Langjiexue) areas (Li et al., 2003b) and in almost the entire LG outcrop region (Zhang et al., 2017). Eventually, its lack of affinity to the Tethys Himalaya was demonstrated by Nd isotopes (Dai et al., 2008) and detrital zircon U–Pb age populations (mainly 250–210 Ma) (e.g., Aikman et al., 2008; Li et al., 2010).

Subsequently, several provenance models have been proposed to interpret the provenance of the LG using detrital zircon U–Pb age populations and Hf isotopes (e.g.,

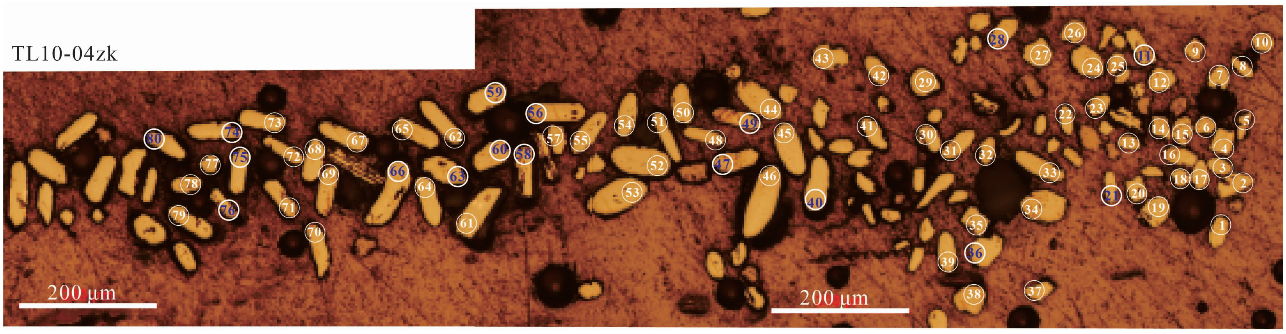

Fig. 1. Image showing the morphology and roundness of detrital zircons from sample TL10-04zk of the Langjiexue Group, Douyu of Longzi, southern Tibet.

Circled numbers are dated zircons using U–Pb isotopes by laser ablation. The 17 zircons with bold and black numbers were dated as 259–227 Ma.

Li G W et al., 2010, 2016; Webb et al., 2013; Cai et al., 2016; Li X H et al., 2016; Wang et al., 2016; Cao et al., 2018; Fang et al., 2018). The provenance model of a distant Gondwanide Orogen was further developed by, for example, Meng et al. (2019). However crucial questions still need to be addressed (see below).

5.1 Vague Paleoproterozoic and Archean populations of detrital zircon U–Pb dates

The featured Late Permian and Triassic detrital zircon U–Pb age populations and Hf isotopes of the LG and QF can be compared to some degree although only nine zircons were recognized as the 260–207 Ma population out of 176 zircons from the QF (Meng et al., 2019). Given that a large drainage system traversed the Australian craton during the Late Triassic, as stressed by Meng et al. (2019), then two Paleoproterozoic and Archean populations of detrital zircon U–Pb ages should also be represented in the age spectra of both units. This is because the late Paleoproterozoic population of 1.7–1.9 Ga and Neoarchean population of 2.6–2.8 Ga with a higher zircon number have been documented in the central Australian basement (e.g., Maidment et al., 2007) and Perth Basin, western Australia (e.g., Cawood and Nemchin, 2000; Veevers et al., 2005). But these two populations are only vaguely represented in both the QF and LG.

Therefore, it is perplexing to understand/interpret why the relative numbers of Paleoproterozoic and Archean detrital zircons in proximal sources are much fewer than those of the Late Permian–Triassic zircons (e.g., Li G W et al., 2010; Webb et al., 2013; Cai et al., 2016; Li X H et al., 2016; Wang et al., 2016; Cao et al., 2018; Meng et al., 2019) in distal areas, if the detrital zircons of both QF and LG were indeed derived from the remote Gondwanide Orogen.

5.2 Scarcity of Late Triassic terrestrial basins within the Australian craton

If large drainage systems existed during the Late Triassic within the Australian craton, it seems reasonable to assume that some coeval large terrestrial basins existed within such systems, yet actually there are only a few recorded. Basins such as the Officer Basin, Cooper Basin, Galilee Basin, and Leigh Creek Basin occur within foredeeps and intramontane settings (e.g., in Queensland and Sydney basin, NSW) of the eastern Australian Orogen and western coastal areas (western edge of Perth Basin) of the Australian craton (e.g., Wopfner, 1982; Babaahmadi et al., 2015). The Late Triassic sequences of the northern coast and shelf of the Australian craton were deposited in a marine passive margin basin (e.g., Li et al., 2013). Therefore, the scarcity of the Late Triassic terrestrial basins does not support the idea of a large drainage system on the Australian craton during the respective time interval.

5.3 Detrital Cr-spinels of arc basalts and peridotites unlikely transported from the Gondwanide orogen

At first glance, the Late Permian–Triassic detrital zircons of the two units are age-compatible with those of the magmatic rocks of the Gondwanide Orogen (“Terra Australis Orogen” of Cawood and Nemchin, 2001). However, upon further consideration, one needs to take into account that there are many detrital Cr-spinels from arc basalts and peridotites in the LG (Li et al., 2016).

These spinels could have been produced in the southwestern Pan-Pacific subduction zone and oceanic crust to the west and in the neighborhood of the Gondwanide Orogen (see Meng et al., 2019, fig. 10), but, clearly, it is basically impossible for them to have traversed the Gondwanide Orogen long distance to enter the assumed large drainage system on the Australian craton. In theory, it would be possible for the Cr-spinels to have derived from older orogens within the Australian craton as part of the drainage systems, but so far, no arc basalts and peridotites have been reported from that craton.

5.4 Clustered and featured (280–210 Ma) zircons of magmatic arc origin (Lhasa Terrane)

Previously, there have been few works on the geochemistry of the clustered and featured (300–200 Ma) zircons from the LG. Geochemical works on the 280–210 Ma detrital zircons were recently performed (Liu et al., 2020), and plots of U/Yb–Hf and U–Yb show that these zircons fall into the continental zircon field; a source of the continental arc field was suggested, which is comparable to those of I-type and S-type granitoids (Liu et al., 2020). This result may suggest that the Gangdese arc “in front” of the Lhasa Terrane is the source area.

The Triassic magmatic rocks were recently discovered in the central Gangdese belt (Ma et al., 2019, and references therein), further corroborating the idea that the Lhasa Terrane was the source area of the LG. Fortunately, geochronological, petrological, and geochemical analyses of the Middle Triassic gabbro-diorite complex of the Gangdese belt have just been completed and published; geochemical results show that the plutonic rocks are characterized by relatively low MgO and high Al_2O contents, calc-alkaline trends, and depletion of Nb, Ta, and Ti (resembling low-MgO high-alumina basalts or basaltic andesites) and by depleted whole-rock $\varepsilon_{Nd}(t)$ values of ~+5 and zircon $\varepsilon_{Hf}(t)$ values peaking at ~+14, which were suggested to represent a subduction-related arc setting (Ma et al., 2019).

The geochemical results of both the Permian–Triassic detrital zircons from the LG and the Triassic plutonic rocks of the Gangdese belt corroborate the idea that the LG’s main source area is the Lhasa Terrane, ruling out sources from the Tethys Himalaya (Indian subcontinent).

6 Opposing Sediment Dispersal Patterns

A southward fan-shaped sediment dispersal pattern characterizes the LG based on thousands of paleocurrent data (Li et al., 2003b, Xu et al., 2011; Wang et al., 2016; Zhang et al., 2017), lithofacies associations (Zhang et al., 2015), ZTR heavy mineral indices, and (sand/mud) grain size ratios (Zhang et al., 2017) across the entire LG outcrop region.

Undoubtedly, the Paleozoic and Triassic–Jurassic successions of the Tethys Himalaya should display a distinct sediment dispersal pattern of clusters of northward paleocurrents perpendicular to the shoreline. This is because northward sediment transport across the northern passive continental margin of India (e.g., Hu et al., 2010) is the fundamental model of sediment dispersal for the Tethys Himalaya sequence. Accordingly, the QF is not an exception. Meng et al.'s (2019, page 794) statement that, "paleocurrent directions measured from the Qulonggongba Formation and the Langjiexue Group are mainly westward to southwestward (Li et al., 2003a; Xu et al., 2011; Wang et al., 2016)" is not really supported because the QF paleocurrent data cannot be found in their article.

In case there are indeed proven westward paleocurrents for the QF, they might be local deviations from the general pattern and a short-lived phenomenon. In their newly proposed paleogeographic model (Meng et al., 2019: fig. 10b), westward paleocurrents could be a figment (as no paleocurrent data were provided), which is theoretically difficult to explain/substantiate in shallow marine environments except for only near-shore zones (breaker zones with swash and backwash) affected by long-shore currents. Generally, in off-shore areas that represent much wider zones within shelves, tidal currents, storm-induced suspensions and rip-currents flow mostly perpendicularly to the shoreline. Only contour currents flow parallel to the shoreline along the shelf break line, but their activity is restricted to the continental slopes and, thus, does not affect shelf areas.

Given that about a 90° counter-clockwise rotation for the Himalayan Superterrane (likely including the Shannan Terrane) has been reached since the Cretaceous (Zhang and Huang, 2017) before it collided with Asia, the main westward paleocurrent direction is recovered from the southward-direction by a clockwise 90° correction for the LG, but not for the QF. Theoretical, but few, reported northward paleocurrent clusters of the QF should become eastward by the same clockwise 90° correction. It is obvious that westward paleocurrents of the LG submarine fan deposystem is opposite to the (recovered) eastward paleocurrent of the QF shelf deposystem, further arguing against the proposition that the deep-sea LG flysch is an in-situ Tethys Himalayan sedimentary sequence (e.g., Cao et al., 2018; Fang et al., 2018; Meng et al., 2019).

7 Conclusions

Whatever multiple tectonic and paleogeographic models proposed, the LG is obviously different from the QF in tectonic nature, age, sedimentary facies, provenance, and paleogeography. Many discrepancies and inconsistencies are pointed out regarding some views of the LG and QF, raising some crucial questions of the deep-sea LG flysch for the model of the remote Gondwanide Orogen in eastern Australia and the in-situ Tethys Himalayan sedimentary sequence.

Analyses of provenance and paleogeography relying on detrital zircon age spectra are too simplistic, and might lead to misunderstanding if various fundamental sedimentary principles on mineralogy, lithofacies, paleocurrent, and transportation and size distribution of clastic grains are poorly considered or even neglected. Thus, additional new observations and key evidence are needed to improve the respective paleogeographic understanding and relationship between the LG and QF.

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