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Transitions among Mariana-, Japan-, Cordillera- and Alaska-type arc systems and their final juxtapositions leading to accretionary and collisional orogenesis

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Abstract: 'Arc system' is used here as a collective term for a variety of arcs that occur along continental margins or in oceanic plates; it includes associated units from adjacent plates. Four major arc systems (Mariana-, Japan-, Cordillera- and Alaska-type) can be distinguished along the Circum-Pacific region. Some Japan-type arc systems in ancient orogens (e.g. the Altaids) may have been largely regarded as microcontinents because they have so-called Precambrian basement. Often the Cordillera-type arc systems can be very complicated, and if they are rifted away from the host continent they become more difficult to recognize. Commonly these arc systems interact mutually and with continental marginal sequences, leading to complicated accretionary and collisional orogens. The alternation between Western Pacific archipelagos and the Eastern Pacific active margin is the stereotype of accretionary and collisional orogenesis. More importantly, these four main types of arc systems can be juxtaposed into a final orogenic collage, which is another main expression of accretionary orogenesis. Only some parts of accretionary and collisional orogens can be terminated by attachment of a continent-size craton such as Tarim or even India, and even so the accretionary and collisional processes may continue elsewhere along strike. The significance of the interactions among these arc systems and their final juxtaposition has not been fully appreciated in ancient orogens. The Altaids together with the Circum-Pacific orogens offers a good opportunity to study such accretionary–collisional orogenesis.

Orogens on Earth are subdivided into two types: collisional and accretionary (Windley 1995, 1998; Cawood *et al.* 2009). However, to distinguish between these two types of orogenesis is sometimes not easy, as each includes some aspects of the other. Collisional orogens have long been a major target of investigations, with the Tethys–Himalaya and Appalachian orogens as the classic examples, but even these collisional orogens also show a long history of accretion before final collision (Dewey 1969; Allègre *et al.* 1984; Chang *et al.* 1986, 1989; Bradley 1989; Grapes & Watanabe 1992; Van Staal 1994; Yin & Harrison 2000; Liou *et al.* 2004; Ratschbacher *et al.* 2004; Aikman *et al.* 2008; Santosh *et al.* 2009). In the mean time, accretionary orogens such as the North American Cordillera and the Altaids also have long been regarded as major sites with complicated accretionary and collisional geodynamic processes (Fig. 1; von Huene & Scholl 1991; Şengör *et al.* 1993; Kimura 1994; Kusky 1997; Condie 2000; Jahn *et al.* 2000; Van der Voo 2004; Kröner *et al.* 2007).

Accretionary orogens are increasingly noted for their considerable continental lateral enlargement and vertical growth with world-class metallogeny (Sillitoe 1974; Heinhorst *et al.* 2000; Jahn *et al.* 2000; Jenchuraeva 2001; Yakubchuk *et al.* 2001; Gray *et al.* 2002; Goldfarb *et al.* 2003; Xiao *et al.* 2008*a*). Therefore accretionary orogens actually have full records that can be studied to better understand the geodynamic evolution of mountain ranges on Earth. They have been the subject of many international efforts worldwide (Cawood & Buchan 2007; Condie 2007; Brown 2009; Cawood *et al.* 2009; Hall 2009), including international programmes such as the International Lithosphere Program (ILP), International Geological Correlation Programme (IGCP), and recently launched joint projects from European, American, and Asian

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Fig. 1. Schematic tectonic map of orogens around the world and the circum-Pacific regions (Tagami & Hasebe 1999; Kröner *et al.* 2007; Rino *et al.* 2008).

countries (Hall & Spakman 2002; Pfänder *et al.* 2002; Tomurtogoo *et al.* 2005; Helo *et al.* 2006; Cawood & Buchan 2007; Condie 2007; Kröner *et al.* 2007; Windley *et al.* 2007; Brown 2009; Cawood *et al.* 2009; Hall 2009; Xiao *et al.* 2009*a*, *c*).

However, there is still controversy about the tectonic architecture and evolution of accretionary orogens, for which there are two major schools of thought: amalgamation of multiple terrane–ocean systems or accretion in terms of a single forearc (Ingersoll & Schweickert 1986; Mossakovsky *et al.* 1993; Şengör *et al.* 1993; Busby & Ingersoll 1995; Dickinson 1995; Şengör & Natal'in 1996*a*, *b*; Yakubchuk 2004, 2008). The focus of much controversy has centred on the recognition and interpretation of high-grade metamorphic rocks in some certain terranes. The proponents of multiple terrane–ocean systems have interpreted some high-grade gneiss–schist complexes as microcontinents (Chamberlain & Lambert 1985; Mossakovsky *et al.* 1993; Salnikova *et al.* 2001; Vaughan & Livermore 2005; Kozakov *et al.* 2007), and this model would necessitate some degree of collision (Mossakovsky *et al.* 1993). On the other hand, some high-grade gneiss–schist complexes have been interpreted as the basement or components of arcs and accretionary complexes, which emphasizes the role of accretion (Haeussler *et al.* 1995; Kozakov *et al.* 1999; Kuzmichev *et al.* 2001; Salnikova *et al.* 2001).

The Altaids of Central Asia and the Circum-Pacific including the Cordillera of Western North America are among the largest accretionary orogens (Fig. 1) that record considerable Phanerozoic continental growth (Coleman 1989; Şengör & Okurogullari 1991; Mascle *et al.* 1996; Condie 2000; Jahn *et al.* 2004; Van der Voo 2004). Both offer an opportunity to unravel the basic evolutionary history of accretionary orogens and they address the above controversy. This paper presents a comparative study of the palaeogeography and evolution of these orogens.

Typical arc systems

Arcs are tectonic belts formed by subduction of a plate of oceanic lithosphere beneath another oceanic or continental plate along a subduction zone with high seismic activity characterized by a high heat flow with active volcanoes bordered by a submarine trench (Windley 1995). As nearly all accretionary orogens are directly or indirectly related to subduction of oceanic plate(s), which generates different arcs, we define an arc system as a collective term for subduction-related tectonic settings along either continental or oceanic plate. We introduce this term because all accretionary orogens occur finally outboard of the margins of a host continent (Fig. 2; Coney *et al.* 1980; Cordey & Schiarizza 1993; Church *et al.* 1995; McClelland *et al.* 2000; Nance *et al.* 2002; Bradley *et al.* 2003; Stern 2004; Ring 2008) and accretionary orogenesis has a close relationship with the formation and

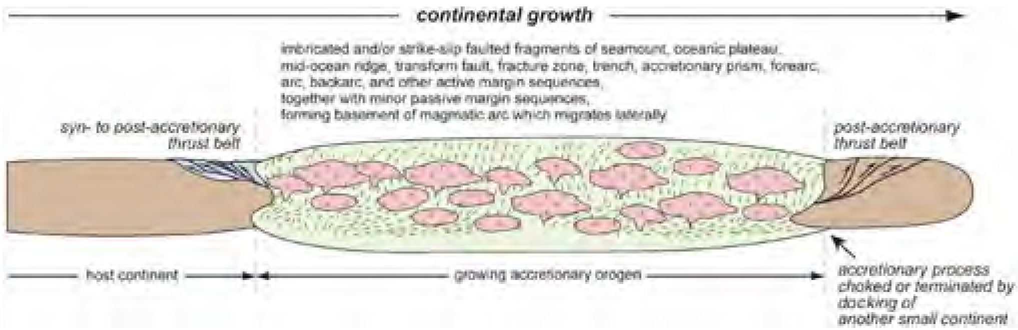

Fig. 2. A cross-sectional model of classic accretionary and collisional orogenesis (modified after Şengör 1992; Şengör *et al.* 1993).

evolution of supercontinents (Ilyin 1990; Dalziel *et al.* 2000; Zhao *et al.* 2002; Cawood & Buchan 2007; Murphy *et al.* 2010). Continental margins play a key role in accretionary orogenesis, and understanding of arc systems helps in unravelling the evolution of accretionary orogens.

Normally when arcs are studied the subduction zone and arc volcanic systems are mostly emphasized; however, the forearc and back-arc regimes are essential components of arc systems (Windley 1995). The back-arc regimes vary and sometimes have more remnant back-arcs and include the opposite side of passive margins and/or the forearc of another arc system (Bloomer *et al.* 1995; Hawkins 1995, 2003; Windley 1995). Other important features include the forearc accretionary complex and even granulite-facies rocks in the deep roots of mature arcs, and some important mineral deposits (Windley 1995). In the present-day circum-Pacific region, four major arc systems (Mariana-, Japan-, Cordillera- and Alaska-type) can be distinguished (Figs 3 & 4).

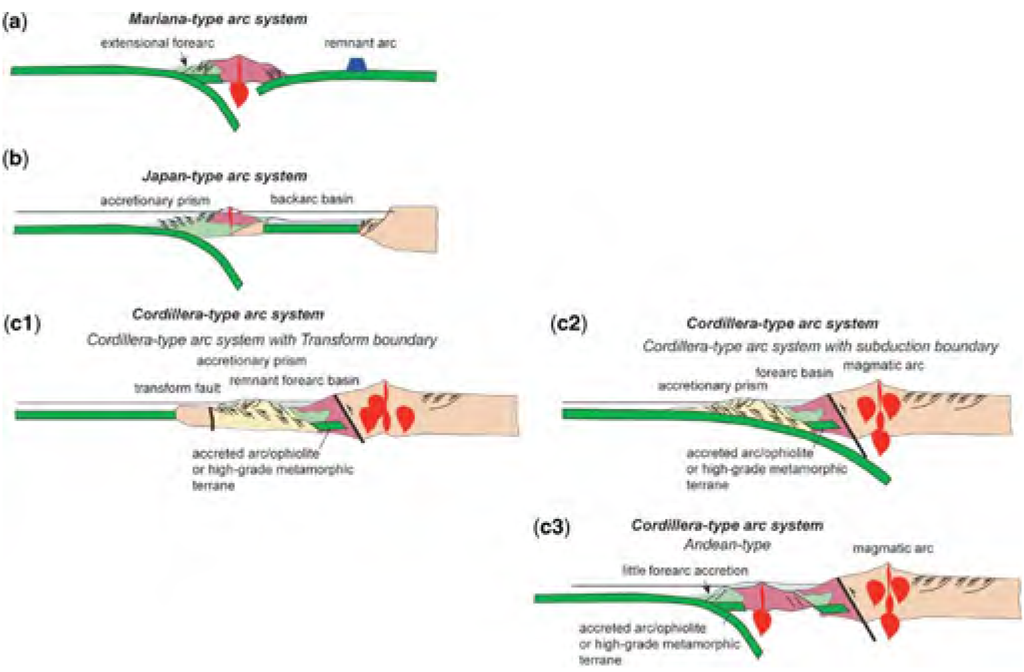

Fig. 3. Diagrams showing (**a**) Mariana-, (**b**) Japan-, and (**c**) Cordillera-types of arc systems related to accretionary and collisional orogens. It should be noted that the Cordillera-type arc system has three sub-types: (**c1**) Cordillera-type I with a transform boundary; (**c2**) Cordillera-type II with a subduction boundary; (**c3**) Cordillera-type III, the Andean-type, with little forearc accretion.

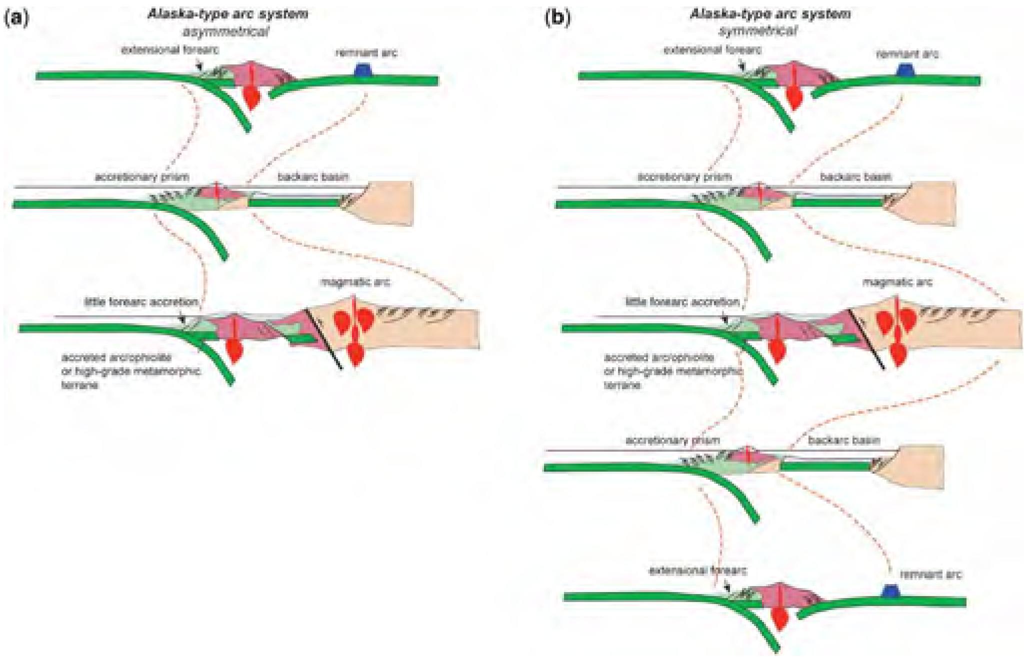

Fig. 4. Diagrams showing Alaska-type arc system related to accretionary and collisional orogens. It should be noted that the Alaska-type arc system has two cases, asymmetrical (**a**) and symmetrical (**b**), and that assemblage of these island arcs can be random.

Mariana-type arc system

The Mariana-type arc system, also termed the Izu–Bonin–Mariana arc system, consists of the Izu–Bonin arc in the north and the Mariana arc in the south (Figs 1 & 3a); it was generated by deep subduction of the Pacific Ocean plate beneath the Philippine Sea plate (Karig 1971; Miller *et al.* 2004). The Philippine Sea plate has moved northwestward and the Pacific slab has undergone possible rollback at the Mariana subduction zone (Deschamps & Fujiwara 2003).

This type of arc system is generated by subduction of one oceanic plate beneath another, characterized by an oceanic island arc, remnant arc(s) and back-arc basin(s) (Karig 1971) that are wide and separated by a remnant arc. In places there is only one back-arc basin. Partial melting of diapirs has produced voluminous mid-ocean ridge basalt (MORB)-type tholeiites, which have split the arc and formed the crust of a widening back-arc basin (Crawford *et al.* 1981; Deschamps & Fujiwara 2003; Gvirtzman & Stern 2004; Miller *et al.* 2004). Therefore, this type of arc system has no significant contribution of continental material during its formation.

Minor sediment accretion occurred along the Mariana-type arc system (Horine *et al.* 1990). The composition of dredged samples from the slopes of the Mariana trench (i.e. island arc tholeiites and boninites) suggests that there is little or no current sediment and/or there has been no oceanic crustal accretion in the Mariana system (Bloomer *et al.* 1995; Plank & Langmuir 1998; Fryer *et al.* 1999). A 9 km schematic section drawn by Hawkins (2003) shows that the rock types on the inner wall of the Mariana Trench are, from top to bottom, volcaniclastic rocks, serpentinites, serpentinized harzburgites, diabases–gabbros, basalts, boninites, quartz diorites, serpentinized harzburgites, basalts, gabbros, diabases, and serpentinized harzburgites. These lithologies are not the same as the typical ophiolitic sequences described in textbooks and illustrate the complications of Mariana-type arc systems. Blueschists also occur in the forearc, implying deep subduction and exhumation (Fryer *et al.* 1999). Usually these kinds of arc systems would generate ophiolites of suprasubduction-zone types (Hawkins 2003; Shervais *et al.* 2004). One can imagine how complicated the situation could be when such rocks of the Mariana-type arc system are juxtaposed into orogenic components in ancient orogens.

Japan-type arc system

The Japan-type arc system is generated by subduction of one oceanic plate beneath another, but with some pre-arc sialic basement (Windley

1995), characterized by an oceanic island arc and back-arc basin(s) (Fig. 3b).

The Japanese island arcs are regarded as one of the best examples of a subduction-related orogen along a continental margin on account of their extensive geological record (Kimura & Mukai 1991; Needham *et al.* 1991; Osozawa 1992; Taira *et al.* 1992*a*; Kimura & Onishi 1994; Faure *et al.* 1995; Isozaki 1997*a*; Isozaki & Ota 2001; Moore & Saffer 2001; Taira 2001; Aoya & Wallis 2003; Yoshikura & Hada 2004). Important features of the Japanese island arcs are that they now have an imbricated crustal thickness of 40 km, being underlain by intrusive plutonic arc rocks and cumulate mafic–ultramafic rocks (Taira *et al.* 1992*b*; Windley 1995; Taira 2001). The Japanese island arcs were rifted from the continental margin of East Asia (Figs 1 & 3), and have undergone semi-continuous accretion since the early Palaeozoic, and the Japan Sea (back-arc basin) developed only in the late Cenozoic (Filippov & Kemkin 2003). This type of island arc system, unlike the Mariana-type arc system, has components of old Precambrian rocks (Maruyama 1997). On its western side the high-grade Hida complex with Permo-Triassic eclogites may be derived from the Sulu belt of eastern China. The early geological history of the Japanese island arc system indicates break-up at about 750 Ma from the Proterozoic margin of China and formation of the proto-Pacific basin (Taira 2001). Arc growth has taken place since the early Palaeozoic along the continental margin of East Asia, as a result of subduction of the proto-Pacific ocean, and the Japan Sea back-arc basin formed at about 20 Ma (Hawkins 1995; Maruyama 1997; Taira 2001; Kawakami *et al.* 2004; Sato *et al.* 2004).

Huge accretionary prisms developed along the forearc of the Japan-type arc system in the Jurassic, Cretaceous, and Tertiary to present day (Cowan 1987; Kimura & Mukai 1991; Hasebe *et al.* 1993; Ogawa *et al.* 1994; Isozaki 1997*a*; Kanamatsu *et al.* 2001; Taira 2001; Miyazaki & Okumura 2002; Ujiie 2002; Yoshikura & Hada 2004). High-pressure metamorphic belts were exhumed along the forearc and within the accretionary prisms (Isozaki 1996, 1997*a*, *b*; Okamoto *et al.* 2000).

Cordillera-type arc system

The Cordillera-type arc system refers to the major western Pacific accretionary domain (Moores 1970, 1998; Coney *et al.* 1980; Draper *et al.* 1984; Cordey & Schiarizza 1993; Garver & Scott 1995; McClelland *et al.* 2000; Lagabrielle *et al.* 2007; Ring 2008). The Cordillera-type arc system has three sub-types (Figs 1 & 3). Cordillera system I is characterized by a transform boundary with only limited areas along strike being subducted by oceanic plates (Fig. 3c1) (Moores 1970, 1998; Cordey & Schiarizza 1993; Garver & Scott 1995; McClelland *et al.* 2000; Miller 2002; Underwood *et al.* 1999). Cordillera system II can have a long subduction boundary (Fig. 3c2), and Cordillera system III is referred to as a continental marginal arc generated by subduction of oceanic plates beneath it with little forearc accretion, similar to an Andean-type arc but without a back-arc basin (Fig. 3c3; Sillitoe 1974; Kay *et al.* 1988; Nelson 1996; Martin *et al.* 1999; Gutscher *et al.* 2000; Milkov *et al.* 2003; Reich *et al.* 2003). A basic characteristic is that there is a wide thrust belt with continent-directed thrust vergence in the retroarc setting, sometimes with a width of more than 1000 km (Moores 1998; McClelland *et al.* 2000; Miller 2002).

Different ages of accretionary prisms develop along the forearc of a Cordillera-type arc system *senso stricto* (Moores 1970; Bebout 1989; Ernst 1993; Isozaki & Blake 1994; Aalto *et al.* 1995; Tagami & Hasebe 1999). Along an Andean-type margin some parts of the trench can have no, or limited, accretionary material, as in the Andean Atacama Desert, where there are no rivers to bring material into the trench (Kay *et al.* 1988; Martin *et al.* 1999; Gutscher *et al.* 2000). High-pressure metamorphic belts are sometimes well developed, such as the well-known Franciscan complex (Bebout 1989; Ernst 1993; Isozaki & Blake 1994; Schemmann *et al.* 2008). Unlike the Japan-type and Mariana-type arc systems, this type of arc system can have oceanic, continental, and transitional geochemical properties (Kay *et al.* 1988; Windley 1995; Martin *et al.* 1999; Gutscher *et al.* 2000).

Alaska-type arc system

The Alaska-type arc system (Figs 1 & 4) is a special type with various degrees of combination of the Mariana-, Japan- and Cordillera-type arc systems (Barker & Sullivan 1989; Bradley & Kusky 1990; Sisson & Pavlis 1993; Haeussler *et al.* 1995; Himmelberg & Loney 1995; Goldfarb *et al.* 1997; Kusky & Bradley 1999; Lytwyn *et al.* 2000; Bradley *et al.* 2003; Nokleberg *et al.* 2005; Cole *et al.* 2006). The Alaskan orogen can be taken as a type example, the nature of which changes westwards from Cordillera-type in the east, via Japan-type in the middle, to Mariana-type in the west (Kusky & Bradley 1999; Kusky & Young 1999). A similar combined arc system can be found in the Sumatra–Banda region, where the Indo-Australian ocean plate is being subducted beneath a continental arc in the NW and a Japan-type arc in the SE (Honza *et al.* 2000; Hall 2002, 2009).

Different ages of accretionary prisms may develop with high-pressure metamorphic belts in this arc system type (Sample & Fisher 1986;

Bradley & Kusky 1990; Haeussler *et al.* 1995; Gutscher *et al.* 1998; Hansen & Dusel-Bacon 1998; Kusky & Bradley 1999; Kusky & Young 1999; Bradley *et al.* 2003). It can have oceanic, continental, and transitional geochemical properties along its Cordillera- and Japan-type arc segments and purely oceanic ones along its Mariana-type arc segment. A wide thrust belt with continent-directed thrust vergence can also develop in the retroarc setting (Clark *et al.* 1995).

Transitions between continental margins and arc systems

The four major types of arc systems are developed in the Circum-Pacific region (Figs 1, 3 & 4). There can be complicated types of accretion, but they are combined with these main types, and they all belong to the active margins of Asia and North America. Systematic investigations along these accretionary orogens show that these four types of arc systems can be mutually transitional. Two major transitional trends are discussed below.

Transition I: between the Mariana-, Japan- and Cordillera-type arc systems

The Mariana-type arc system involves an interaction between two oceanic plates, mostly in terms of subduction of one beneath the other. An intra-oceanic island arc will be generated with no contribution from any continental material.

Usually this kind of arc system extends for a relatively long distance, such as the Mariana–Izu–Bonin arc chain (Horine *et al.* 1990; Kanamatsu *et al.* 1996; Miller *et al.* 2004). When part of this long arc chain collides with a promontory or a rifted ribbon of the active margin of a host continent, a flip of subduction polarity can occur, forming a Cordillera-type arc system (Fig. 5). This is the geodynamic process that formed the Cordilleran active margin from the mid-Jurassic to the Neogene, when a mid-Jurassic intra-oceanic arc with west subduction polarity was accreted to the North American continent in the late Jurassic (Ingersoll & Schweickert 1986; Busby & Ingersoll 1995; Dickinson 1995).

The Japan-type arc system results from subduction of an oceanic plate beneath a thin continental fragment and it has a back-arc basin. As convergence continues, this arc system will collide with the host continent, closing the back-arc basin(s) and thus evolving into a Cordillera-type arc system (Fig. 5). This kind of geodynamic process is currently taking place along the Taiwan Island where an east-dipping subducted oceanic basin is colliding with the Luzon island arc (Fig. 1) (Huang *et al.* 2000; Chang *et al.* 2001; Lin 2002; Shyu *et al.* 2005).

In general, the subduction is beneath a host continent, which is characterized by a Cordillera-type arc system, and this can evolve with a high-angle slab when conditions are favourable, leading to extension in the back-arc, which can generate back-arc basins or marginal basins (Leggett *et al.* 1985; Wakita 1988; Kimura & Onishi 1994;

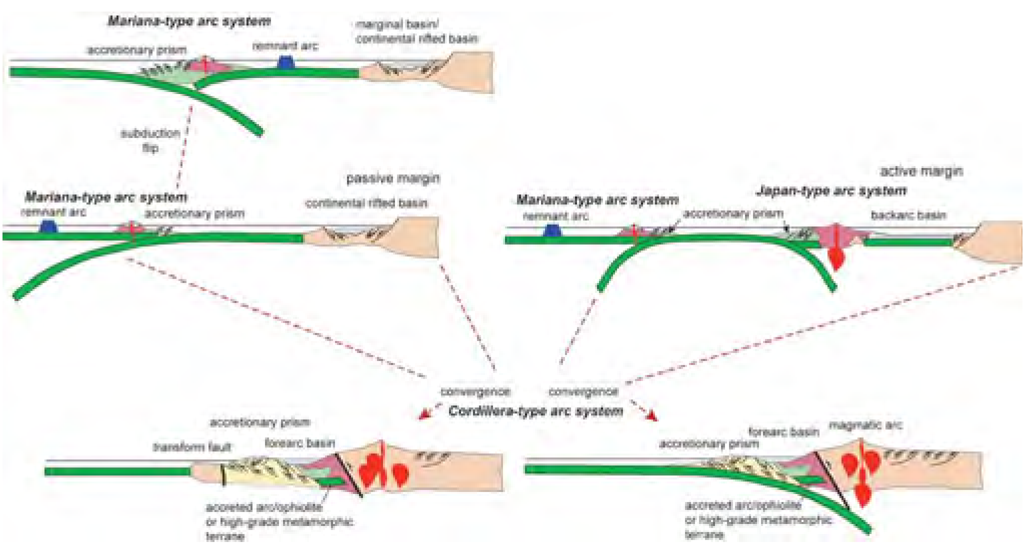

Fig. 5. Transitions between various types of arc systems related to accretionary and collisional orogens.

Okamoto *et al.* 2000; Taira 2001). Gradually a Japan-type arc system will be formed away from the host Cordillera-type arc system with a back-arc basin or basins.

Sometimes entrapment of an oceanic basin can generate back-arc basins with oceanic arcs that are characterized either by a Precambrian continental basement or by a purely Mariana-type arc system (Nokleberg *et al.* 2005). The former can be regarded as a transition from a Mariana- to a Japan-type arc system. A direct transition from a Japan- or Cordillera- to a Mariana-type is not common.

Transition II: between the Alaska-type and other types of arc systems

Transition I mentioned above can be best understood from its cross-sectional character. When looked at along the strike of arc systems, the role of the Alaska-type arc system is most important. The Alaska-type arc system combines the characters of the other three types, but in a more complicated manner (Kay 1978; Vrolijk *et al.* 1988; Holbrook *et al.* 1999). This type itself shows a transition along its trend (Fig. 4). In the asymmetrical case, an Alaskan-type arc system can have a core of the Cordillera-type arc system with each wing consisting of the Japan- and Mariana-type arc systems along strike (Fig. 4a). The order of the Japan- and Mariana-type arc systems can vary.

A complicated situation sometimes arises when the Alaska-type arc systems can have two transitional trends, as shown in the symmetrical case in Figure 4b, which means they can have double wings of intra-oceanic arcs with a core of Cordillera-type arc system. The order of the Japan- and Mariana-type arc systems in both wings can also vary. In this case, a four-fold complication would be expected.

In the SW Pacific, the Central Papua New Guinea arc system with continental crust basement has double wings of different intra-oceanic arc systems (Bloomer *et al.* 1995; Yamamoto *et al.* 2010).

Other transitions can be achieved by similar processes to Transition I mentioned above. For instance, the Alaskan-type arc system can evolve with each of the components of arc systems changing into another type. The tectonic evolution of the SW Pacific region in the last 50 Ma has been investigated in great detail (Hall 2002; Hall & Spakman 2002) and this scenario illustrates the complicated transitions among various kinds of arc systems including the Alaskan-type.

Discussion

The circum-Pacific accretionary orogens offer some modern examples for the study of accretionary processes. They can be roughly subdivided into the eastern (Cordillera-type arc system) and western (Japan- and Mariana-type arc systems) Pacific margins, with the Aleutians (Alaska-type arc system) as a special connection between them (Fig. 1).

Accretionary and collisional orogenesis: alternation of Circum-Pacific active margins

Systematic research has revealed that the Eastern Pacific active margin, represented by the Cordillera-type arc system in this paper, had archipelago palaeogeography since the Palaeozoic (Moores 1970; Unruh *et al.* 1995; Wakabayashi & Dilek 2000; Schemmann *et al.* 2008). A Japan-type island arc system developed near the North America craton, which is the host continent, with a back-arc basin between them (Fig. 6). The arc together with an accretionary complex migrated oceanward. This arc could have been enlarged on both sides by subduction of oceanic plates or accretion of other arcs or other terranes. Growing accretionary complexes may have also contributed to the growth of the arc system. In a later stage, this arc system would have become attached to the host continent (Fig. 6). With transitions between and amalgamation of these classic types of arc systems, the Eastern Pacific active margin has evolved into the present-day complicated accretionary stage. From this description, it is obvious that the Western Pacific archipelagos are the past of the Eastern Pacific.

The Western Pacific archipelagos involve continental ribbons and back-arc basins and nearly continuous trench systems from the Macquarie Ridge, via the Kermadec–Tonga Trench, to the Mariana Trench, and then to the Japan and Kurile Trench, which is connected with the Eastern Pacific via the Aleutian Trench in the Alaska-type arc system (Brueckmann 1989; Ballance 1993; Gutscher *et al.* 1999; Pankhurst *et al.* 1999; Ranero & von Huene 2003; Dilek *et al.* 2007). As the Indo-Australian plate is currently colliding with the Asian plate (Fig. 1), after its indentation into the archipelagos of SE Asia, a complicated scenario will develop with closure of the back-arc basins, giving rise to huge strike-slip fault systems (Van Staal *et al.* 1998), and then possibly will be evolving into a Cordillera-type arc system. Therefore, it seems that the Eastern Pacific active margin is the future of the Western Pacific archipelagos.

The interaction between the East Pacific Rise and the North America plate is causing formation of the Gulf of California, which is floored by oceanic crust (Fig. 1), and in future a continental ribbon (Baja California Range) will be translated northwards and will finally be rifted away from

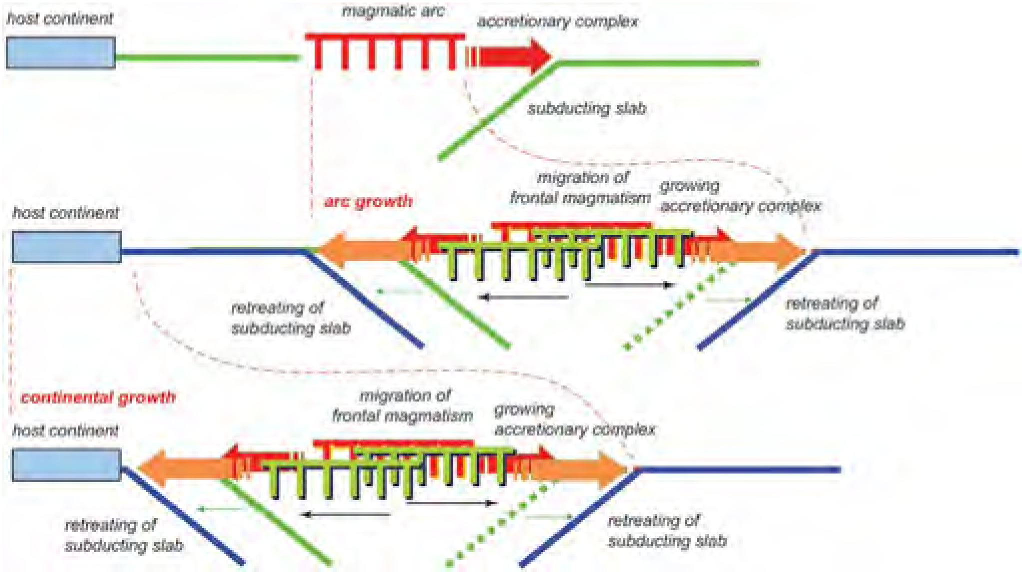

Fig. 6. Tectonic models of various types of arc systems related to accretionary and collisional orogens (modified after Şengör *et al.* 1993; Dickinson 1995).

the North American plate (Benoit *et al.* 2002; Zhang *et al.* 2009), the very beginnings of a new archipelago. Therefore the Western Pacific and Eastern Pacific scenarios can mutually change.

Juxtapositions of the typical arc systems and continental margin sequences

The four main types of arc systems can exist at different stages of palaeogeography. They can also coexist at one period of time or after a relatively long time one will evolve into another, but generally one or several types may coexist. The coexistence of these arc types provides a prime example of an archipelago palaeogeography of many accretionary orogens (Williams *et al.* 1989; Hsü *et al.* 1995; Scott & Gauthier 1996; Davis *et al.* 1998; Honza *et al.* 2000; Xiao *et al.* 2001, 2002*a*, *b*, 2003, 2009*b*, *c*). Some Japan-type arc systems in ancient orogens (e.g. the Altaids) may have been generally regarded as microcontinents because they have have so-called Precambrian basement. Often the Cordillera-type arc systems can be very complicated, and if they are rifted away from the host continent they become more difficult to recognize.

More importantly, these four main types of arc systems can be juxtaposed into a final orogenic collage, which is another main expression of accretionary orogenesis. One phase or several phases of accretionary orogenesis will finally amalgamate all these types of arc systems, together with continental margins such as passive margins, forming a wide and complicated orogenic collage, leading to arc growth and continental growth (Bloomer *et al.* 1995; Chaumillon & Mascle 1997; Ducea 2001; Badarch *et al.* 2002; Buslov *et al.* 2002).

Arc–arc collision is not uncommon in orogenesis. In the northern part of eastern Indonesia the Halmahera and Sangihe Arcs are the only intra-oceanic arcs in the world, which are currently colliding (Fig. 1; Hall & Spakman 2002; Hall 2009). The orogenic development of Inner Mongolia was characterized by two wide accretionary complexes that belonged to two Cordillera-type arc systems (Xiao *et al.* 2003). Amalgamation of active marginal sequences is also documented in the Caucasus (Khain 1975).

All these arc systems, as they have long chains, can be easily rotated and/or oroclinally bent. A good example is the Kazakhstan orocline, and this feature has been supported by palaeomagnetic data (Şengör *et al.* 1993; Şengör & Natal'in 1996*a*, *b*; Van der Voo 2004; Abrajevitch *et al.* 2008; Levashova *et al.* 2009). Other good examples are the western end of the Cantabrian orocline of Variscan Europe, and a ribbon continent that was buckled and accreted to the northwestern margin of North America (Van der Voo 2004).

Termination of accretionary and collisional orogenesis: the Altaids

The alternation between these typical arc systems and their interactions together with other marginal sequences are the main geodynamic processes of accretionary and collisional orogenesis, which is characterized by a long-lived history, a scenario not fully explained by the Wilson Cycle (Dalziel 1997; Dalziel *et al.* 2000; Lawver *et al.* 2003; Cawood & Buchan 2007). How then does a complicated accretionary and collisional orogen terminate? The Altaids (Central Asian Orogenic Belt) provides the type example.

The Altaids is one of the largest accretionary orogenic collages in the world, with the highest rate of Phanerozoic continental growth and significant metallogeny (Şengör & Okurogullari 1991; Şengör *et al.* 1993; Jahn *et al.* 2004; Wu *et al.* 2007; Utsunomiya & Jahn 2008). It is widely accepted that subduction-related development of the Altaids started in the late Precambrian (Khain *et al.* 2002; Kröner *et al.* 2007) and it gradually migrated southward (present coordinates), as recorded in the vast areas of Russia, Mongolia, China, and Kazakhstan and other Central Asian countries (Figs 7 & 8).

The late Palaeozoic to early Mesozoic accretion is best documented in two key areas, North Xinjiang in China and Kokchetav–Balkash in Kazakhstan in the west and Inner Mongolia in the east, together with neighbouring Mongolia, mainly called the 'Kazakhstan' and 'Tuva–Mongol' oroclines (Şengör *et al.* 1993; Xiao *et al.* 2003, 2004*a*, *b*, 2009*c*). The late Palaeozoic orogens of North Xinjiang and adjacent areas developed by continuous southward accretion along the wide southern active margin of Siberia with formation of an Alaska-type arc system (Kokchetav–North Tien Shan), some Japan-type arc systems (Altay, Chinese Central Tien Shan) and some Mariana-type arc systems (Balkash, West Junggar, and East Junggar) (Figs 8 & 9). Permian Alaskan-type zoned mafic–ultramafic complexes intruded along major faults in the Tien Shan (Xiao *et al.* 2008*b*). The final amalgamation of the passive margin of Tarim with the huge accretionary system to the north may have lasted to the end of the Permian to early or mid-Triassic (Xiao *et al.* 2003, 2004*a*, *b*, 2009*c*).

In Inner Mongolia of China and adjacent areas two wide accretionary wedges developed along the southern active margin of Southern Gobi–Mongolia and the northern active margin of the North China craton, which may have lasted to the Permian and mid-Triassic (Xiao *et al.* 2003, 2004*a*, *b*, 2009*c*; Zhang *et al.* 2007*a*, *b*). The final products of the long-lived accretionary processes in this part of the southern Altaids include a late Palaeozoic to Permian Cordillera-type arc system (northern

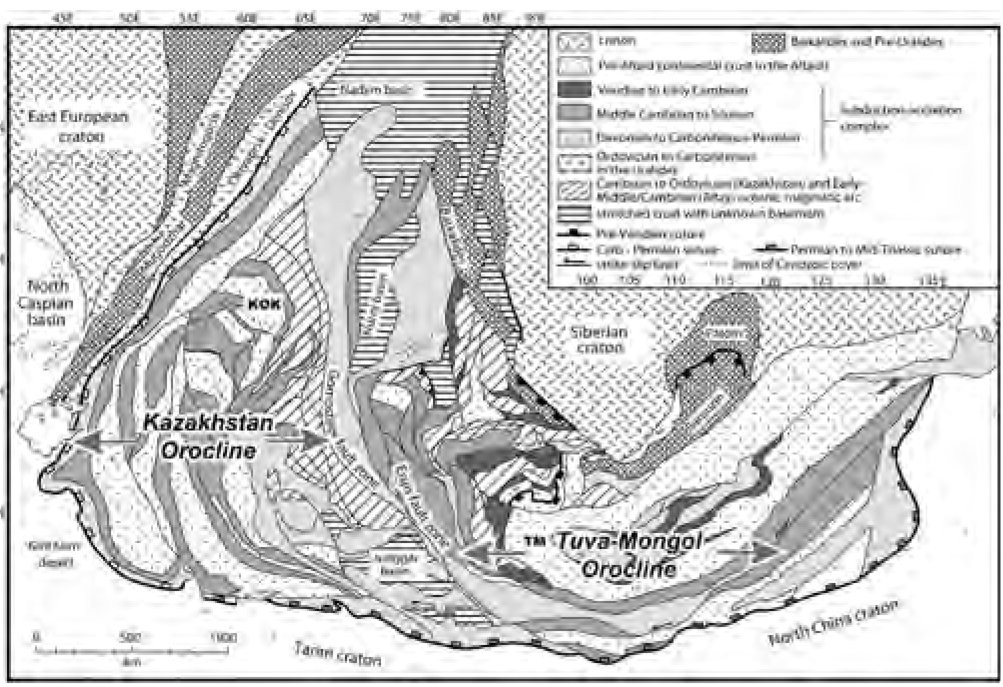

Fig. 7. Schematic tectonic map of Asia showing the Altaids and other accretionary and collisional orogens (modified after Şengör 1992; Şengör *et al.* 1993).

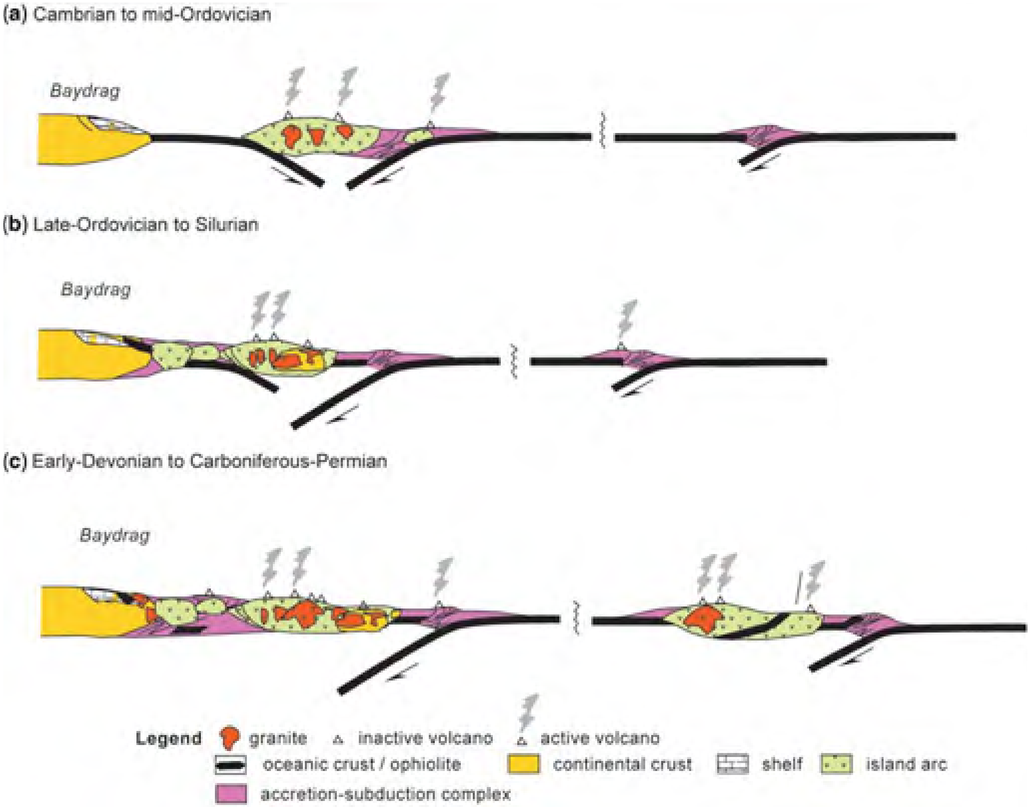

Fig. 8. Tectonic evolutionary model of various types of arc systems related to the Altaids (modified after Şengör *et al.* 1993; Xiao *et al.* 2004*b*, 2009*c*; Windley *et al.* 2007).

part of the North China craton), a Japan-type arc system (Southern Gobi–Mongolia), and some Mariana-type arc systems (for instance, Bainaimiao), with late Palaeozoic to mid-Triassic accretionary wedges composed of radiolarian cherts, pillow lavas, and ophiolitic fragments, and high-pressure to ultrahigh-pressure metamorphic rocks (Wang & Fan 1997; Xiao *et al.* 2003, 2004*a*, *b*, 2009*c*; Zhang *et al.* 2007*a*, *b*).

The docking of the Tarim and North China cratons against the southern active margin of Siberia at the end of the Permian to the mid-Triassic resulted in the final closure of the Palaeoasian Ocean and terminated the accretionary orogenesis of the southern Altaids in this part of Central Asia. This complex geodynamic evolution led to the formation of giant metal deposits in Central Asia and to substantial continental growth.

Conclusions

'Arc system' is defined as a collective term for subduction-related tectonic environments distributed either along a continental margin or in an oceanic plate. Based on structural, plutonic and volcanic, sedimentary, metamorphic, and palaeogeographic data, the Mariana-, Japan-, Cordillera- and Alaska-type arc systems can be recognized. Commonly these arc systems interact mutually and with continental marginal sequences, leading to complicated accretionary and collisional orogens. Some Japan-type arc systems in ancient orogens (e.g. the Altaids) may have been generally regarded as microcontinents because they have so-called Precambrian basement. Often the Cordillera-type arc systems can be very complicated, and if they are rifted away from the host continent they become more difficult to recognize.

The alternation between Western Pacific archipelagos and the Eastern Pacific active margin is the stereotype of accretionary and collisional orogenesis. More importantly, these four main types of arc systems can be juxtaposed into a final orogenic collage, which is another main expression of accretionary orogenesis. This could not be terminated in one Wilson Cycle and thus is the reason

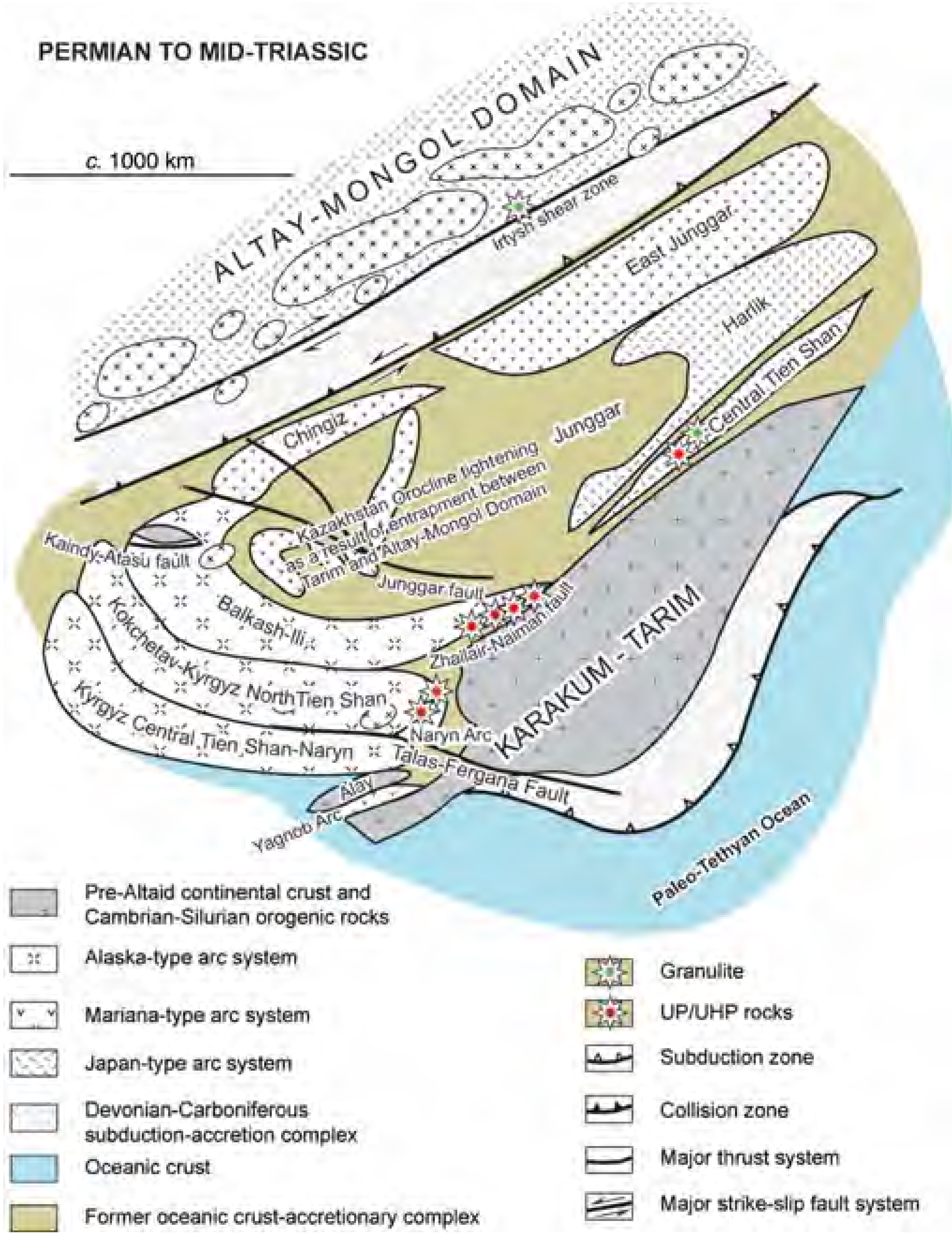

Fig. 9. Palaeogeography of various types of arc systems related to the Altaids (modified after Şengör *et al.* 1993; Xiao *et al.* 2009*c*).

why most accretionary orogenesis is long-lived. Only some segments of huge accretionary and collisional systems can be terminated by attachment of a subcontinent-sized cratonic block such as the Tarim or the Indian craton; nevertheless, the processes of accretionary and collisional orogenesis continue elsewhere. The Altaids is a prime example of a terminated accretionary–collisional orogen.

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