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ABSTRACT

The southern Ural Mountains of Russia contain a well-preserved, well-exposed Paleozoic accretionary wedge and forearc that can be readily compared to those in active arc-continent collision zones. The early convergent history in the southern Ural Mountains is marked by the generation of boninite-bearing arc tholeiites in the Magnitogorsk forearc, followed by arc tholeiite to calc-alkaline volcanism. With the entry of the East European craton continental crust in the subduction zone, volcanism waned and stopped, and high-pressure metamorphism of its leading edge took place. The arrival of the full thickness of the continental crust at the subduction zone is marked by increased sedimentation in the forearc basin and deposition of arc-derived volcaniclastic turbidites across the subducting slab. These, together with offscraped continental material, the exhumed high-pressure rocks, and a lherzolite massif, formed an accretionary wedge. A broad melange zone containing ultramafic fragments separates the forearc basement from the accretionary wedge, and marks the damage zone that developed along the backstop region. Shallow-water carbonates deposited unconformably on top of the mildly deformed arc record the end of the collision and the collapse of the arc.

INTRODUCTION

Throughout geologic time, island-arc development and subsequent arc-continent collision have been important processes in collisional orogenesis. In many fossil orogens, however, arc-continent collision is often obscured by syncollisional to postcollisional intrusion, deformation, fragmentation, metamorphism, and erosion, making it difficult to confidently determine geodynamic processes that are comparable in detail to those currently active. Like many Paleozoic orogens, the Uralides (Fig. 1) grew by island-arc accretion to a continental margin (East European craton), followed by ocean closure and terminal collision. A major difference between the Uralides and other Paleozoic orogens is that it is relatively intact, especially in the south where it is unaffected by postorogenic fragmentation (e.g., Echtler et al., 1996), and has not been deeply eroded. Furthermore, in recent years significant advances have been made in the understanding of the Uralide volcanic-arc complexes, in particular in the well-exposed southern Ural Mountains, where new age and stratigraphic data, geochemical data, reflection seismic data, and structural data have been acquired (e.g., Maslov et al., 1993; Berzin et al., 1996; Brown et al., 1998; Spadea et al., 1998). On the basis of such data, Puchkov (1997) and Brown et al. (1998) noted that the geodynamic setting of the Magnitogorsk arc and East European craton collision in the southern Ural Mountains had a number of similarities to arc-continent collisions currently taking place along the northern margin of Australia. Nevertheless, a comprehensive model detailing the geodynamic processes that were active during the convergent history and final arc-continent collision, and their comparison with those in currently active settings, had not been developed for the southern Ural Mountains.

GEOLOGIC BACKGROUND

The southern Ural Mountains of Russia constitute part of a collisional orogenic belt that developed during two distinct deformation events. From the Late Devonian to Early Carboniferous, continental lithosphere of the East European craton was subducted beneath the Magnitogorsk arc, resulting in the development and emplacement of an accretionary wedge over the subducting slab and suturing of the arc to the continental margin along the Main Uralian fault zone (Puchkov, 1997; Brown et al., 1998). From the Late Carboniferous through the Late Permian–Early Triassic, the ocean to the east of the accreted Magnitogorsk arc closed, resulting in it and its accretionary wedge being thrust westward, along with the East European craton Precambrian basement and its Paleozoic preorogenic platform cover, to form a foreland thrust and fold belt and a largely carbonate foreland basin (Brown et al., 1997). It is the Late Devonian arc-continent collision that is discussed in this paper.

The accretionary wedge (Fig. 1) is composed of Silurian to Middle Devonian continental slope and platform sedimentary rocks (Suvanyak - Complex and Timirovo thrust system) that were detached from the East European craton, and are overthrust by ~5 km of late Frasnian and Famennian syncollisional volcaniclastic turbidites sourced from the Magnitogorsk arc (Zilair nappe) (e.g., Puchkov, 1997; Brown et al., 1998). These units are flanked to the east by eclogite- and blueschist-bearing gneisses of the Maksutovo Complex that record a peak metamorphic age of ca. 380–370 Ma (Matte et al., 1993; Lennykh et al., 1995). The highest structural level in the accretionary wedge is the Kraka lherzolite massif (Savelieva et al., 1997). The accretionary wedge is sutured to the Magnitogorsk arc along the east-dipping Main Uralian fault zone, a melange as wide as ~10 km that contains several ultramafic fragments.

Eastward, in the immediate hanging wall of the Main Uralian fault, the oldest unit found in the Magnitogorsk forearc is the Emsian (age determinations in the Magnitogorsk arc are from conodont data of Maslov et al., 1993) high-Mg basaltic andesite to andesitic Baimak-Buribai Formation, in which basic-intermediate boninitic lavas, dikes, and shallow intrusive rocks have been described (Spadea et al., 1998). Locally, the Baimak-Buribai Formation is overlain by a condensed section of Eifelian to Famennian cherts, tuffaceous sandstones, and conglomerates, and regionally by the Zilair Formation (see following). Its eastern margin is overthrust by the Emsian to Eifelian Irendyk Formation (Fig. 2A), which consists of andesitic basalts, hyaloclastic flows, agglomerates, and intercalations of volcaniclastic sandstones. The Irendyk Formation is

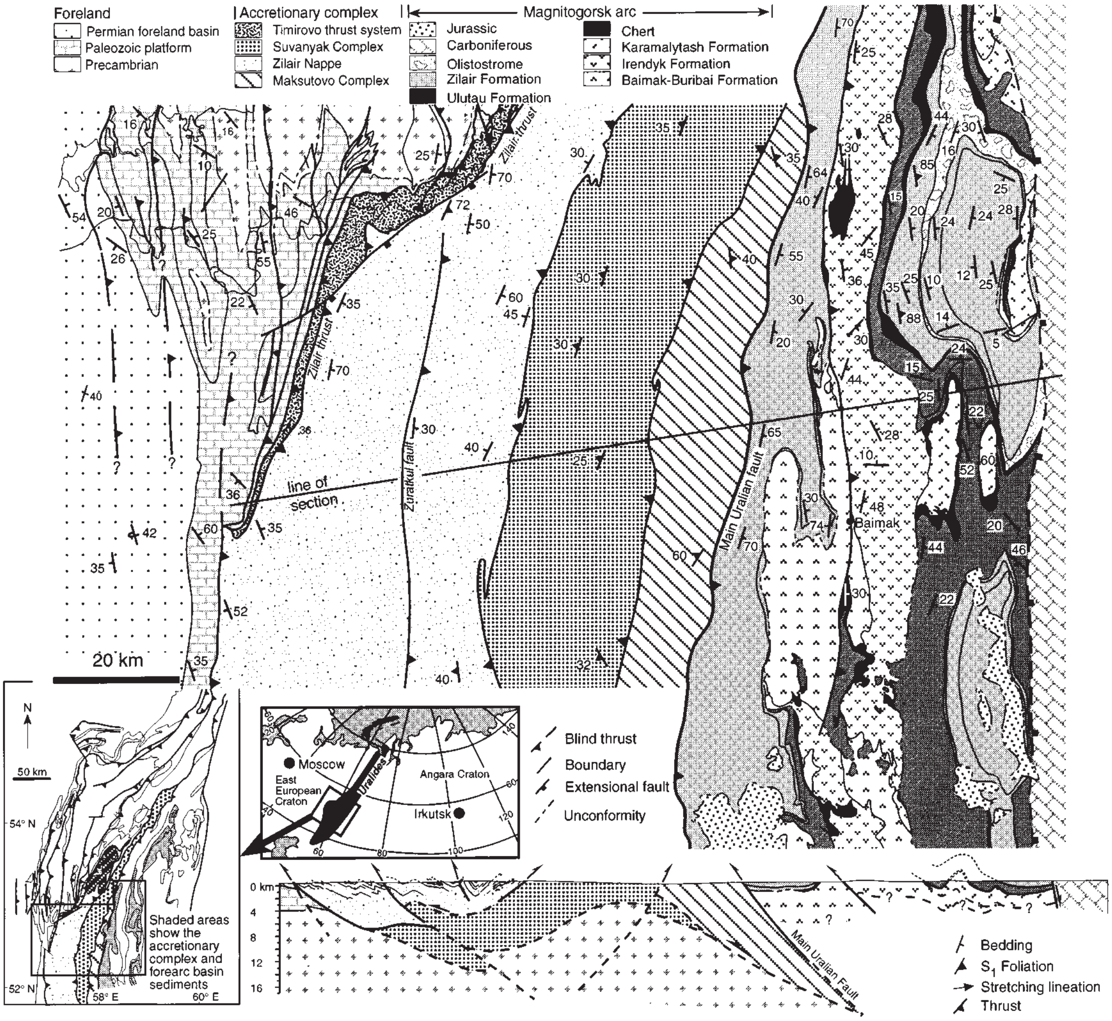

Figure 1. Detailed map and cross section of part of forearc basin and accretionary complex in southern Ural Mountains. Location is shown in inset.

overlain by the predominantly dacitic volcanics of the Eifelian to Givetian Karamalytash Formation. The Magnitogorsk arc volcanic rocks all have oceanic island-arc geochemical and isotopic signatures (Fig. 2, A and B).

The volcanic units form the basement on which as much as 5000 m of westward-thickening forearc basin sediments were deposited (Fig. 2C). Givetian jaspers that directly overlie the volcanic units are widespread in the basin. These are everywhere stratigraphically overlain by Givetian volcaniclastic sandstones, microconglomerates, and tuffaceous cherts of the Ulutau Formation. The stratigraphically highest unit is the Frasnian to Famennian Zilair Formation, which consists of turbiditic volcaniclastic sandstones, siliceous siltstones, and interbedded cherts. Synsedimentary deformation and olistostromes are common in the forearc sediments, but are widespread in the Zilair Formation, where olistostromes as large as several tens of square kilometers developed (Fig. 1). Regionally, the Zilair Formation is correlated with the volcaniclastic sandstones that are in the Zilair nappe. Shallow-water Lower Carboniferous carbonates unconformably overlie the openly folded arc.

COMPARISION OF FOREARC AND ACCRETIONARY COMPLEX PROCESSES

Tertiary boninites from the western Pacific are restricted to the forearc region of island arcs, and are thought to record processes that occur during the subduction of young, hot oceanic lithosphere (e.g., Crawford et al., 1989). The boninites of the Baimak-Buribai Formation therefore provide a geodynamic setting and starting point for the interpretation of forearc processes in the southern Urals (Fig. 3A). Spadea et al. (1998) interpreted the absence of arc-derived volcaniclastic or terrigenous sediments in the lower sequences of the Baimak-Buribai Formation to indicate that the arc tholeiites and boninites erupted in a suprasubduction-zone setting at the onset of intraoceanic subduction. By the end of the Emsian, volcanism had changed from arc tholeiite to the island-arc calc-alkaline suites of the Irendyk Formation, marking the evolution to a mature island-arc setting that lasted until the end of the Eifelian. The eruption of dacites within the Karamalytash Formation, however, records a compositional change during the Givetian that may reflect a continental source. Volcanigenic massive sulfide deposits hosted by the Karamalytash Formation display Pb isotope ratios that are indicative of an old continental crustal source (Sundblad et al., 1996). The continental source is thought to be the East European craton, because the age of high-pressure metamorphism in the Maksutovo Complex indicates that it had entered the subduction zone by that time (Fig. 3B). In areas of active arc-continent collision such as Papua New Guinea, Timor, and Taiwan, arc volcanism waned and stopped in the accreted arc 1–3 m.y. after the entry of the continental crust into the subduction zone, although in all cases volcanism still occurs outboard of the accreted arc. In the southern Ural Mountains, magmatic activity in the accreted arc appears to have waned shortly after the entrance of the East European craton into the subduction zone, and stopped during the Givetian, a time span of ~5 m.y. (Fig. 3C).

In Papua New Guinea, Timor, and Taiwan accretionary wedge and arc uplift have been taking place at rates of 0.8–10 mm yr^{-1} since the arrival of the continental crust at the subduction zone (Abbott et al., 1997; De Smet et al., 1990; Jahn et al., 1986). In Timor and Taiwan the accretionary wedge is being uplifted and eroded, providing the major sediment source for the accretionary complex (Audley-Charles, 1986; Huang et al., 1997). In Papua New Guinea, however, it is the forearc that is now being uplifted and that supplies the sediments to the accretionary complex (Abbott et al., 1994). Abbott et al. (1994) attributed a change from a mixed source to an exclusively volcanic source in Papua New Guinea to mark the arrival of the Australian crust at the subduction zone. We extrapolate this idea to the southern Ural Mountains, where the change to a volcanic arc sediment source by the Givetian is believed to mark uplift and erosion of the arc due to the arrival of the East European craton at the subduction zone. By the Frasnian, the sediments had breached the outer arc high and were being deposited on the East European craton and incorporated into the accretionary complex as the Zilair nappe (e.g., Fig. 3B). The widespread occurrence of synsedimentary deformation and olistostromes at that time indicates basin instability that is interpreted to record seismic activity related to the entry of the full thickness of the East European craton into the subduction zone. Active seismicity in Papua New Guinea, Timor, and Taiwan (e.g., Abers and McCaffrey, 1994; Charlton, 1991; Tsai, 1986) indicates that continental crust can continue to underthrust the arc for at least 3–5 m.y. after its entry into the subduction zone. Such a process may provide a mechanism for triggering soft-sediment deformation and olistostrome formation in poorly consolidated forearc sediments (Fig. 3C).

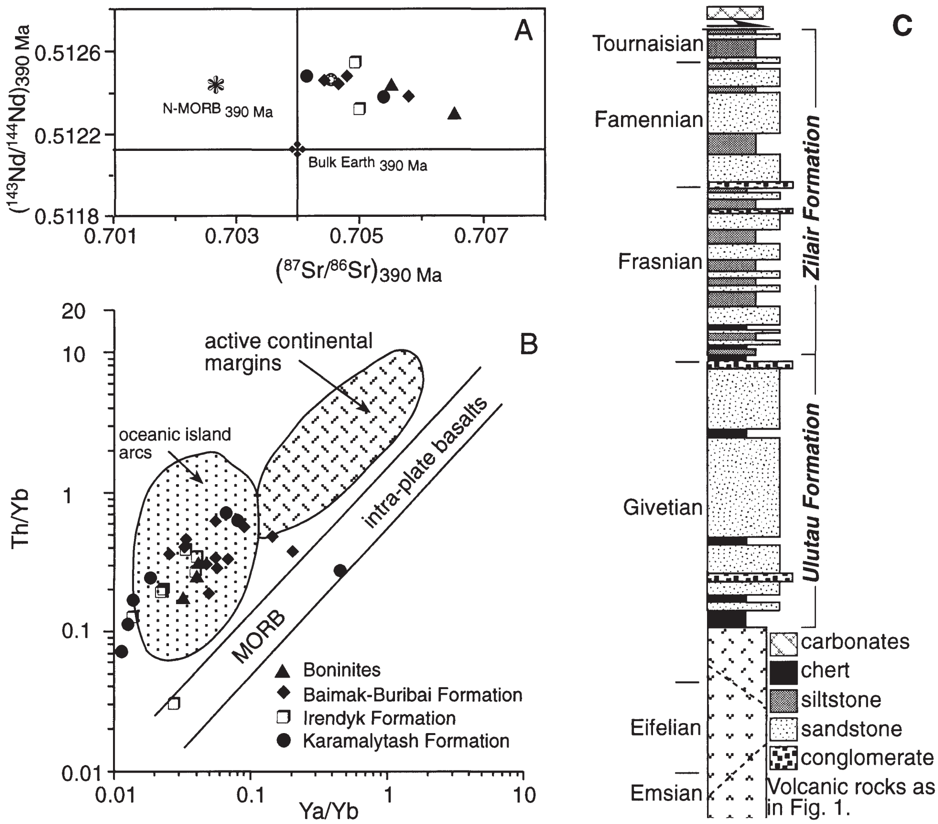

Figure 2. Geochemical and isotope data for Magnitogorsk extrusive rocks. N-MORB—normal mid-ocean ridge basalt. A: Emsian age-corrected Nd and Sr isotope ratios for Baimak-Buribai, Irendyk, and Karamalytash Formations showing depleted mantle sources and secondary radiogenic Sr enrichment. B: Th/Yb vs. Ta/Yb plot showing mostly intraoceanic arc affinities (after Pearce, 1983). C: Schematic stratigraphic column for forearc-basin stratigraphy.

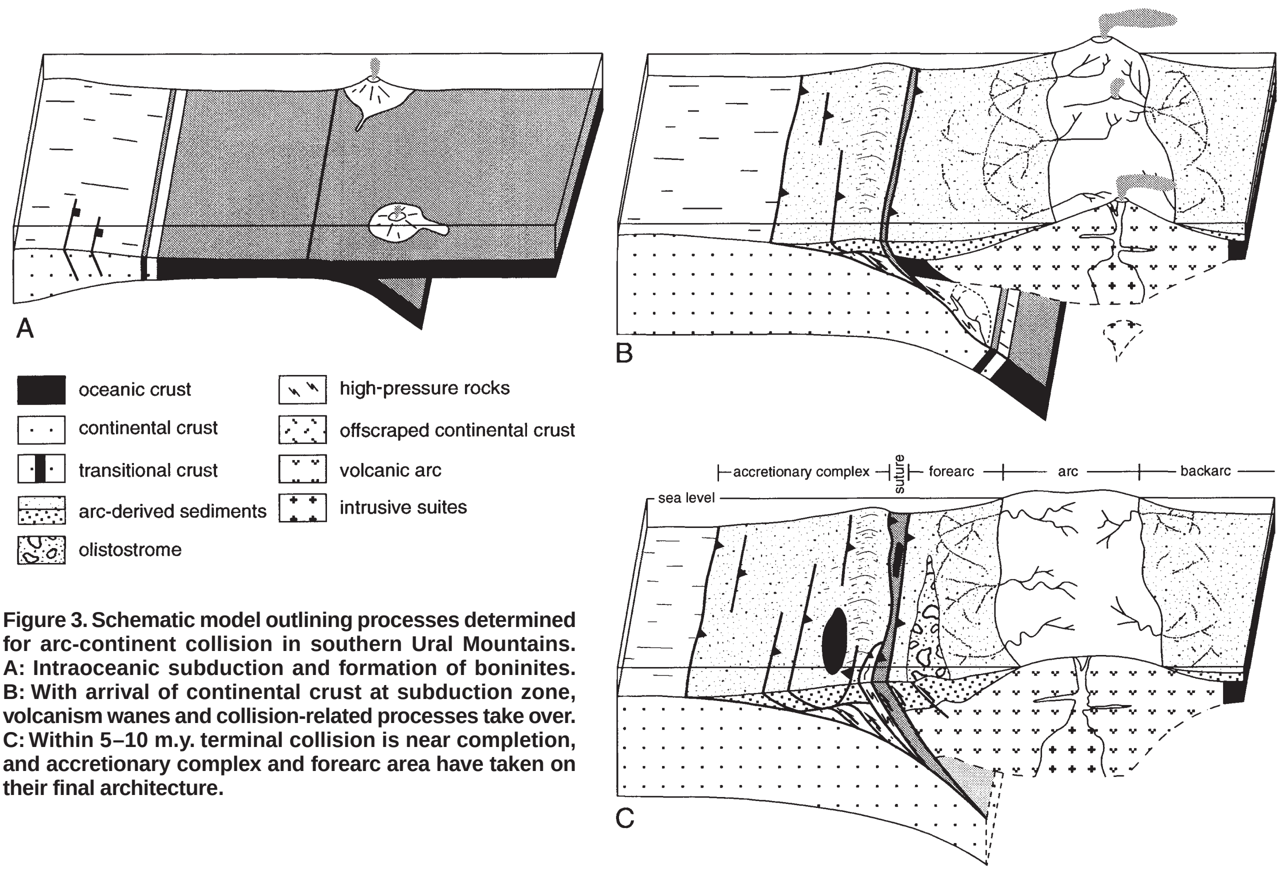

Figure 3. Schematic model outlining processes determined for arc-continent collision in southern Ural Mountains. A: Intraoceanic subduction and formation of boninites. B: With arrival of continental crust at subduction zone, volcanism wanes and collision-related processes take over. C: Within 5–10 m.y. terminal collision is near completion, and accretionary complex and forearc area have taken on their final architecture.

Active arc-continent collisions are taking place along a suture zone in which the rigid volcanic arc forms either an arcward- or trenchward-dipping backstop (e.g., Abbott et al., 1994; Huang et al., 1997; Snyder et al., 1996). In the southern Ural Mountains, the suprasubduction-zone volcanic material that underlies the forearc basin appears to have formed a rigid backstop to the accretionary wedge that protected the forearc-basin sediments from strong deformation. Reflection seismic profiling has shown the backstop to dip arcward (e.g., Brown et al., 1998), and the Main Uralian fault is interpreted to reflect the damage that occurred along the backstop. Ultramafic fragments that are along the Main Uralian fault may represent pieces of mechanically eroded mantle trapped in the damage zone, or extracted from it to travel along with the accretionary wedge (e.g., Kraka).

By far the most difficult part to fit into the model is the subduction and exhumation history of the Maksutovo Complex. The Maksutovo Complex is thought to represent material derived from the leading edge of the East European craton that underwent high-pressure metamorphism and deformation in the subduction zone (e.g., Hetzel et al., 1998). This is similar to the interpretation for blueschists in Taiwan, which are thought to have been derived from the Eurasian continental crust and tectonically included into the accretionary wedge (Ernst, 1982). The exhumation history of the Maksutovo Complex is difficult to trace, but its location at the rear of the accretionary wedge suggests that it was exhumed, perhaps buoyantly (e.g., Chemenda et al., 1995), along the backstop. Exhumation appears to have taken place in a compressional regime, because convergence was taking place continuously following high-pressure metamorphism. Derivation of the Maksutovo Complex metasedimentary rocks from the leading edge of the East European craton suggests that sediment subduction may have been occurring early in the collisional history, although offscraping and accretion (e.g., Suvanyak Complex and Timirovo thrust system) were active as thicker continental crust entered the subduction zone.

By the Tournasian the arc edifice had collapsed below sea level and shallow-water carbonates were deposited across it, indicating the cessation of the arc-continent collision, and providing an end for our model. Dorsey (1992) showed that the Luzon arc in Taiwan collapsed at the onset of collision. This mechanism may also explain deposition of the carbonates across the Magnitogorsk arc following collision.

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