Structure and evolution of the Magnitogorsk forearc basin: Identifying upper crustal processes during arc–continent collision in the southern Urals

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Structure and evolution of the Magnitogorsk forearc basin: Identifying upper crustal processes during arc-continent collision in the southern Urals

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Abstract. The southern Urals of Russia contain a well-preserved example of a Paleozoic arc-continent collision in which the intraoceanic Magnitogorsk volcanic arc and its forearc basin sediments accreted to the East European Craton during the Devonian. The Magnitogorsk arc records the evolution from incipient intraoceanic subduction to a mature arc, and by comparing its surface geological features with those in active arc-continent collision settings it is possible to identfy upper crustal processes that were active in the southern Urals. The arc edifice can be divided into western and eastern volcanic fronts that were active during different stages of arc evolution and for which two distinct phases of forearc basin development can be recognized. The late Lower to Middle Devonian Aktau Formation represents a remnant of the intraoceanic to collisional forearc basin to the Irendyk volcanic front, whereas the Middle Devonian to Lower Carboniferous Ulutau, Koltubanian, and Zilair Formations were deposited in a suture forearc basin to the east Magnitogorsk volcanic front. It was not until the Late Devonian that these two basins were joined. Structural mapping, combined with reflection seismic profiling, shows these basins to be affected by open, nonlinear, volcanic basement-cored synsedimentary folds. The Karamalytash anticline appears to have the geometry of a growth fold that formed during deposition of sediments in the suture forearc basin. The forearc region is affected by minor thrusting that involves the volcanic basement, although it is not clear if these thrusts reactivate preexisting trench-parallel faults. Synsedimentary deformation, slumping, and olistostrome development were common throughout the suture forearc basin history but were especially widespread during the Late Devonian, when the full thickness of the continental crust is interpreted as having arrived at the subduction zone.

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1. Introduction

Arc terranes are common in fossil and active orogenic belts, and arc-continent collision has been shown to be an important process in collisional orogenesis, as well as a primary mechanism of continental crustal growth throughout geological time [e.g., *Sengör et al.*, 1993]. In recent years, considerable advances have been made in the understanding of arc-continent collision processes, largely as a result of studies in active settings such as those in the Circum-Pacific [e.g., *Abbott et al.*, 1994a; *Huang et al.*, 1997; *Snyder et al.*, 1996]. For example, in Papua New Guinea, Timor, and Taiwan the structural architecture and syntectonic sediments in the suture forearc basin and accretionary complex have provided key insights to upper crustal arc-continent collision processes [*Abbott et al.*, 1994a, 1994b; *Charlton et al.*, 1991; *Hughes et al.*, 1996; *Huang et al.*, 1997; *Dorsey*, 1992; *Teng*, 1990], whereas reflection seismic profiling and active seismicity studies have investigated processes at lower crustal and upper mantle levels [*Snyder et al.*, 1996; *Abers and McCaffrey*, 1994]. In many fossil orogens, arc terranes are often strongly deformed, metamorphosed, and fragmented by postaccretion tectonic activity [e.g., *Leggett et al.*, 1982; *van Staal*, 1994; *Bedard et al.*, 1998; *Puchkov*, 1997], making it difficult to determine arc-continent collision processes from the variably preserved tectonostratigraphic units. The southern Uralide orogen of Russia (Figure 1), however, has been shown to contain an exceptionally well-preserved example of a Paleozoic arc-continent collision in which the upper crustal geological features can be determined at a level of detail comparable to those in active settings [e.g., *Brown et al.*, 1998; *Brown and Spadea*, 1999]. This paper presents a detailed investigation of the structure and evolution of the Magnitogorsk forearc, focusing on the architecture of the forearc basin. It provides a new, detailed data set that allows us to compare the southern Urals arc-continent collision with those now active in the circum-Pacific, helping to identify the upper crustal processes that were active during the accretion of the Magnitogorsk arc to the East European Craton.

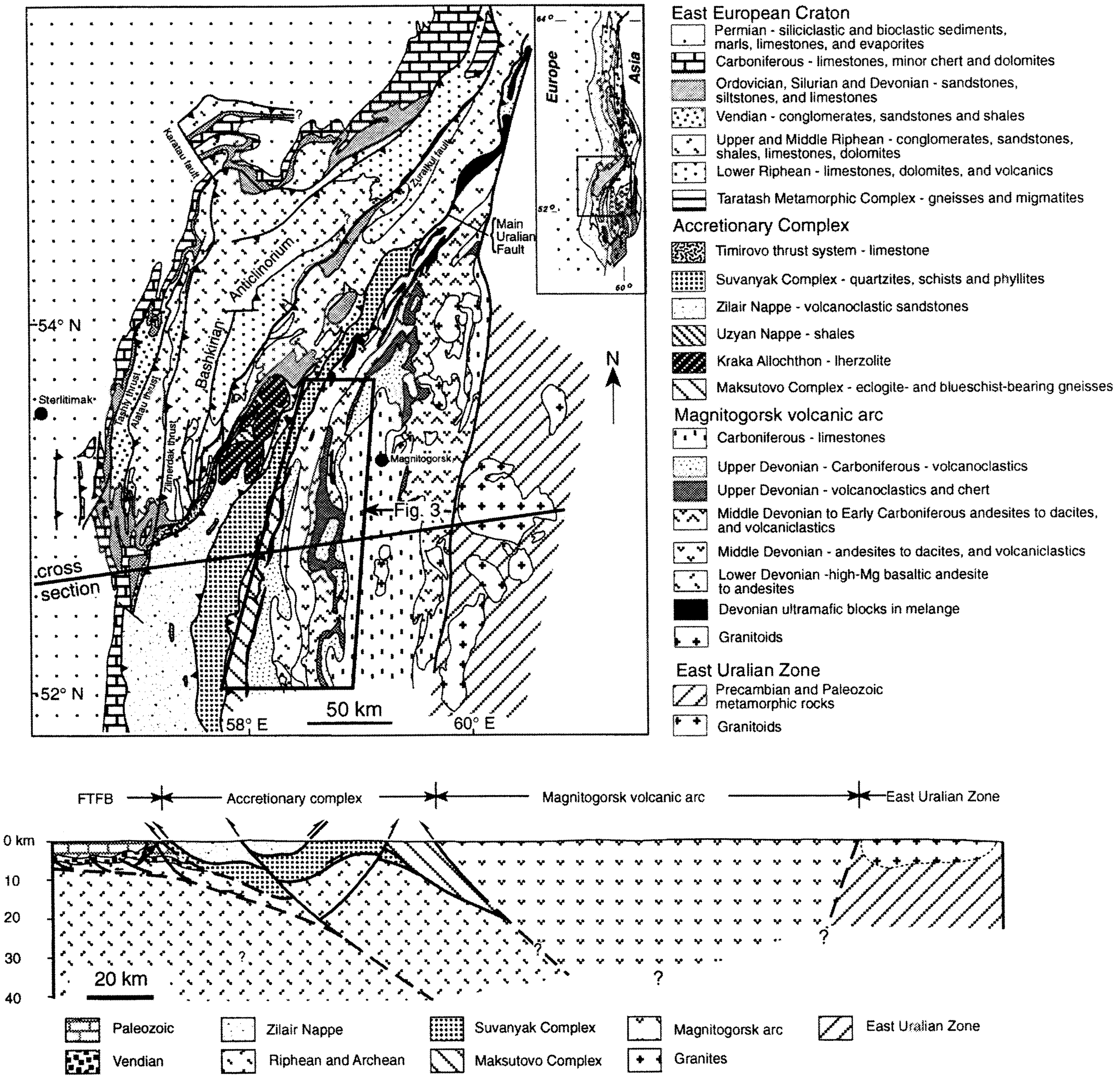

Figure 1. Geological map of the southern Urals showing the lithotectonic units of the arc-continent collision. (bottom) A schematic cross section (indicated on the map) showing the tectonic position of the main geological features of the southern Urals (FTFB, foreland thrust and fold belt). The location of Figure 3 is indicated.

2. Geological Framework

The southern Urals (Figure 1) contain a well-preserved example of a Paleozoic arc-continent collision in which the Magnitogorsk volcanic arc accreted to the East European Craton in the Middle and Late Devonian [e.g., *Brown and Spadea,* 1999] (Figure 2). Beginning in the Early Devonian, the tectonic setting in the southern Uralides was dominated by the development of the Magnitogorsk volcanic arc above an east dipping (current coordinates) intraoceanic subduction zone, while the easternmost East European Craton was evolving as a passive continental margin [e.g., *Puchkov,* 1997; *Brown et al.,* 1998; *Brown and Spadea,* 1999]. With the entrance of East European Craton continental crust into the subduction zone in the Middle Devonian [*Brown and Spadea,* 1999], volcanism in the Magnitogorsk arc shifted eastward where it continued into Early Carboniferous [*Puchkov,* 1997]. During this time a broad suture forearc basin developed above the Early and Middle Devonian arc complex and filled with sediments derived from the eastern volcanic front. In the Late Devonian these sediments breached the outer arc high and were deposited in the trench, where they were incorporated into the accretionary complex that was being thrust over the subducting continental crust [e.g., *Alvarez-Marrón et al.,* 2000; *Brown and Spadea,* 1999; *Brown et al.,* 1998]. The Magnitogorsk arc and its forearc basin are unmetamorphosed, preserving primary igneous and sedimentary textures [e.g., *Spadea et al.,* 1998; *Maslov et al.,* 1993], including vent fauna in volcanic-hosted massive sulphide deposits [*Zaykov et al.,* 1996].

The Magnitogorsk arc is sutured to the East European Craton along the eastdipping Main Uralian fault. The Main Uralian fault forms a wide mélange zone that incorporates Late Devonian age fragments, derived from the Magnitogorsk volcanic arc, and oceanic crust and mantle. In the present study area the Upper Devonian volcaniclastic sediments of the forearc basin (see

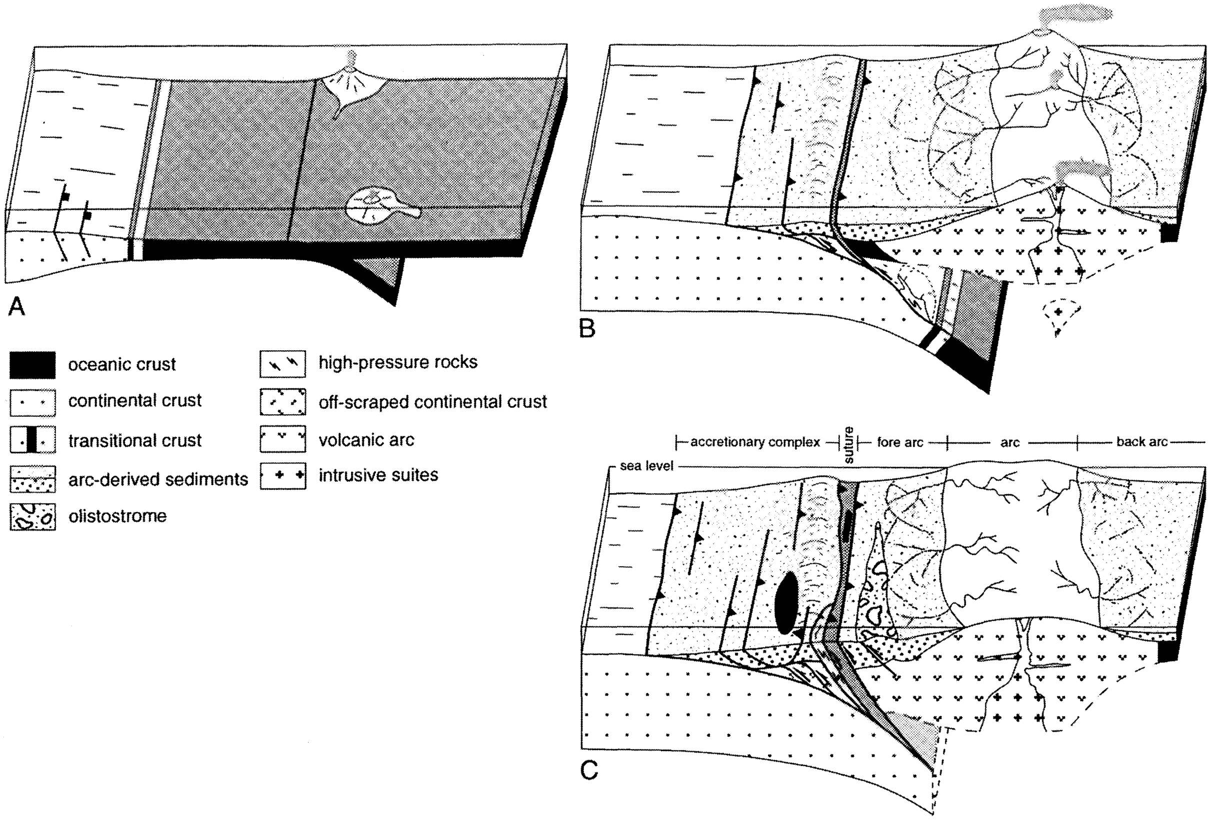

Figure 2. Schematic model outlining processes determined for arc-continent collision in the southern Ural Mountains: (a) Early Devonian. (b) Middle to Late Devonian. and (c) Late Devonian to Early Carboniferous. [after *Brown and Spadea*, 1999].

section 3.3) and Lower Carboniferous limestones are also affected by deformation associated with the Main Uralian fault and locally form kilometer-scale rafts within the serpentinite mélange. Recent single-zircon dating of a late, undeformed phase of the Syrostan batholith by *Montero et al.* [2000], which intrudes into the Main Uralian fault in the southern Urals, yielded an age of 327 ± 2 Ma, suggesting that tectonic activity along the suture zone had ended by the late Early Carboniferous.

3. Magnitogorsk Arc

3.1. Volcanic Edifice

The Magnitogorsk arc (Figure 1 and 3) is composed of Early, Middle, and Late Devonian age arc-tholeiite to calc-alkaline volcanic units [e.g., *Seravkin et al.,* 1992]. The lowermost unit, the Emsian Baimak-Buribai Formation, consists of basaltic lava flows intercalated with pyroclastics, hyaloclastites, agglomerates, volcaniclastics, thin beds of tuffaceous chert, and, locally, boninitic lavas and dikes [*Kuz'min and Kabanova,* 1991]. *Spadea et al.* [1998] and *Brown and Spadea* [1999] interpret the Baimak-Buribai Formation as having been erupted in a suprasubduction zone setting at an early stage of the intraoceanic subduction. From the latter part of the Emsian through the lowermost Eifelian, volcanism evolved to island arc calc-alkaline suites of the Irendyk Formation. The Irendyk Formation consists of lava flows intercalated with pyroclastics, hyaloclastites, agglomerates volcaniclastics, and, locally, thin beds of tuffaceous chert. The Irendyk Formation is overlain by basaltic to rhyolitic flows of the uppermost Eifelian Karamalytash Formation. The Irendyk and Karamalytash Formations mark the evolution to a mature island arc setting (which we here name the Irendyk volcanic front) that lasted until the end of the Middle Devonian to the beginning of the Late Devonian.

From the Givetian onward, volcanism shifted eastward to form the predominantly andesitic to dacitic east Magnitogorsk volcanic front [e.g., *Puchkov, 1997*]. The Givetian to lowermost Frasnian Ulutau Formation (see section 3.3) in the East Magnitogorsk zone consists mainly of andesitic and dacitic lava flows, near-vent breccias, and sills intruded into tuffaceous and volcanoclastic sandstones and agglomerates [e.g., *Yazeva et al.,* 1989]. During the Givetian to earliest Famennian, calc-alkaline basaltic andesite lava flows and agglomerates with rare thin, green chert interbeds and comagmatic intrusions formed in the East Magnitogorsk volcanic front. By the end of the Devonian, volcanism consisted of subalkaline trachybasalt to trachyrhyolite volcanic centers in the central part of the arc, changing to bimodal tholeitic and subalkaline basaltic to rhyolitic volcanism [*Salikhov et al.,* 1993; *Yazeva et. al.,* 1989] in the central and eastern part of the Magnitogorsk arc during the Early Carboniferous. Volcanism ceased during the earliest Bashkirian epoch of the Late Carboniferous. The east Magnitogorsk volcanic

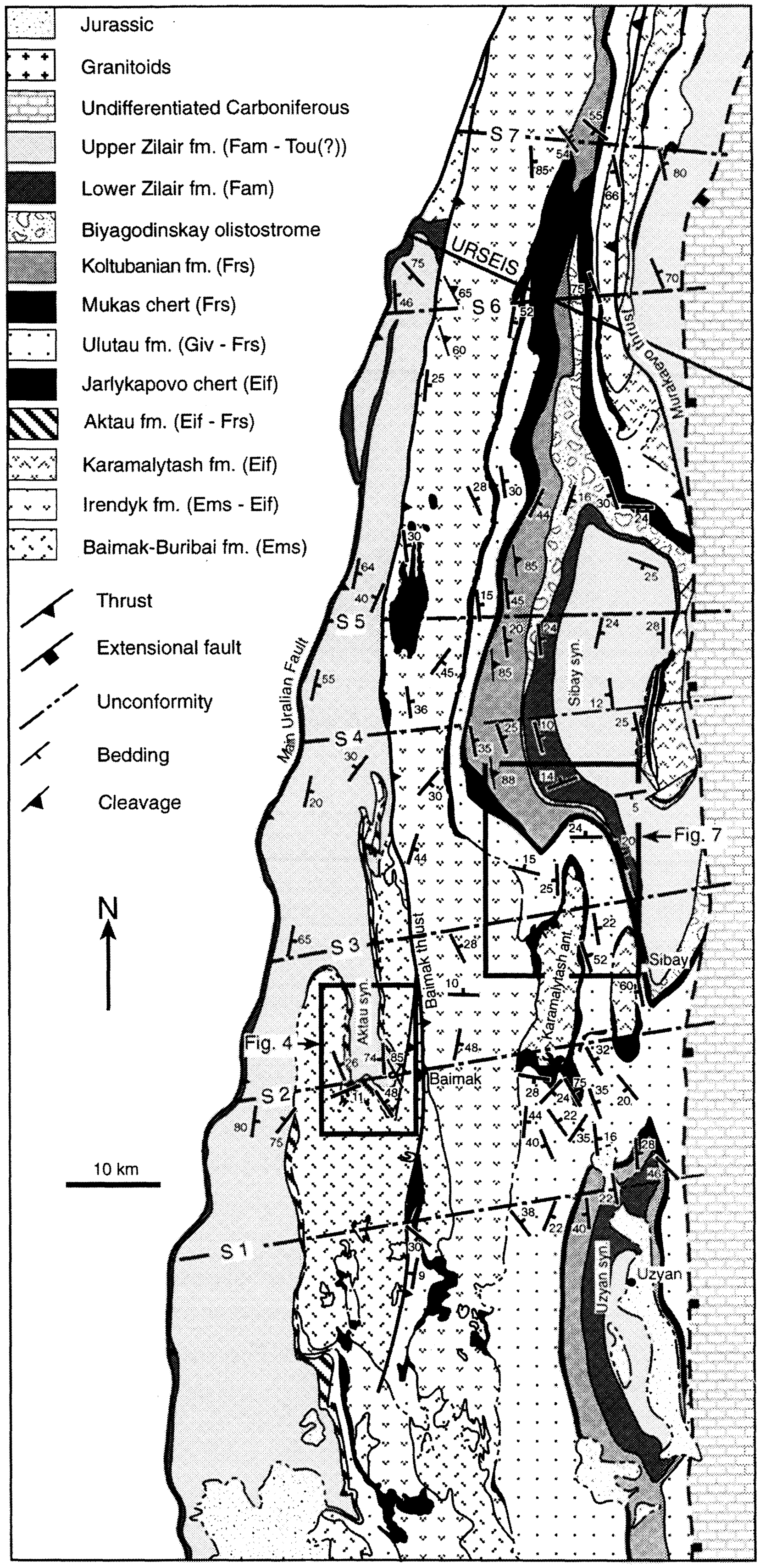

Figure 3. Detailed geological map of the westernmost Magnitogorsk arc showing the Irendyk volcanic front and the outcropping basins. The map is bound to the west by the arc-continent suture, the Main Uralian fault. The locations of the cross sections in Figure 6 (S 1, etc.) and the location of the Urals Seismic Experiment and Integrated Studies (URSEIS) profile in Figure 8 are indicated. The locations of Figure 4 and 7 are also indicated. Fam is Famenian, Tou is Tournaisian, Frs is Frasnian, Giv. Is Givetian, Eif is Eifelian, and Ems is Emsian.

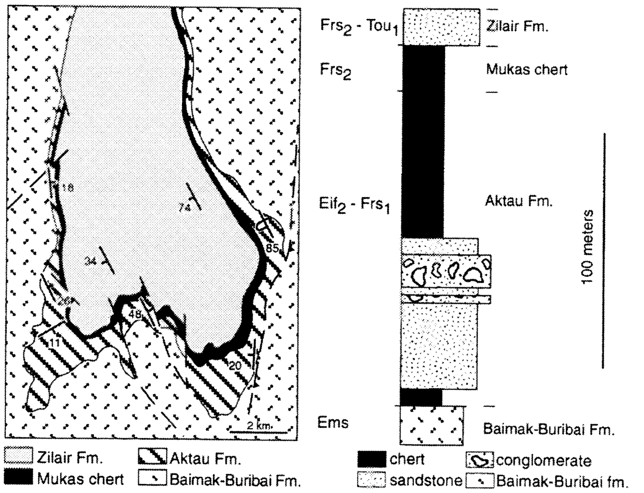

Figure 4. Schematic geological map and a stratigraphic column of the Aktau synform [after *Maslov and Artyushkova,* 1991]. New mapping shows the eastern limb of the synform to be overturned in the footwall to a thrust that splays off the Baimak thrust.

front was the primary source for the Late Devonian suture forearc basin fill that is discussed in section 3.3.

3.2. Aktau Forearc Basin

In the central and southern part of the map area the Middle to Upper Devonian Aktau Formation outcrops along the western margin of the Baimak-Buribai Formation (Figure 3). In a section immediately west of Baimak, in the Aktau synform (Figure 4), it consists of up to 150 m of uppermost Eifelian to lowermost Frasnian interbedded tuffaceous sandstones, cherts, and jaspers and minor conglomerate overlain by Frasnian Mukas cherts and Frasnian to Tournasian volcanoclastics of the Zilair Formation (see section 3.3) [*Maslov and Artyushkova,* 1991]. The Aktau Formation is interpreted here to be a remnant of the forearc basin to the Irendyk and east Magnitogorsk volcanic fronts in which sediments continued to accumulate during the collision of the arc with the East European Craton.

3.3. Magnitogorsk Suture Forearc Basin

The Magnitogorsk suture forearc basin consists of up to 5000 m of westward thickening Givetian to Famennian chert and volcanoclastic sediments (Figure 5) that overlie the volcanic edifice and remnant forearc basin of the Irendyk volcanic front. The lowest sedimentary unit in the Magnitogorsk suture forearc basin is the Givetian Jarlykapovo Formation, which consists of several tens of meters to ~200 m of jasper and chert that overlie the Irendyk Formation and is coeval with the Karamalytash Formation. The Bugulygyr jasper, which overlies the Karamalytash Formation, is correlated with the uppermost part of the Jarlykapovo Formation.

The Jarlykapovo Formation is stratigraphically overlain by the westward thickening, northward thinning Givetian to lowermost Frasnian Ulutau Formation. The Ulutau Formation ranges in thickness from several hundred meters to ~2000 m and consists of thinly to thickly (i.e., centimeter to meter scale) bedded, fine- to coarse-grained, poorly sorted, generally grain-supported, volcanomictic sandstone, with thin interbeds of tuffaceous chert,and, locally, thin beds of siliceous shale. Clasts in the sandstone consist predominantly of subrounded plagioclase, clinopyroxene, quartz, and dacitic and/or basaltic clasts, with a matrix of prehnite-pumpellyite + chlorite + epidote ± chalcedony. Cross-bedding and ripple marks are found locally but are not common. Olistostromes of the order of several hundreds of square meters and containing Ulutau material, volcanics, and, locally, blocks of limestone are widespread [e.g., *Kopteva,* 1981].

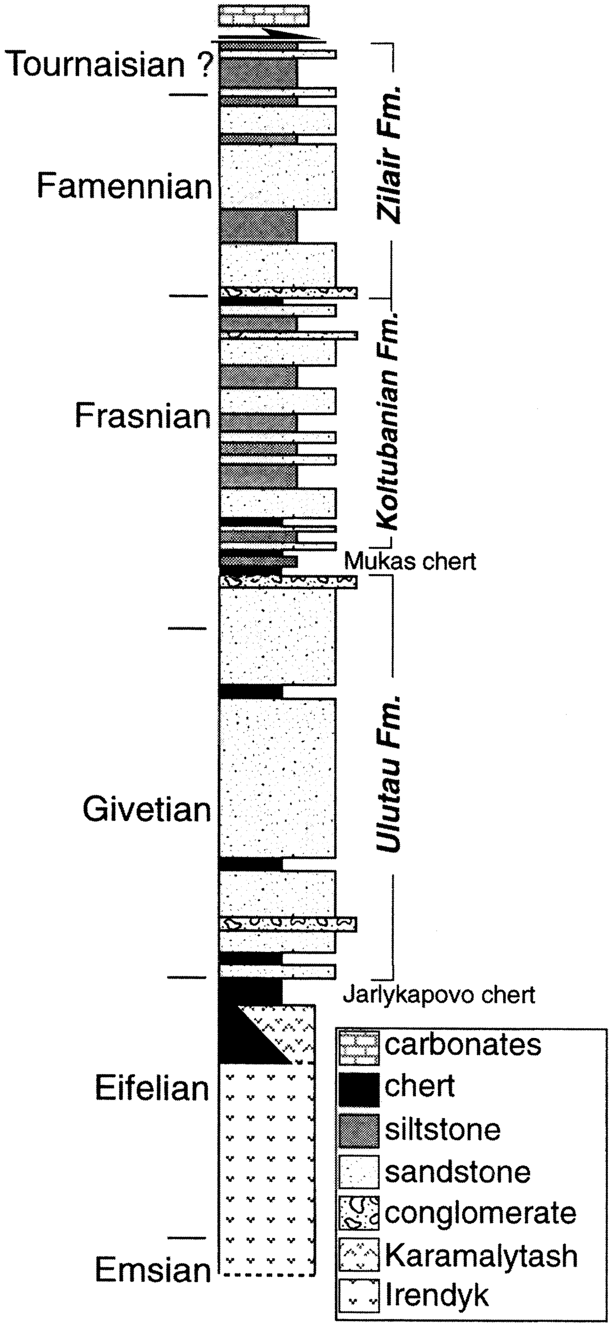

Figure 5. A simplified composite stratigraphic column of the suture forearc basin. The ages for the various units have been determined from conodont analyses by *Maslov et al.* [1993].

Throughout the Magnitogorsk suture forearc basin the Mukas chert forms a 10-100 m thick, tuffaceous chert unit that everywhere overlies the Ulutau Formation, forming an excellent structural marker (Figure 3). *Artyushkova and Maslov* [1999] have shown that the upper boundary of the Mukas chert is strongly diachronous and that it grades laterally into and is coeval with the Koltubanian Formation flysch. The Frasnian age Koltubanian Formation is composed of up to 1500 m of westward thickening cherty flysch that consists of thinly bedded (centimeter scale), fine- to coarse-grained, poorly to moderately sorted, generally grain-supported, volcanomictic siliceous sandstone, with interbeds of tuffaceous chert, grading into siliceous siltstones in the upper part of the formation. The upper part of the Koltubanian Formation is marked by widespread synsedimentary deformation and olistostrome formation (see section 4.3).

The Famennian to lowermost Tournaisian Zilair Formation consists of up to 2000 m of westward thickening flysch. It is composed predominantly of subrounded to rounded quartz, plagioclase, lithic clasts, and basalt and/or dacite clasts, with a matrix of chalcedony + chlorite ± epidote ± calcite ± hydromica. Metamorphic minerals such as garnet, mica, and rare glaucophane have also been reported [*Arzhavitina*, 1977]. Internal sedimentary structures such as graded bedding, cross-bedding, and ripple marks are found locally but are not common. Very few current markers have been found. The Zilair Formation in the suture forearc is the eastern equivalent of the Zilair Formation found in the south Urals accretionary complex [*Alvarez-Marrón et al.*, 2000; *Brown et al.*, 1998].

To the east the volcanoclastic sediments of the suture forearc basin are unconformably overlain by shallow water, Lower Carboniferous limestones. These limestones are juxtaposed against the forearc basin sediments of the study area along a steeply east dipping extensional fault. Elsewhere, these limestones unconformably overlie the arc stratigraphy. The forearc region is locally intruded by Middle to Late Carboniferous gabbroic dikes [*Seravkin et al.*, 1992]. Southward, in the Uzyan synform, undeformed Jurassic clastic sediments unconformably overlie both the forearc sediments and the Lower Carboniferous shallow water carbonates (Figure 3).

4. Structure of the Forearc Basins

4.1. Cross Sections

Seven parallel cross sections have been constructed from the Main Uralian fault in the west to the Lower Carboniferous limestones in the east (Figure 6). Cross section 6 is crossed by the Urals Reflection Seismic Experiment and Integrated Studies (URSEIS) reflection seismic profile (Figure 3), which provides constraints on the shallow structure and dip direction of the Main Uralian fault and the Murakaevo thrust (see section 4.2.). The lack of laterally continuous marker horizons in the volcanic sequences makes it impossible to determine the internal structure of these units with any confidence or to correlate many features with reflectivity in the seismic profile. Consequently, the volcanic units in the cross sections are shown as internally homogeneous units whose subsurface extent is not well constrained.

The forearc basin is bound to the west by the Main Uralian fault and to the east by an extensional fault with a throw to the east of several hundred meters. It is internally imbricated along the west verging Baimak thrust, a several hundred meter wide, ENE dipping mylonite zone with its top to the west sense of movement that thrusts the Irendyk Formation in its hangingwall over the Baimak-Buribai and Zilair Formations in its footwall. Northward, the Baimak thrust merges with the Main Uralian fault, and it can be traced in outcrop ~50 km south of the town of Baimak (Figure 3). The Baimak thrust divides the Magnitogorsk suture forearc basin into two units. The Ulutau Formation is found in only one location to the west of the Baimak thrust, and the Koltubanian Formation is not developed (Figure 6). In the south (sections 1 and 2 in Figure 6), the western part of the forearc basin is affected by open, west vergent, kilometer-scale folds that disappear northward, and the Baimak thrust places the Ulutau Formation on top of the Baimak-Buribai Formation (Section 1 in Figure 6). Immediately west of Baimak, the eastern limb of the Aktau synform is overturned beneath a thrust that is interpreted as splaying off the Baimak thrust. Northward, kilometer-scale blocks of the Zilair Formation are incorporated into the Main Uralian fault and are completely surrounded by serpentinite. The internal deformation in these forearc blocks is highly variable, ranging from practically undeformed to moderately sheared.

To the east of the Baimak thrust the structure is that of a pair of elongated synforms, the Sibay synform in the north and the Uzyan synform in the south (Figure 3). These synforms are separated along strike by a volcanic basement high that culminates in the basement-cored Karamalytash anticline (Figure 3). Both synforms are open and somewhat flat bottomed, with gentle limb dips. Along the western limb of the Sibay synform, there is a several kilometers wide band of penetrative, steeply east dipping to vertical cleavage, but it cannot be traced south of the Karamalytash anticline.

The Karamalytash anticline (Figure 3 and 7) is a gently north-south plunging, slightly asymmetric fold, with nearly vertical limb dips along the eastern side of its volcanic core and gentler dips on the western side. In map view (Figure 7) the Koltubanian and Zilair Formations appear to thin eastward over the northern hinge of the Karamalytash anticline, giving it the appearance of a growth fold. A synsedimentary fault has been interpreted as occurring along the western margin of the anticline [*Kopteva*, 1983], but we find no evidence of this in the field. Along the southern termination of the anticline, decameter-scale folding and minor thrusting (displacements of meters) occurs.

Northward, in sections 6 and 7 of Figure 6, the east vergent Murakaevo thrust places Irendyk and Karamalytash rocks on top of the Zilair Formation. The Irendyk Formation volcaniclastics have been folded into a tight hangingwall anticline, and the Zilair Formation displays an open footwall syncline. The Murakaevo thrust is marked along much of its length by a ~100 m wide band of serpentinites that merges northward with the Main Uralian

Figure 6. Cross sections 1-6 across the westernmost Magnitogorsk arc. The locations are shown in Figure 3 as S 1, etc. Note that in section 1 the Baimak thrust is shown as an inverted extensional fault.

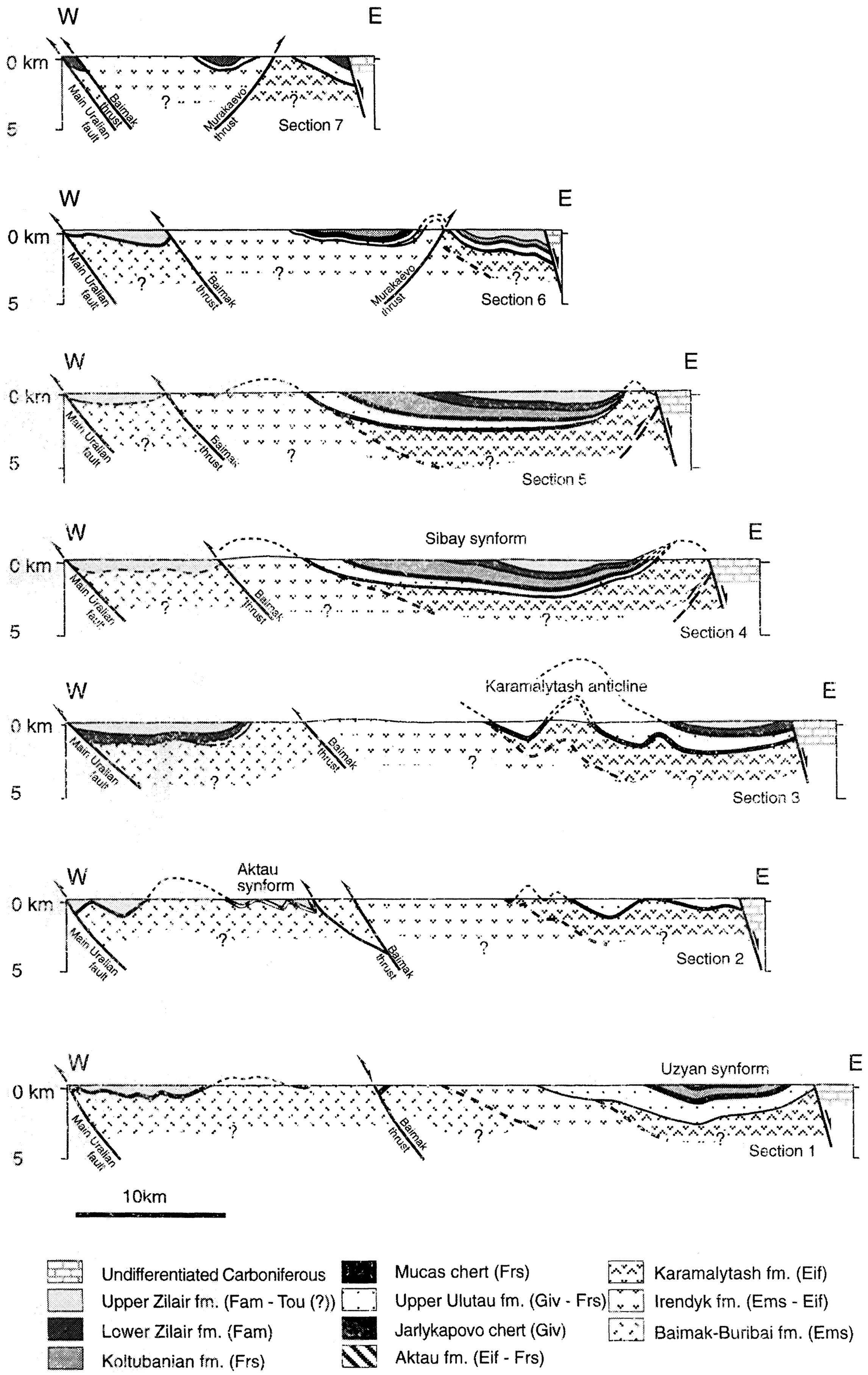
W
E
0 km
5
Main Uralian fault
Baimak thrust
Murakaevo thrust
Section 7
W
E
0 km
5
Main Uralian fault
Baimak thrust
Murakaevo thrust
Section 6
W
E
0 km
5
Main Uralian fault
Baimak thrust
Section 5
W
Sibay synform
E
0 km
5
Main Uralian fault
Baimak thrust
Section 4
W
Karamalytash anticline
E
0 km
5
Main Uralian fault
Baimak thrust
Section 3
W
Aktau synform
E
0 km
5
Main Uralian fault
Baimak thrust
Section 2
W
Uzyan synform
E
0 km
5
Main Uralian fault
Baimak thrust
Section 1
10km
Undifferentiated Carboniferous
Upper Zilair fm. (Fam - Tou (?))
Lower Zilair fm. (Fam)
Koltubanian fm. (Frs)
Mucas chert (Frs)
Upper Ulutau fm. (Giv - Frs)
Jarlykapovo chert (Giv)
Aktau fm. (Eif - Frs)
Karamalytash fm. (Eif)
Irendyk fm. (Ems - Eif)
Baimak-Buribai fm. (Ems)

Figure 6.

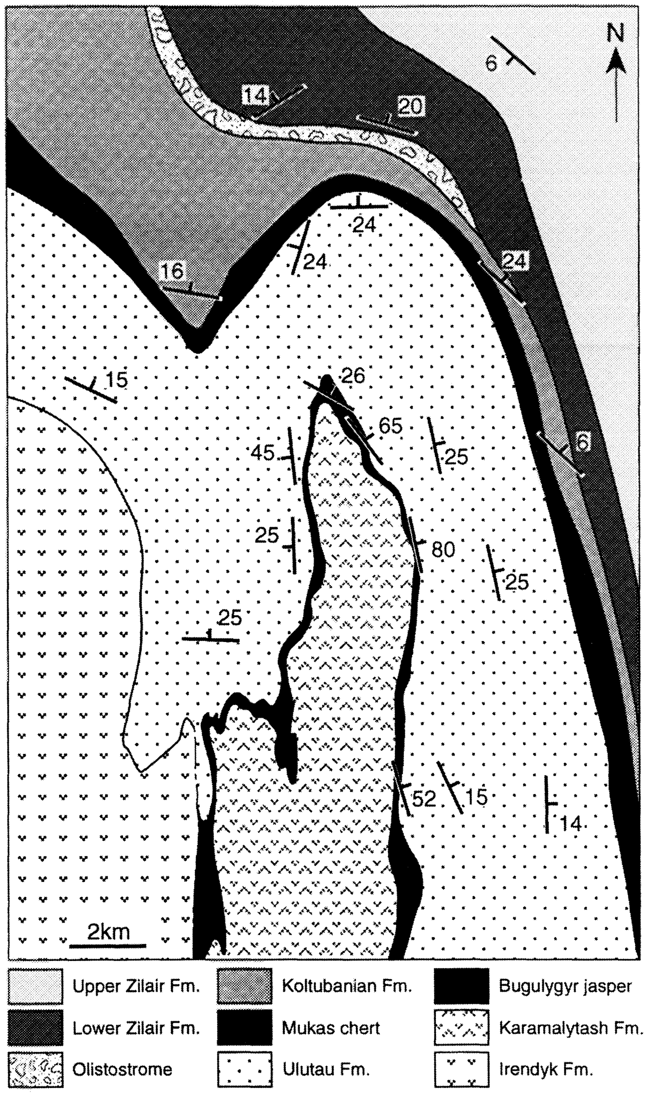

Figure 7. Detailed map of the northern hinge zone of the Karamalytash anticline. The Koltubanian and lowermost Zilair Formations thin eastward over the crest of the northplunging anticline. This geometry is indicative of a growth fold.

fault. Southward, it is cut by the extensional fault that juxtaposes the Carboniferous limestones against the forearc basin sediments, indicating that the thrust predates the Carboniferous. In one location an undeformed granodiorite dike intrudes into the serpentinites of the Murakaevo thrust.

4.2. Reflection Seismic Profile

The URSEIS profile was acquired by a multinational consortium in 1995 [*Berzin et al.,* 1996] under the auspices of EUROPROBE, and the vibroseis data, a portion of which is presented here, is described regionally by *Echtler et al.* [1996]. The common depth point (CDP) reflection profile has been plotted onto a straight line that crosses the main structural grain obliquely (Figure 3).

The upper 4 seconds two-way time (TWT) of a time-migrated section of the URSEIS profile extending from the East European Craton in the west to the Carboniferous carbonates in the central part of the Magnitogorsk arc is shown in Figure 8. The Main Uralian fault zone is weakly imaged as a broken band of moderately east dipping reflections that extend from CDP 100 to approximately CDP 180 and can be traced to ~3 seconds at approximately CDP 400 and intermitently to the bottom of the section at approximately CDP 600. From CDP 180 to approximately CDP 430 the upper 0.5 seconds image the syncline shown in section 6 (Figure 6). The contact between the Zilair Formation and the underlying Baimak-Buribai Formation is well imaged at ~0.5 seconds. The Baimak thrust reaches the surface at approximatley CDP 400. In the upper 1.5 seconds the zone of east dipping reflectivity to the east of CDP 400 to approximately CDP 690 is related to the Irendyk Formation, which outcrops in the hangingwall of the Baimak thrust. At depth the Baimak thrust is poorly imaged, although truncated reflectivity suggests that it dips moderately eastward. From CDP 690 to approximately CDP 1100 the upper 1 second, images the upper Ulutau and Zilair Formations within the Sibay synform. A bright continuous reflector that reaches the surface at CDP 690 and dips eastward to approximately CDP 950 at 1 second is interpreted to be the contact between the Ulutau sediments and the Irendyk volcanics. A package of bright, west dipping reflections that project to the surface at approximately CDP 1175 corresponds to the Murakaevo thrust. The short, bright reflection package marked A appears to crosscut the Murakaevo thrust, but at higher migration velocities it moves westward into the hangingwall, indicating that its position in the current section is a result of migration velocity. From CDP 1175 to approximately CDP 1400, the upper 0.5 seconds is poorly reflective. This area corresponds to the easternmost forearc basin sediments. The area from CDP 1400 to the end of the profile corresponds to the Carboniferous carbonates.

4.3. Synsedimentary Deformation

Synsedimentary deformation is widespread in the Magnitogorsk suture forearc basin. The Jarlykapovo Formation (including the Bugulygyr jasper), for example, often displays tight to isoclinal intraformational folds (Figure 9a), disrupted bedding, veining, and brecciation that is not reflected in the beds or units immediately overlying it, nor is the fold style reflected in the large-scale structure of the basin (see below), indicating that these features are synsedimentary. Locally, decameter-scale olistostromes are developed in the Ulutau clastics, but larger-scale slumping and olistostrome formation have also been recognized in the Ulutau Formation [e.g., *Kopteva,* 1981].

The Mukas chert often displays chaotic folding, brecciation, and slumping on a variety of scales (Figure 9b). Locally, within the Koltubanian Formation, coherent slumps can be mapped for hundreds of meters in structural thickness and up to 1 km in length (Figure 9c). Such slumps are characterized by folded and brecciated horizons underlain and overlain by undeformed beds that everywhere have the regional dip. Olistostromes of a decametric to hectametric scale and larger are common and widespread in the Koltubaninan Formation clastics. A spectacular example is the Biyagodinskay olistostrome, which is developed in the area to the north of Sibay, between the Koltubanian and Zilair Formations (Figure 3). The Biyagodinskay olistostrome has an outcrop area of ~250 to ~300 km^2 (although much of it projects beneath the Zilair Formation and, consequently, does not

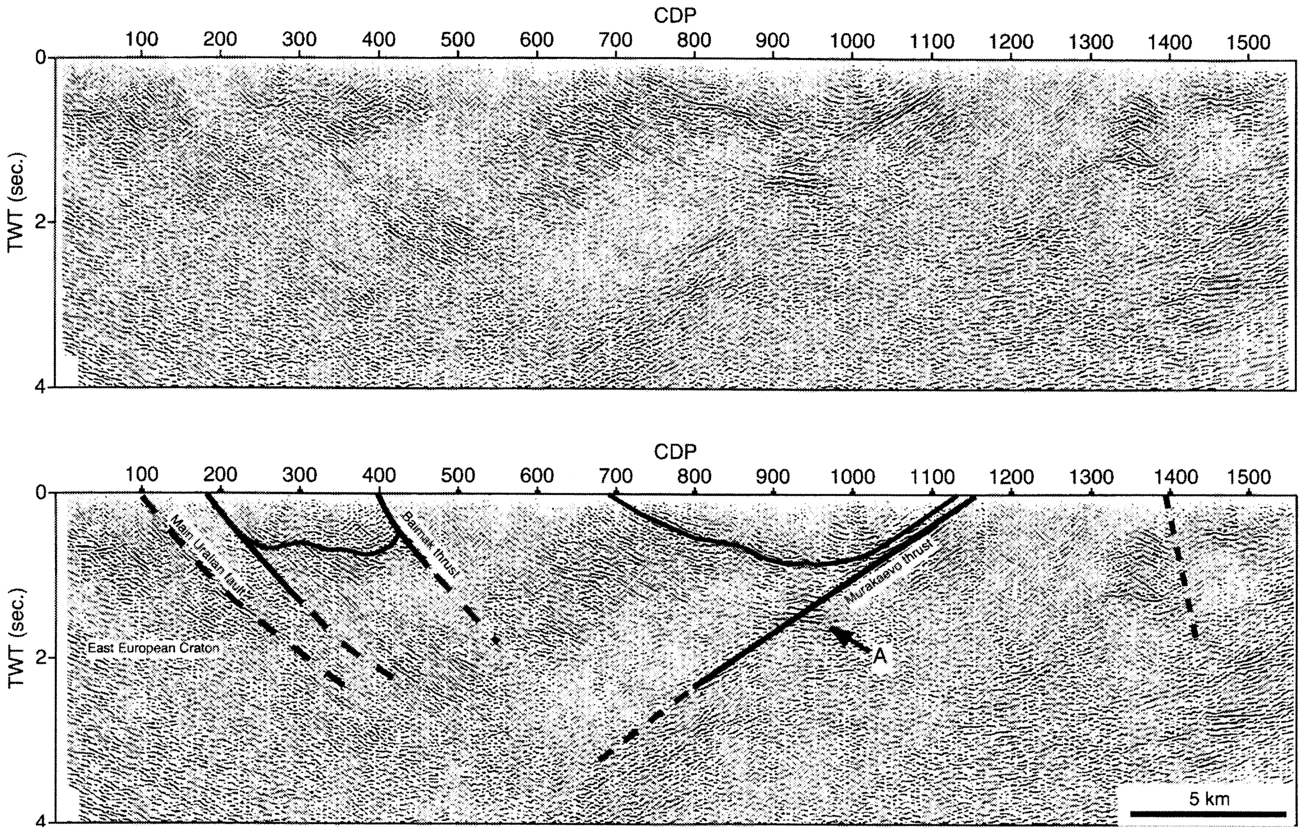

Figure 8. (a) Uninterpreted and (b) interpreted time-migrated portion of the URSEIS vibroseis reflection seismic profile that crosses the westernmost part of the Magnitogorsk arc. The migration velocity used is 5000 m s^{-1}, which gives the best resolved image of the sediments in the uppermost crust. At higher migration velocities the reflections marked A migrate into the hangingwall of the Murakaevo thrust. Acquistion parameters for the profile are given by *Echtler et al,* [1996].

outcrop) and a thickness of several hundred meters. It consists of blocks of the Koltubanian and, possibly, Ulutau Formations, as well as several large blocks of volcanics, possibly the Karamalytash Formation, and limestone. Synsedimentary deformation is less common in the Zilair Formation.

5. Discussion

With the entrance of continental crust into the subduction zone in an arc-continent collision setting, volcanism appears to stop in the accreting arc, and volcanic activity shifts outboard of the collision zone to form a new volcanic front, leaving the extinct volcanic front behind, now in a forearc position (see the Timor-Australia collision [e.g., *Synder et al.,* 1996] or the Papua New Guinea–Australia collision, [e.g., *Cullen and Pigott,* 1989] and Taiwan–Eurasia collision, [e.g., *Teng,* 1990]). Such an evolution appears to have been the case in the southern Urals, where the Irendyk volcanic front ceased activity shortly after the arrival of the continental crust at the subduction zone in the Eifelian. At this time, volcanism shifted eastward to form the east Magnitogorsk volcanic front, which continued activity into the Carboniferous. This shift in the location of volcanism to the east Magnitogorsk volcanic front had significant implications for the deposition and deformation of syncollisional sediments.

In generalized tectonic models of intraoceanic island arc development a forearc basin develops on volcanic or oceanic crust in front of the volcanic edifice [e.g., *Dickinson and Seely,* 1979; *Charvet and Ogawa,* 1994] where it can accumulate a large thickness of arc-derived clastic sediments, cherts, and carbonates [e.g., *Dickinson,* 1995]. The only trace of an intraoceanic forearc basin in the southern Urals is found in the Aktau Formation, which we interpret as the remnant of the forearc basin to the Irendyk volcanic front and which continued to accumulate sediments after arc-continent collision began. The absence of a larger forearc basin in the southern Urals can in part be explained by recent physical modeling of arc-continent collision processes by *Shemenda* [1994], *Chemenda et al.* [1997] and *Tang et al.* [2000] which predict that once continental crust enters the subduction zone at the onset of arc-continent collision, breakup and perhaps the wholesale subduction of the intraoceanic forearc, including the forearc basin, may occur. Such a mechanism was suggested for the southern Urals by *Chemenda et al.* [1997], although the widespread occurrence of the boninite-bearing basalts of the Baimak-Buribai Formation, which is believed to have erupted in a suprasubduction zone setting at the onset of subduction [*Spadea et al.,* 1998], together with the remnant of the Aktau forearc basin, indicates that wholesale subduction of the Magnitogorsk forearc block did not occur. This

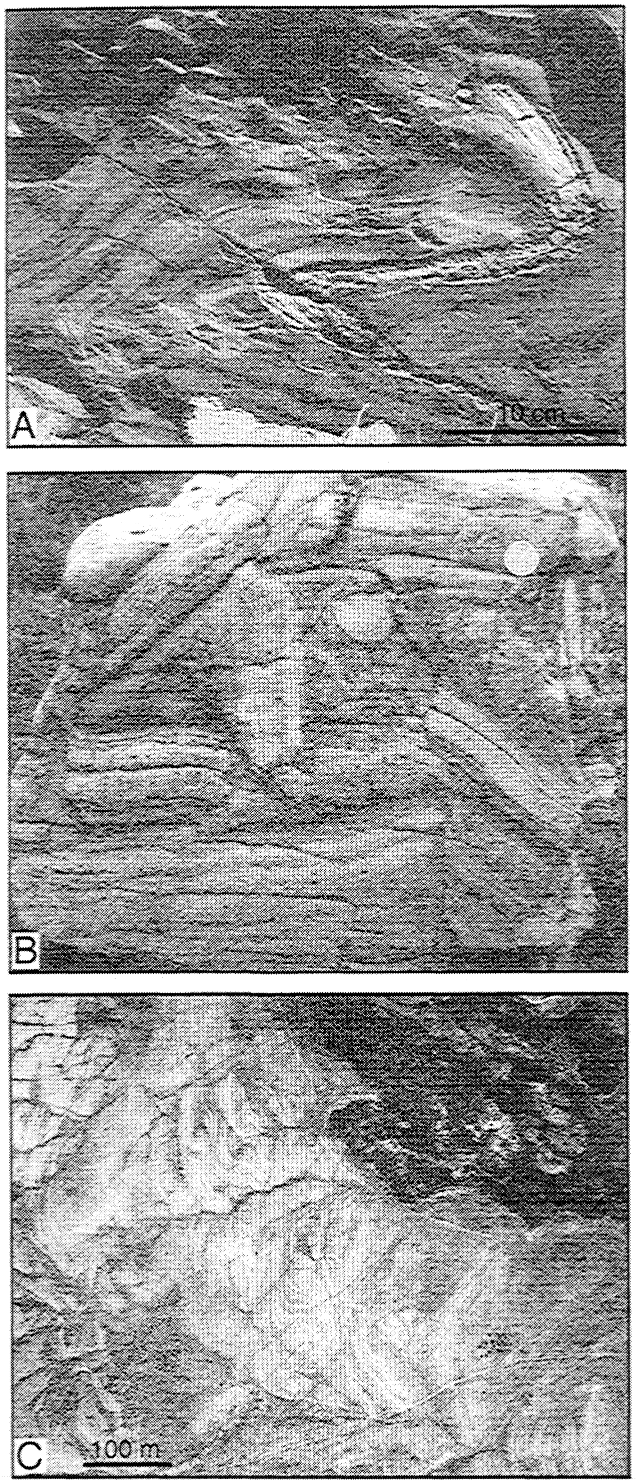

Figure 9. (a) Field photograph of synsedimentary folding in the Bugulygyr jasper, (b) field photograph of a synsedimentary breccia in the Mukas chert, and (c) detail of an air photo showing large-scale slumping. Note that the beds above and below the folded area are not affected by the folds.

does not preclude that subduction erosion of at least part of the forearc did take place, since Zilair Formation sediments within the Main Uralian fault mélange indicates that tectonic erosion was an active process late in the history of the arc-continent collision.

As the arc-continent collision progressed, sediments were increasingly derived from the east Magnitogorsk volcanic front and deposited across the Irendyk arc edifice and, by the late Frasnian, across the subducting East European Craton continental crust to the west, forming a suture forearc basin. The ~5000 m thickness of the sediments in the suture forearc basin suggests that a significant amount of subsidence occurred once the arc-continent collision started. It is difficult to determine what subsidence mechanisms were active (see *Dickinson* [1995] for an overview of this problem), although loading caused by the buildup of the east Magnitogorsk arc massif may have been a contributing factor [e.g., *Lundberg and Dorsey*, 1988]. Whatever the basin-forming mechanism, by the Frasnian a sufficient thickness of sediments had accumulated that they breached a major barrier to the west that appears to have been formed by the Irendyk volcanic front and were deposited on the Aktau Formation and across the subducting continental crust. Prior to this, throughout the Givetian and into the Frasnian, the Aktau forearc basin accumulated sediments in isolation from what was happening to the east. The development of several depocenters in active forearc basins is common [e.g., *Dickinson,* 1995, and references therein], although they appear to be on a much larger scale than those in the Magnitogorsk arc.

The suture forearc basin asymmetry, and especially the thinning and locally onlapping relationships of the suture forearc basin sediments with the volcanic basement-cored anticlines, suggests that synsedimentary fold development was active in the suture forearc basin. For example, the thinning of the Koltubanian and Zilair Formations over the Karamalytash anticline indicates that the fold grew during the deposition of these units. The growth development with respect to sedimentation in the Uzyan synform is not clear. Although deformation, especially faulting, during sedimentation in a forearc is widespread [see *Dickinson,* 1995, and references therein], synsedimentary growth folding does not appear to be common. The Karamalytash anticline therefore provides a rare example of synsedimentary folding that indicates that growth folding was an active upper crustal process during arc-continent collision in the southern Urals.

The internal structure of the suture forearc basin displays an irregular and nonlinear juxtapositon of anticlines and synclines suggestive of inversion of a preexixting fault system (for example, see *Cooper and Williams* [1989] and the examples therein). However, it is not clear if the involvement of the volcanic substratum and the structural juxtaposition of anticlines and synclines in the Magnitogorsk suture forearc basin is related to inversion of the trench-parallel faults commonly developed in the forearc region of volcanic arcs [e.g., *Lallemand et al.,* 1999; *Chemenda et al.,* 2000] or to the development of a new, irregular fault system during the collision. The Baimak and Murakaevo thrusts are both deep-seated structures (e.g., Figure 8) that are good candidates for having been trench-parallel faults that were active during the evolution of the arc and which were active as thrusts during the final stages of the arc-continent collision. Whatever its early kinematic history, during the late stages of the arc-continent collision the Baimak thrust appears to represent a failed attempt to subduct the forearc block [e.g., *Chemenda et al.,* 1997].

The widespread occurrence of synsedimentary deformation in the sediments of the Middle to Late Devonian suture forearc basin indicates deposition in an active tectonic environment. Synsedimentary folding and brecciation, slumping, and olistostrome formation appear to have been especially widespread during the Frasnian and Famennian, during deposition of the Koltubanian Formation. This has been interpreted by *Brown et al.* [1998] and *Brown and Spadea* [1999] as recording increased basin instability caused by seismic activity related to the arrival of the full thickness of the East European Craton continental crust at the subduction zone. The Biyagodinskay olistostrome is an especially spectacular example of olistostrome formation in a forearc position that may record a large, and possibly catastrophic, event in the rock record. (Note that the sediment slump that caused the 1998 Papua New Guinea tsunami [*Tappin et al.,* 1999] was of the order of 5 x 5 km and ~300-450 m thick (D. Tappin personal communication, 2000) and was generated by a magnitude 7.0 earthquake. The tectonic setting of the Papua New Guinea slump was the same as that of the Biyagodinskay olistostrome.) The Jarlykapovo Formation, and in particular the Bugulygyr jasper, records synsedimentary deformation that is found throughout the basin. The timing of synsedimentry deformation in the Jarlykapovo Formation is not clear. It may have occurred prior to, during, or after deposition of the overlying sediments. If it was during or after their deposition, then the forearc basin sediments, in part or in their entirety, are detached from the volcanic basement along the Jarlykapovo Formation and Bugulygyr jasper, and the whole suture forearc basin may therefore have slid intermittently along this synsedimentary detachment.

6. Conclusions

The Magnitogorsk volcanic arc can be divided into the Irendyk and east Magnitogorsk volcanic fronts that were active during intraoceanic island arc formation and during arc-continent collision, respectively. Two phases of forearc basin development can also be recognized, a late Lower to Middle Devonian intraoceanic to collisional forearc basin to the Irendyk volcanic front (represented by the Aktau Formation) and a Middle Devonian to Lower Carboniferous suture forearc basin to the east Magnitogorsk volcanic front. Structural mapping, combined with reflection seismic profiling, shows that these basins are only weakly deformed by open, nonlinear, volcanic basement-cored synsedimentary folds and by minor thrusting that involves the volcanic basement. Synsedimentary deformation, slumping, and olistostrome development were common throughout the suture forearc basin history but were especially widespread during the Late Devonian.

From the detailed geological descriptions provided we would like to emphasize the very well preserved state of the arc-continent collision zone in the southern Urals. The state of preservation allows a direct comparison to be made between geological features in the Magnitogorsk arc and arcs in several active arc-continent collision zones in the southwest Pacific. A number of upper crustal processes that have been interpreted from these active arc-continent collisions can therefore be applied to the interpretation of the Paleozoic rock record in the southern Urals. This is in contrast to other Paleozoic orogens (and even elsewhere in the Urals) where, to the best of our knowledge, arc-continent collision zones are generally strongly deformed, metamorphosed, fragmented, intruded, and deeply eroded, making the determination of upper crustal processes difficult if not impossible. The southern Urals therefore provide an excellent example that suggests that a number of upper crustal arc processes that are currently active in arc-continent collision and which can be correlated spatially from one subduction system to another may also be correlated temporally, at least as far back as the Middle Paleozoic. Furthermore, it seems safe to say that the rates at which these processes occurred for the entire arc-continent collision system in the southern Urals [*Brown et al.,* 2000; *Brown and Spadea,* 1999], as well as the resultant crustal architecture [*Brown et al., 1998; Alvarez-Marrón et al.,* 2000], are much the same as those determined from active systems.

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