

# Placer Tin Ores from Mt. Cer, West Serbia, and Their Potential Exploitation during the Bronze Age

A. Huska,<sup>1,2,\*</sup> W. Powell,<sup>1,2</sup> S. Mitrović,<sup>3</sup> H. A. Bankoff,<sup>3</sup> A. Bulatović,<sup>4</sup> V. Filipović,<sup>4</sup> and R. Boger<sup>1,2</sup>

<sup>1</sup>Department of Earth and Environmental Sciences, Brooklyn College, City University of New York, Brooklyn, New York

<sup>2</sup>Earth and Environmental Sciences Program, Graduate Center, City University of New York, New York, New York

<sup>3</sup>Department of Anthropology and Archaeology, Brooklyn College, City University of New York, Brooklyn, New York

<sup>4</sup>Arheološki Institut, Srpska Akademija Nauka i Umetnosti, Belgrade, Serbia

## Correspondence

\*Corresponding author; E-mail:  
ahuska@gc.cuny.edu;  
slobodanmitrovic@gmail.com

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Tin is a rare metal that is essential for making bronze, the defining technology of the Bronze Age. The source(s) of tin for Aegean bronze is undetermined but several small Bronze Age tin mines have been documented in the circum-Aegean region. The discovery of Bronze Age archaeological sites in West Serbia near a tin placer deposit on the flanks of Mt. Cer led to an investigation of this site as a potential additional Bronze Age tin mine in the region. Geochemical prospecting of stream sediments flowing from Mt. Cer allowed for categorization of streams based on relative tin grade. Tin grade is highest in the Milinska River, a likely combination of a broad catchment area with multiple ore-bearing tributaries, and a topographic profile that favors the accumulation of placer deposits. A survey of cornfields along the southern pluton margin discovered archaeological sites spanning the Neolithic to the Iron Age. Unlike older and younger sites, those of the Bronze Age were found only along the Milinska and Cernica Rivers where placer tin grades are highest, but appear to be absent where tin is scarce or absent. This suggests that these sites were associated with the exploitation of the tin ore. © 2014 Wiley Periodicals, Inc.

## INTRODUCTION

The European Bronze Age (2200–1050 B.C.E.) was a period in which bronze was the material predominantly used to make functional parts of implements, and signifies a key stage in technological evolution. Bronze is made by alloying copper with tin, and although copper is present in many places, tin is rare. Thus, tin became fundamental in economic production and social reproduction. The majority of societies had neither copper nor tin, and as a result, there was an increase in exchange systems along long-distance trade routes, including those in western Serbia. The source(s) of tin for Aegean bronze is undetermined but several small Bronze Age tin mines have been documented in the circum-Aegean region. Subeconomic tin deposits occur within the Alpine Orogen in Eastern Europe and the Middle East, and include at least two cassiterite-bearing deposits that were mined during the Bronze Age: Kestel in the Taurus Mountains

of Turkey (Yener et al., 1989; Yener & Vandiver, 1993; Willies, 1995) and Deh Hosein in the Zagros Mountains of Iran (Nezafati et al., 2009).

Tin occurrences in West Serbia have been discussed as a possible additional source of Bronze Age tin (e.g., Muhly, 1985; Penhallurick, 1986; McGeehan-Liritzis & Taylor, 1987; Durman, 1997; Harding, 2000). Maps documenting the approximate distribution of placer ore south of Mt. Cer were presented in the archaeological literature by Durman (1997). However, no systematic survey had been conducted to locate archaeological sites associated with these ores, or to correlate them with the character and distribution of tin ore in the streams that flow from Mt. Cer. The discovery of Bronze Age archaeological sites in West Serbia near the tin placers on the flanks of Mt. Cer led to further investigation of this region (Bankoff et al., 2011). The primary purpose of this study was to document both the relative distribution of tin ore and the location of archaeological sites adjacent to Mt. Cer, and to determine if the two correlate (Bankoff et al., 2013). Here we report the results of geochemical and field archaeological surveys in the region, and present evidence

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that Bronze Age sites may have been situated to exploit these placer tin ores.

## TIN IN EUROPE AND SOUTHWEST ASIA

Tin (Sn) is a rare metal with an average crustal concentration of 1.7 parts per million (ppm) (Rudnick & Gao, 2003). Primary tin deposits are associated exclusively with granitic rocks of a limited compositional range and derivational environment: ilmenite series, peraluminous ( $\text{Al}_2\text{O}_3 > \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$ ), S-type granites that are produced by the partial melting of metasedimentary rocks and emplaced in continental orogenic settings (Ishihara, 1981; Pollard, 1995; Černý et al., 2005). Such granites of crustal origin contain alumino-silicate minerals such as muscovite, biotite, corundum, topaz, garnet, and may contain Ta-rich minerals such as microlite  $[(\text{Na},\text{Ca})_2\text{Ta}_2\text{O}_6(\text{O},\text{OH},\text{F})]$ , and columbite  $[(\text{Fe},\text{Mn})(\text{Nb},\text{Ta})_2\text{O}_6]$  (Pollard, 1995; Černý et al., 2005).

Cassiterite ( $\text{SnO}_2$ ) is the primary tin ore mineral. Being dense (6.9 g/cm<sup>3</sup>), hard (6–7 Mohs hardness), and chemically stable under surface conditions, detrital cassiterite may accumulate and concentrate in sediments downstream from weathered bedrock ore sources (placer deposits). Fluvial placers are deposited in rivers and streams, where energy levels decrease downstream and down-gradient. In such deposits, cassiterite concentrations are usually confined to coarse sand and gravel (Garnett & Bassett, 2005). Other heavy minerals that are commonly associated with tin placers include garnet, zircon, ilmenite, rutile, magnetite, monazite, topaz, columbite, and tantalite (Garnett & Bassett, 2005). The fine-grained and unconsolidated nature of placer deposits allow for relatively easy ore extraction with primitive mining technology such as panning and sluicing.

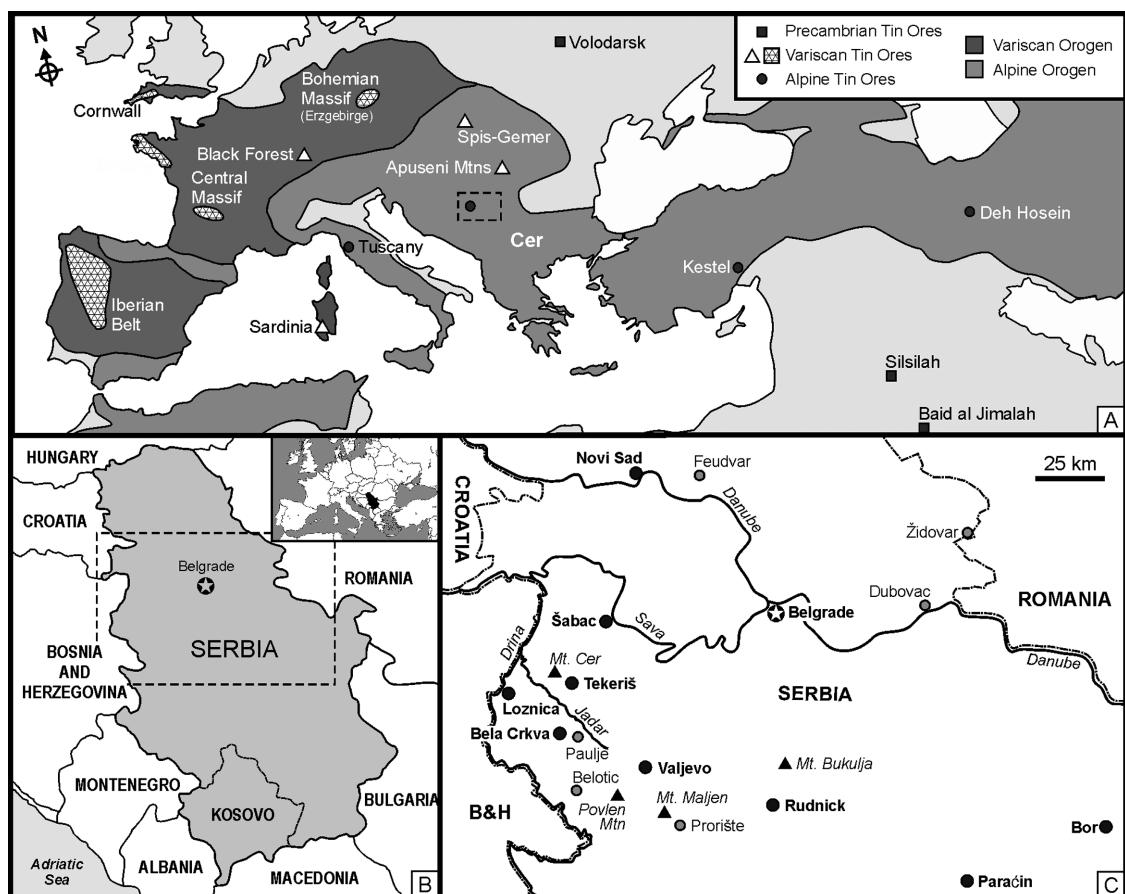
The largest occurrences of tin ores in Europe are found in the ores of Cornwall, the Iberian Belt, and Central Europe, including the Erzgebirge mountains on the border of the Czech Republic and Germany (Figure 1A). All of these major deposits are associated with postorogenic highly evolved peraluminous granites related to the Late Palaeozoic Variscan Orogeny. Details regarding exploitation of the European tin sources in the latter stages of the Bronze Age (ca. 1600–1200 B.C.E.) are uncertain. Medieval mining of deposits of the Erzgebirge has been documented (Taylor, 1983), and these ores appear to have supplied tin for the bronzes of the Central European Bronze Age Únětice and Tumulus cultures (Bouzek et al., 1989; Bartelheim & Niederschlag, 1998). The geographic correlation of the Erzgebirge ores and Unetice culture, along with its characteristic metal objects, suggests that the tin for these artifacts was mined locally, possibly from easily extractable fluvial placer cassiterite deposits,

given that no Bronze Age bedrock mines have been documented (Bouzek et al., 1989). Prehistoric streaming for alluvial tin leaves little or no trace of extraction activities at the mine site (Thornycraft et al., 1999, 2004). Although densely settled areas do not overlap with the distribution of alluvial tin in general, at least one “camp” has been documented along a tin-bearing river (Bouzek et al., 1989).

Smaller subeconomic tin deposits occur within the younger Alpine Orogen in Eastern Europe and the Middle East. This Mesozoic orogenic belt that extends from Spain to Southeast Asia formed as a result of the suturing of Gondwana-derived continental fragments with Eurasia. At least two Alpine tin-bearing deposits have been interpreted to have been mined during the Bronze Age, Kestel in the Taurus Mountains of Turkey, and Deh Hosein in the Zagros Mountains of Iran (Figure 1A).

The Deh Hosein tin–copper deposit consists of more than 75 large open depressions along mineralized horizons adjacent to the Astaneh pluton (Nezafati et al., 2009). Charcoal that has a calibrated radiocarbon date of 1775–1522 B.C.E. occurs in an intermediate layer of the mine (Nezafati et al., 2009). Lead isotope ratios of Deh Hosein ores were compared with bronze artifacts. Most analyzed Luristan objects, as well as some from the southern Persian Gulf, Mesopotamia and Jordan, were isotopically compatible with these ores (Nezafati et al., 2009). This evidence suggests Deh Hosein ores were exploited as early as the third millennium B.C.E., and supplied tin to the ancient civilizations of Iran and Mesopotamia (Nezafati et al., 2009).

The tin deposits at Kestel lie within the Niğde Massif metamorphic core complex, a polymetallic Cu-Pb-Zn-Ag-Au ore camp (Willies, 1995). Cassiterite mineralization is concentrated within the Üç Kapılı granitoid intrusion in association with quartz–hematite veins, as minor occurrences in pegmatites- and tourmaline-bearing quartz veins, and as secondary alluvial placer cassiterite deposits in three nearby rivers (Yener et al., 1989; Yener & Vandiver, 1993; Willies, 1995; Lehner et al., 2009). Radiocarbon analysis from charcoal samples at Kestel date the mine at 2874–2133 B.C.E., confirming its exploitation in the Early Bronze Age (Yener et al., 1989). Analysis of rim sherd of Göltepe crucibles show cassiterite on the interior surfaces, suggesting that the crucibles were used in reduction firing of the tin from Kestel (Yener & Vandiver, 1993; Earl & Özbal, 1996). Although Sharp and Mittwede (1994) suggest that tin ore concentrations were too low for effective concentration, and that tin traces in crucibles may have been a residue associated with lead smelting, subsequent trace element studies have documented elevated tin concentrations in metalliferous residues on crucible surfaces (Yener et al., 2003; Lehner et al., 2009).



**Figure 1** (A) Tin localities in Europe and Southwest Asia and (B) map of Serbia. (C) Map of study area. Black dots correspond to modern cities; gray dots correspond to archaeological sites.

Furthermore, experimental work by Earl and Özbal (1996), and Laughlin and Todd (2000) determined that simple heating and grinding of the hematite-rich ore allowed for effective separation of cassiterite from waste material, thereby making the low-grade Kestel ore viable.

Most archaeological studies that deal with tin sources for Bronze Age Aegean cultures (e.g., Muhly, 1985; Gillis et al., 2003) stress the presence of tin ore sources in Cornwall, the Iberian Peninsula, or Central Europe. Brittany, Sardinia, and Tuscany are mentioned also, but it is unproven that any of these sources were utilized during the Bronze Age (Muhly, 1985; Penhallurick, 1986; see also Taylor, 1983). Citing available literature, Harding (2000: 201) suggested that parts of West Serbia are underresearched, "and could prove to be extremely important" as sites of Bronze Age tin mining.

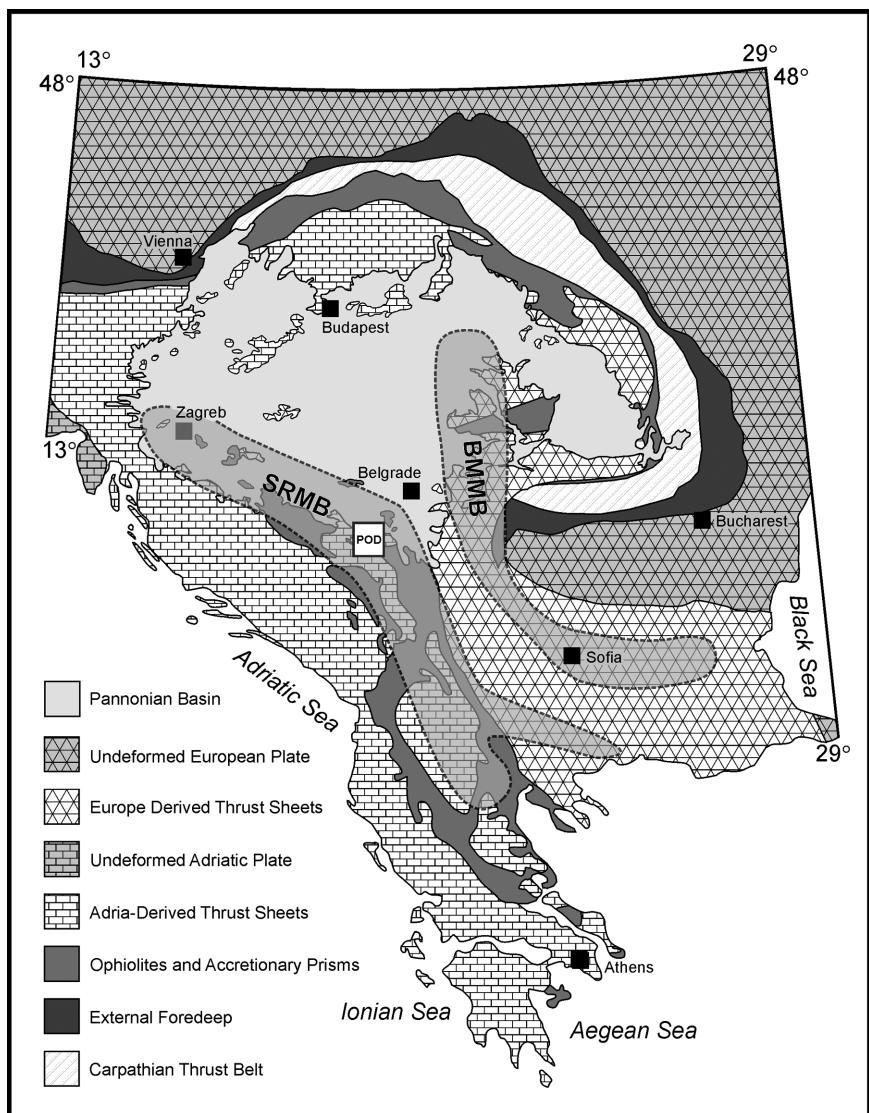
Tin has been known to occur in West Serbia since the mid-20th century, and has been discussed as a possible source of Bronze Age tin (e.g., Muhly 1985; Penhallurick, 1986; McGeehan-Liritzis & Taylor, 1987; Durman, 1997; Harding, 2000). Mining companies and national geologi-

cal surveys have conducted feasibility studies of the placer deposits (e.g., Tomić, 1991; Živković, 1996). Based on a 1000 m<sup>3</sup> bulk sample, Tomić (1991) projected that the alluvial deposits of the Lešnica and Cernica Rivers contain approximately 2700 tons of tin within 13 million tons of gravel.

Kestel and Deh Hosein demonstrate that small Sn deposits that would be considered subeconomic by modern standards were potentially exploitable for bronze production if the ore was extractable by primitive mining techniques, and deposits were situated near trade routes. Similarly, the relatively small Alpine tin ore deposits of West Serbia could have been exploited for local bronze production as well as trade along the Balkan Peninsula, thereby contributing to the total bronze production of the region.

## **GEOLOGY OF WEST AND CENTRAL SERBIA**

Serbia (Figure 1B) lies within the Dinaride segment of the Alpine–Balkan–Carpathian–Dinaride orogenic belt that

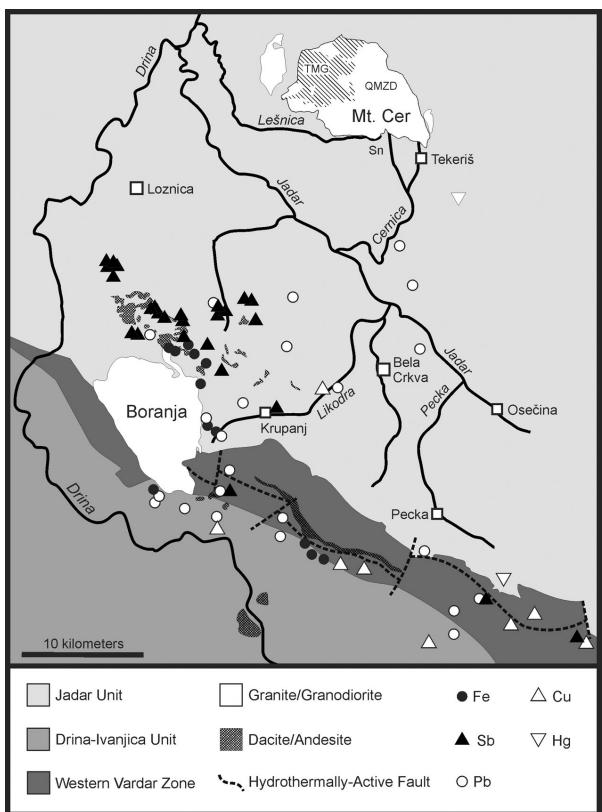


**Figure 2** Metallogenic Belts and Units of the Dinaride segment of the Alpine–Balkan–Carpathian–Dinaride orogenic belt.

formed due to the closure of the Tethys Ocean and its marginal seas in the Late Cretaceous and subsequent rotation and transcurrent faulting of the Adria microplate (Karamata, 2006). Cretaceous–Tertiary convergence between Gondwana and Eurasia and the continuous subduction of Mesozoic oceans resulted in two distinct tectonic and metallogenic belts in the region (Heinrich & Neubauer, 2002) (Figure 2). The Banatitic Magmatic and Metallogenic Belt is a 750 km long, L-shape band from Romania and Serbia to Bulgaria (Berza et al., 1998; Heinrich & Neubauer, 2002) that includes the world-class Cu-Au deposits of the Bor region, Eastern Serbia with >20 million tons Cu (Herrington et al., 1998). The Serbomacedonian-Rhodope metallogenic zone extends

from the Bosnian Dinarides, through the Rhodopes, and to Thrace (Figure 2). It hosts volcanogenic and vein-type Pb-Zn deposits, porphyry Cu-Au-Mo, and epithermal Au mineralization (Heinrich & Neubauer, 2002; Neubauer, 2002).

The Podrinje Ore District of West Serbia lies within the Serbomacedonian-Rhodope metallogenic zone (Figures 2 and 3). The region is underlain by the Adria-derived Drina-Ivanjica thrust sheet and Jadar Block, as well as the ophiolitic Western Vadar Zone. These units were intruded by two phases of felsic magmatism: (1) Oligocene calc-alkaline granitoids that are associated with postcollisional transpression; and (2) Miocene granitoids that are related to postcollisional extension that was



**Figure 3** Geological map of the Podrinje Ore District. Compiled from Zavod za geološka i geofizička istraživanja (1971), Mojsilović et al. (1975), and Kubat et al. (1976).

concurrent with the opening of the Pannonian Basin (Cvetković et al., 2007; Lorinczi & Houseman, 2010; Koroneos et al., 2011). The Oligocene I-type, metaluminous Boranja granodiorite pluton (Figure 3) is spatially associated with a suite of polymetallic ore deposits that zone outwards from Fe–Cu skarns adjacent to the pluton, to intermediate Pb–Zn deposits, a wide zone of Sb mineralization, and an outermost zone of fluorite (Karamata et al., 1994; Pamić et al., 2002; Palinkaš et al., 2008). Ore minerals include magnetite, chalcopyrite, stibnite, Sb-oxides, galena, sphalerite, and pyrite (Palinkaš et al., 2008).

The Miocene S-type granitoids of Mt. Cer and Mt. Kulja (approximately 50 km to the southeast) (Figure 1B) lie on the southern margin of the Pannonian Basin in west and central Serbia, respectively, and are both associated with Sn–U–Nb–Ta mineralization (Cvetković et al., 2007; Koroneos et al., 2011). The Mt. Cer pluton (Figure 3) is an E–W trending laccolith covering an area of 60 km<sup>2</sup> within the Jadar Block (Karamata et al., 1994; Koroneos et al., 2011). The bulk of the pluton is composed of two compositional phases: (1) metaluminous, I-type quartz monzonites to quartz mon-

zodiorites (QMZD); and (2) peraluminous, S-type, two-mica granite (TMG) (Figure 3). The QMZD is composed of quartz, plagioclase, biotite, hornblende, with accessory titanite, allanite, magmatic epidote, zircon, apatite, rutile, magnetite, and ilmenite as accessory minerals (Koroneos et al., 2011). The TMG consists of quartz, K-feldspar, plagioclase, muscovite, and biotite, with garnet, tourmaline, apatite, rutile, and zircon as accessory minerals (Koroneos et al., 2011). Tourmaline granite and pegmatites occur as small bodies and dikes (Zavod za Geološka i Geofizička Istraživanja, 1971; Mojsilović et al., 1975).

Bedrock cassiterite mineralization in Mt. Cer has been described by Janković (1990), as reported by Palinkaš et al. (2008). Cassiterite is associated with pegmatites and greisens. The pegmatite bodies are small and vein-like, with quartz, microcline, albite, plagioclase, and some muscovite, biotite, beryl, tourmaline, zircon, and apatite as the main minerals, and cassiterite, columbite, rutile, sphalerite, monazite, and chalcopyrite as accessory. Greisens are quartz–muscovite and quartz–muscovite–tourmaline–fluorite types, with cassiterite, tantaloniobates, bismuthinite, fluorite, and scheelite as constituent minerals. Secondary alluvial deposits of cassiterite have been documented at the base of the pluton in the Lešnica and Cernica River valleys (Durman, 1997; Monthel et al., 2002; Palinkaš et al., 2008). The tin-bearing granites of West Serbia display geological and metallogenetic similarities to other Alpine tin-bearing localities in Turkey and Iran, where evidence for Bronze Age mining and smelting has been documented. The geographic proximity of Serbian tin ores to numerous small copper deposits (Figure 1B), including Rudnik and the deposits of the Povlen mountains, adjacent to the tin ores of Kulja and Mt. Cer, respectively, as well as regional proximity to enormous copper sources such as Bor in eastern Serbia could have allowed for significant bronze production in the region.

## BRONZE AGE CULTURES OF WEST SERBIA AND NEIGHBORING REGIONS

A feasible culture historical-chronological system for the former Yugoslav states has long been established (Garašanin, 1983a, 1983b, 1983c, 1983d, 1983e, 1983f; Vinski-Gasparini, 1983; Zотовић, 1985). The relationships between this system and the periodizations of archaeological cultures of neighboring regions have also been explored (Tasić, 1984, 2001, 2002; Bankoff & Greenfield, 1985; Ehrich & Bankoff, 1992;), and technological and stylistic properties of the material culture of individual groups have been documented (Garašanin, 1973; Tasić, 1983). Linguistic evidence has been compared with the

archaeology to delve into possible origins of Bronze Age cultural groups (Čović, 1983), and typological series of artifacts have been designed (Benac, 1983). Thus, a solid basis for detailed archaeological research has existed for decades.

There are differences between sites in the northern plains of the Vojvodina (North Serbia to the Hungarian-Romanian border) and mountainous central and southern Serbia. These are detailed in the literature: relative numbers of settlements (Garašanin, 1973, 1983a, 1983b, 1983c, 1983d, 1983e, 1983f, 1983g, 1983h; Koledin, 2004), differing settlement types (northern tells, e.g., Židovar [Gavela, 1953; Lazić, 1997], Feudvar [Hänsel & Medović, 1998], and southern hill fort settlements like Ljuljaci [Bogdanović, 1986; Bulatović & Stanković, 2012]), and cremation under tumuli (Garašanin, 1973, 1983a, 1983b, 1983c, 1983d, 1983e, 1983f, 1983g, 1983h; Lazić, 2007), or in "flat urnfields," are more common to the north of these rivers (Tasić, 1983, 2003). Nevertheless, these groups exhibit general similarities in the organization of subsistence activities (Bankoff & Greenfield, 1985; Guma, 1995). This allows one to characterize them as regional parts of the same tradition (Harding, 2000; Sherratt, 2004; Kristiansen & Larsson, 2005; Kohl, 2007), and perhaps even as belonging to the "Bronze Age world system" (Sherratt, 1993, 2004; Kristiansen & Larsson, 2005). Although preference for local ceramic decorative motives and certain ceramic forms exist, pottery, metal, and other portable items of the respective groups speak of contact and interaction. On closer inspection, connections may be unstable and often shifting (Muhly, 1985; Pare, 2000; Tasić, 2002; Gillis et al., 2003).

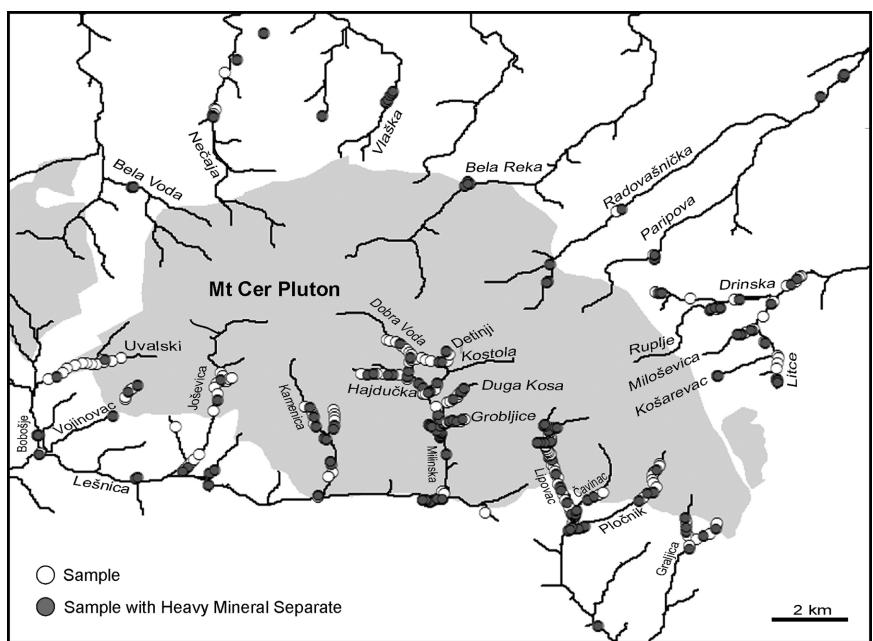
Despite its proximity to tin sources, habitation sites of Loznica County and the Jadar Valley of West Serbia have remained largely unexplored archaeologically. Interest in this area dates to the 1890s, but has been directed exclusively toward the excavation and cultural connections of the tumulus (mound) graves in the vicinity of Belotić and Bela Crkva (Figure 3) and the south of the Jadar region, especially around Čačak. In Serbian culture historical terms, the Maljen slopes around Valjevo and the Jadar River are the heartland of the Belotić-Bela Crkva Group in the Early Bronze Age, while the Middle to Late Bronze Age in the same area is represented by the so-called West Serbian Vatin culture (first mentioned in Garašanin & Garašanin, 1958). Ceramics, especially urn ossuaries, their covers, and associated fineware two-handled "beakers" (Garašanin 1983d; Canić-Tešanović & Gligorić, 2001) stylistically and typologically are very close to those of the Vatin culture of northeastern Serbia (Vojvodina). The variety of objects made of bronze and the presence of (assumed Baltic) amber in tumulus

burial contexts, especially in the Drina and Jadar Valleys (Palavestra, 1993; Lazić, 2007) further distinguish West Serbian tumulus graves in the later Bronze Age (Madas, 1990; Canić-Tešanović & Gligorić, 2001; Filipović, 2008). Of note are the bronze pins, some up to a meter in length, found in the West Serbian graves clustered around the hills south of Mt. Cer. Thirteen of these pins have been recorded, and while they have some parallels to later Central European finds (Novotna, 1980), they are unique to this region (Vasić, 2003). Another idiosyncratic characteristic of the grave mounds of the Jadar, and West Serbia in general, is the presence of fire installations found inside the burial circle (Garašanin, 1983d; Zotović, 1985; Filipović et al., 2008).

The north slopes of Mount Maljen and the Jadar Valley (Figure 1B) are the densest in Bronze Age remains (71 M/LBA tumuli, a total of 86 graves [Lazić, 2007; Filipović, 2008]). In the last two decades some 20 prehistoric tumuli dating to the Late Bronze Age were excavated at burial areas in Prorište and Paulje (Figure 1B) alone (Madas, 1990; Canić-Tešanović & Gligorić, 2001; Filipović, 2008; Filipović et al., 2008). Cremation, the preferred treatment of the deceased, does not lend itself to demographic research (Garašanin, 1983a, 1983b, 1983c, 1983d, 1983e, 1983f, 1983g, 1983h; Tasić, 1983; Vranić, 2002; Lazić & Mikić, 2007; cf. O'Shea, 1996). Relative chronology, given the dearth of radiocarbon dates for this area, limits West Serbian Vatin burial mound cemeteries to about 1500–1150 B.C.E. (cf. Forenbaher, 1993; Gogaltan, 1998, 1999 for dates from neighboring areas).

## METHODS

Archaeological survey focused on the Milinska and Lešnica River valleys, and the adjacent terraces. The survey utilized a team of 6–10 field walkers. The summer ground cover made artifacts and architectural traces difficult to see under grassy and stubble-filled fields. Thus, the sample area chosen for survey consisted of all accessible cornfields along the course of the river valleys from which geochemical prospecting samples had been taken. This amounted to approximately 1% of the total Jadar area. Although not strictly randomly determined, this strategy took advantage of the paucity of vegetation under the crop cover, and the assumption that the location of the modern cornfield was independent of former occupation sites. Cornfield transects were walked along rows, artifactual material was collected, and coordinates of concentrations recorded by GPS. The collected material was washed and examined in the field laboratory.



**Figure 4** Geochemical sample location map.

Following standard geochemical exploration techniques, reconnaissance samples were taken from the mouths of each tributary flowing from the main body of the Mt. Cer pluton to determine the extent of placer tin mineralization. On the southern side of the pluton, a minimum of five samples were taken from the mouths of each tributary flowing into the Lešnica (Milinska Reka, Kamenica, Joševica, and Bobusje) and Cernica (Čavinač, Pločnik, and Lipovac) Rivers (Figure 4). Similar sampling on the northern side focused on the tributaries of the Drinska (Ruplje, Miloševica, Košarevac, Litica), and other streams along the northern margin (Bela Voda, Nećaja, Vlaška, Bela Reka, Radovašnica, and Paripova) (Figure 4). Each sample was dried, sieved, weighed, and processed and analyzed for tin using an Olympus Innov-X Delta Classic DC-4000 (with 3-Beam Soil software) portable X-ray fluorescence (XRF) handheld apparatus with a tin detection limit of 150 ppm. For each tributary from which initial sampling yielded tin values below the detection limit, upstream sampling (~100 m spacing) near the granite contact was conducted to confirm the absence of cassiterite. For each tributary determined to be tin-bearing at its mouth, extensive upstream sampling of the tributary and its secondary tributaries was conducted to establish in which watershed(s) bedrock tin sources outcrop.

A total of 385 samples (Figure 4) of river sand (approximately 1 kg each) were dried and sieved into four size fractions: gravel (>2 mm), very coarse sand (>850 µm),

coarse sand (850–420 µm), and finer sediments (<420 µm). Each size fraction was weighed and analyzed for tin with XRF. The finer sediment fraction (<420 µm) from a subset of 179 samples was further subdivided and sieved into three additional size fractions: medium sand (420–250 µm), fine sand (250–125 µm), and very fine sand to clay (<125 µm), and each size fraction was reanalyzed for tin by XRF to determine if there was an optimal size fraction for tin analysis.

A total of 175 heavy mineral separates ( $>2.89 \text{ g/cm}^3$  using sodium polytungstate) were prepared from the coarse sand fraction, with a minimum of three samples from each discrete watershed within the Mt. Cer pluton (Figure 4). The coarse sand fraction was used because separation by heavy liquid was more efficient, and yielded grains large enough for subsequent hand-picking for scanning electron microscopy (SEM) analysis. Heavy mineral separates were reanalyzed for tin. The purpose of this phase of sampling and tin analysis was to document which streams carry cassiterite and the relative abundance of tin in each river, rather than to determine the absolute concentration of tin in any given sample (i.e., ore grade).

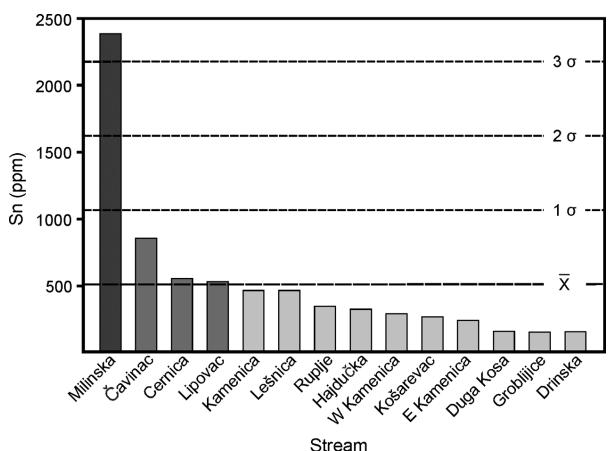
A subset of 65 heavy mineral separates, which included representative samples from each stream and all samples with  $>150 \text{ ppm Sn}$ , were subdivided into five fractions using a Frantz isomagnetic separator: a 0.4 A garnet-dominated fraction; a 0.5 A hornblende-dominant fraction; a 0.7 A fraction containing a varied assemblage of

minerals including epidote, tourmaline, and staurolite; a 1.0 Å fraction composed mainly of composite grains; and a nonmagnetic titanite-dominant fraction in which cassiterite concentrates. Minerals in each magnetic fraction were identified based on composition, determined by SEM/energy-dispersive spectroscopy (SEM-EDS) analysis using a Hitachi TM-1000 SEM with a SwiftED energy-dispersive X-ray spectrometer. SEM-EDS analyses confirmed the presence of cassiterite.

To determine the approximate grade of tin ore that could be extracted from the richest ore localities, composite bulk samples were obtained from large sandbars from two locations: (1) three sample sites at the bend in the Milinska River, and (2) three sample sites in the Cernica River downstream of the confluence with the Pločnik River (Figure 4). Approximately 10–15 kg of sand from each sample site was wet-sieved to remove grains larger than coarse sand and fed through a compact stream sluice (approximately 1.25 m long and 0.25 m wide). The sluice concentrate was passed through the sluice a second time to further concentrate the ore. The final sluice concentrate was sieved into three size fractions (very coarse sand, coarse sand, and finer sediments). The finer two fractions were processed further with sodium polytungstate. All concentrates from a given site were amalgamated to produce a bulk concentrate for each of the two rivers to approximate the modern ore grade at these sites.

## RESULTS

From the complete set of sand samples ( $n = 385$ ), only three samples (all within the  $<420 \mu\text{m}$  size fraction) yielded detectable tin when analyzed by XRF. Samples were further subdivided into medium sand (420–250  $\mu\text{m}$ ), fine sand (250–125  $\mu\text{m}$ ), and very fine sand to clay ( $<125 \mu\text{m}$ ) based on the findings of Fletcher and Loh (1996), who noted that placer tin values are most consistent in the silt and fine sand fraction (63–125  $\mu\text{m}$ ). Of the 179 samples chosen for further sieving, three samples originally considered to be tin-barren in the  $<420 \mu\text{m}$  size fraction returned detectable Sn values (one in the 420–250  $\mu\text{m}$ , two in the 250–125  $\mu\text{m}$  size fraction). Thus, the finest sediment fraction returns the most robust results. However, the ore grade present currently in Mt. Cer streams is insufficient for effective geochemical prospecting based on grain size alone, regardless of the size fraction used. Simple sluicing increases tin concentration by an order of magnitude. The  $<420 \mu\text{m}$  fraction of sluice concentrates is consistently more enriched in tin than the medium and coarse sand fractions, consistent with the findings of Fletcher and Loh (1996).

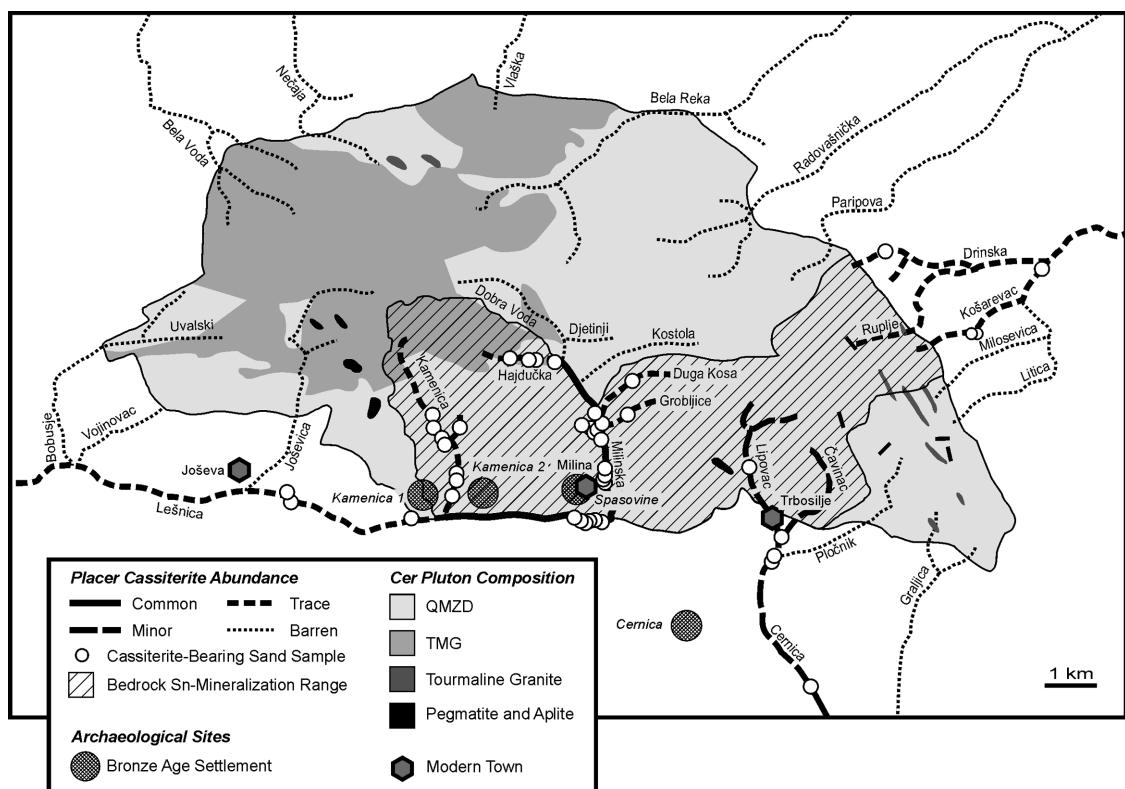


**Figure 5** Classification of streams based on relative tin concentrations in the heavy mineral fraction of sand. Trace—less than the mean; Common—less than one standard deviation above the mean; Abundant—greater than one standard deviation above the mean.

Streams were categorized with respect to tin concentrations based upon tin values returned from 48 cassiterite-bearing heavy mineral separates (>150 ppm): (1) Barren—all samples below detection limit; (2) Trace—average concentration below the mean (512 ppm); (3) Minor—less than one standard deviation (574 ppm) above the mean; and (4) Common—more than one standard deviation above the mean (Figure 5).

The Milinska River, with at least three tin-bearing tributaries, is distinct in that average tin concentrations in individual samples are over three standard deviations above the mean, and the bulk ore concentrate at the bend in the Milinska River yielded 0.5% Sn. The average tin values in individual samples from the Cernica, and its two cassiterite-bearing tributaries the Čavinac and Lipovac, are above average, and the ore concentrate from the Cernica yielded 0.4% Sn. All of these streams drain from the southeastern region of the Mt. Cer pluton. The watersheds of all tin-bearing streams indicate that bedrock Sn-mineralization is limited to the south-central portion of the pluton (Figure 6).

Although garnet occurs in sediments from all streams that flow from Mt. Cer, garnet tends to be most abundant in cassiterite-bearing streams; commonly garnet comprises >50 wt% of the heavy mineral fraction of sands from the Milinska and Cernica (and tributaries), whereas most Sn-barren streams yield heavy mineral separates with <10 wt% garnet (Figure 7A). Garnet is uniform in appearance, generally occurring as rose-colored euhedral crystals <2 mm in diameter, and belongs to the pyralspite series—average composition 46% almandine (Fe), 46% spessartine (Mn), 4% pyrope (Mg), and 4% grossular (Ca). Such Mn-rich garnets are a common accessory



**Figure 6** Distribution of tin and Bronze Age archaeological sites around Mt. Cer. Intrusive phases are based on Zavod za geološka i geofizička istraživanja (1971) and Mojsilović et al. (1975). QMZD = quartz monzodiorites; TMG = peraluminous, S-type, two-mica granite.

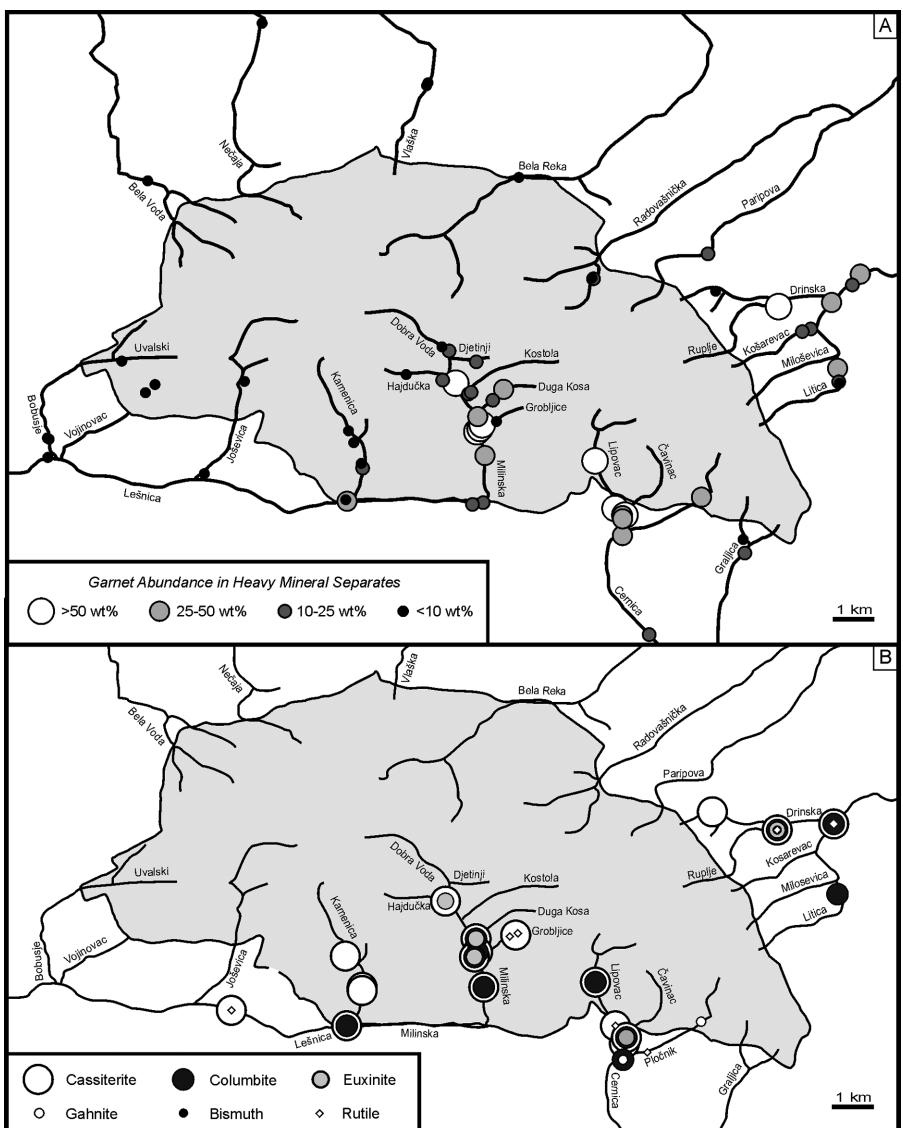
mineral in late differentiates of granitic rocks (aplates and pegmatites) (e.g., Manning, 1983).

Magnetite and ilmenite are broadly distributed as trace components in stream sediments around the Mt. Cer pluton. Titanite ( $\text{CaTiSiO}_5$ ) is a significant component of the heavy mineral fraction in all sediment samples examined (average of 16 wt%), but rutile ( $\text{TiO}_2$ ) is present only in sand that weathered from the tin-mineralized portion of the pluton (Figure 7B). The Nb-Ta-bearing minerals columbite [ $(\text{Fe}, \text{Mn})(\text{Nb}, \text{Ta})_2\text{O}_6$ ] and euxenite [ $(\text{Ca}, \text{U})(\text{Nb}, \text{Ti}, \text{Ta})_2\text{O}_6$ ] occur commonly as trace components of cassiterite-bearing sands (Figure 7B). Columbite is Nb–Fe-rich, with an average Nb:Ta composition of 80:20, and Fe:Mn of 68:32. Euxenite composition is variable. Other ore minerals that are spatially associated with placer cassiterite include gahnite ( $\text{ZnAl}_2\text{O}_4$ ) and native bismuth (Figure 7B).

Archaeological survey discovered four new Bronze Age sites in the Jadar region, all of which are situated on river terraces adjacent to the Lešnica and Cernica Rivers: Spasovine, Kamenica 1, Kamenica 2, and Cernica (Figure 6). All have Late Bronze Age material on the surface, usually mixed with earlier and/or later material.

Small exploratory trenches were excavated at several of these sites, and have produced additional artifacts, and evidence for stratigraphy. However, no architectural features were discovered, apparently having been destroyed by plowing and erosion. Survey along the other river terraces in the northern Jadar tributary area found sites of other periods (from Palaeolithic through Roman/Byzantine) distributed apparently without regard to the presence or absence of tin ores in the neighboring streams. These included the Palaeolithic sites of Trbosilje 1 and Trbosilje 2, the Eneolithic and Iron Age cave site of Kovačevića Pećina, other Eneolithic sites of Begluci near Kamenica, and Mali Gradac (Bulatović et al., 2013), multi-period sites such as Likodra, Kruglić, and Kićer (Bankoff et al., 2013) and the Early Iron Age site of Trojanov Grad.

Spasovine (44°34'31.79"N, 19°27'44.86"E; elev. 192 m) lies in the territory of the village of Milina on the road from Trbosilje toward Loznica (Figure 6). With an area of approximately 5 ha, it is perched on top of a gently sloping plateau overlooking the valley of the Milinska River (a major Jadar tributary), at the bend of the tin-bearing river where the highest cassiterite

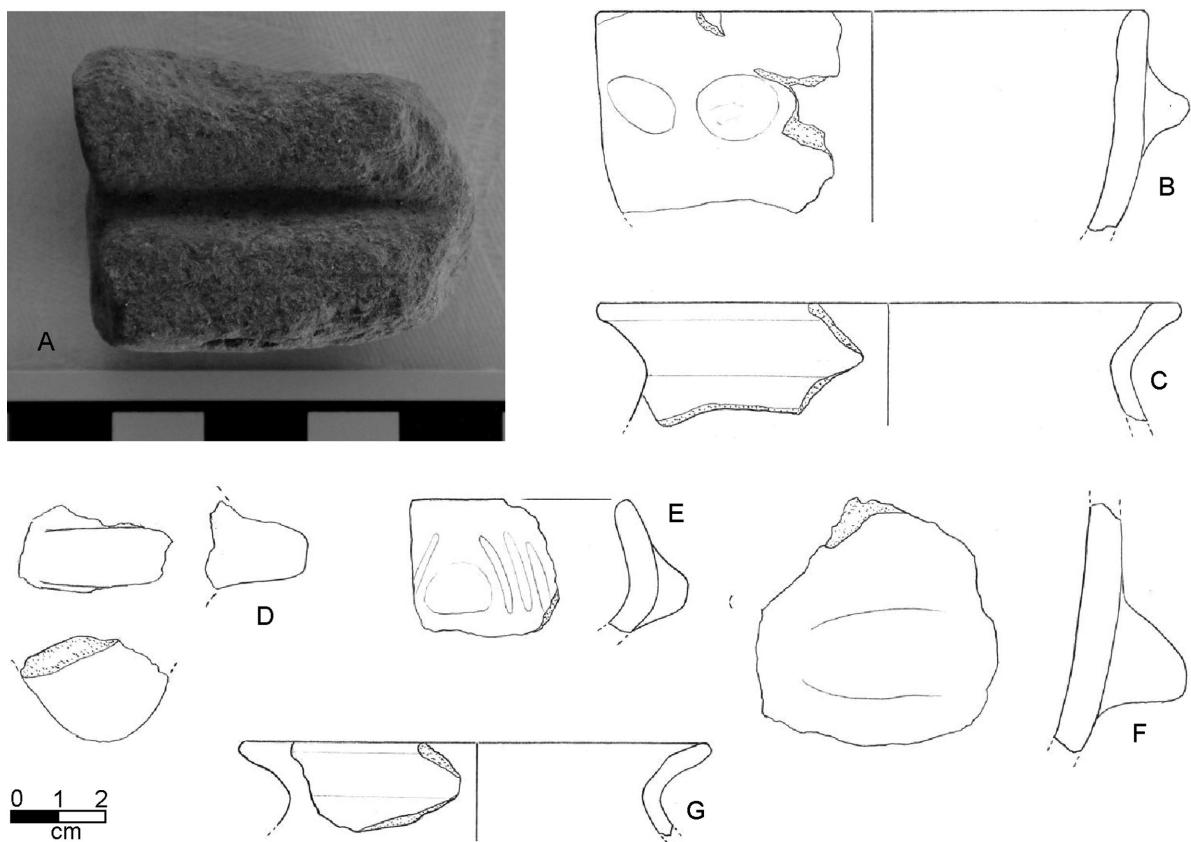


**Figure 7** Mineral occurrence maps: (A) Garnet abundance in heavy mineral separates from river sand; (B) occurrences of ore minerals in river sand.

concentrations occurred. Flanked by two mountains, Cer to the north and Iverak to the south, the valley terrain on the site's side of the Milinska is flat and open toward the west, all the way to Loznica. The lower of the two mountains, Iverak, runs east-west along the 44th parallel, and lies between the valleys of the Milinska to the north and Jadar to the south. Spasovine (a habitation site) and Paulje (a tumulus cemetery) are on opposite sides of Iverak, some 15 km apart.

Two Spasovine test pits sought remains of *in situ* architecture. The objective was to check whether Spasovine bears evidence of domestic or other units. On excavation, no preserved architectural features were encoun-

tered. However, the exposed area, chosen for its concentration of material, recovered ceramics that securely date the site to Late Bronze Age and show characteristics related to other known sites from the region, especially Paulje, which was apparently in continuous use into the Iron Age. A thorough field survey of the site area at Spasovine resulted in finds of stone hammers and abraders, Belegiš-type (*West Serbian variant of Vatin*) pottery, fragments of burnt daub, and a stone mold for casting pins or needles, suggesting metallurgical activity. The mold fragment, a surface find, is 3.6 cm long by 3.1 cm wide and 2.2 cm thick (Figure 8A). It seems to be either an open mold or one side of a closed mold for casting



**Figure 8** Example artifacts from Spasovine: (A) fragment of pin mold, 10 mm divisions for scale; (B) through (G) typical pottery sherds with corresponding scale bar in lower left corner.

the pointed end of a rather thick straight pin. Typologically nondescript, its chronological setting is uncertain. Its importance lies in that it indicates at least some metallurgical activity at Spasovine.

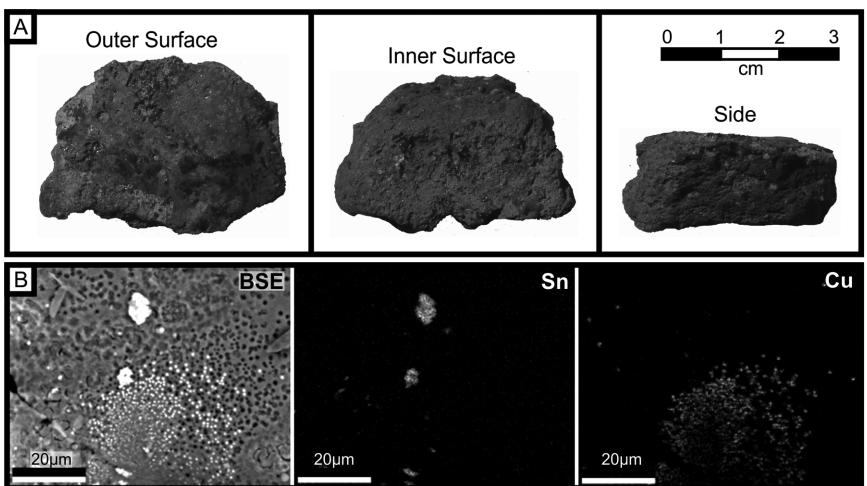
A ceramic fragment with an irregular vitreous coating on its outer surface provides additional evidence of bronze metallurgy at Spasovine. On-site XRF analysis indicated that the glass is compositionally variable across the sherd, but contains as much as 2.7% Cu and 383 ppm Sn. SEM-EDS analysis confirmed the presence of these metals in prills that range from 1 to 8  $\mu\text{m}$  in diameter, with Cu and Sn prills occurring adjacent to each other (Figure 9).

Kamenica 2 (Figure 6) ( $44^{\circ}34'31.93''\text{N}$ ,  $19^{\circ}27'30.77''\text{E}$ , elev. 187 m) lies on the gently sloping terrace at the confluence of the Lešnica and Kamenica Rivers. Surface collection provided an assemblage of sherds over an area of approximately 2 ha. Like Spasovine, some 500 m to the east, the pottery was indicative of Eneolithic, Early Bronze Age, and Late Bronze Age date. No test trenches were opened.

Kamenica 1 (Figure 6) ( $44^{\circ}30'30.25''\text{N}$ ,  $19^{\circ}27'20.08''\text{E}$ , elev. 184 m) lies approximately 250 m farther to the west, this site also extends up the slope of the terrace north of the Lešnica west of the Kamenica, covering an area of approximately 3 ha. The few ceramic and lithic finds were similar to that of Kamenica 2, although the surveyed area between them was sterile of artifacts.

Cernica (Figure 6) ( $44^{\circ}33'57.46''\text{N}$ ,  $19^{\circ}29'23.45''\text{E}$ , elev. 248 m), the final later Bronze Age site surveyed, lies to the southwest of the other three mentioned, on the terrace of the Cernica River, some 2.25 km from Spasovine. Separated from the other sites by the Trbosilje ridge, this site is along the easternmost tin-bearing stream descending from Mt. Cer. Ceramics found during the survey included the rim of a faceted-rim bowl, indicating a slightly later time than the others.

In general, the material collected from the surface of these sites consisted of ceramics and lithics. The lithic assemblage is varied, including grindstone fragments, some chipped lithics, stone hammers, and a fragmentary mold for a pin or needle from Spasovine. For the most part,



**Figure 9** Ceramic sherd from Spasovine with outer glassy surface containing tin and copper prills. (A) Photographs of sherd; (B) backscatter electron image and Sn and Cu X-ray maps of base of glass.

both coarser and finer ceramic wares occur as small (<50 mm), highly rolled and worn fragments. Reduced and oxidized wares are represented; surfaces (insofar as it could be determined) for the finer wares with thinner walls were black-slipped and burnished. Coarser fragments have large grit temper. Lug handles, as well as remnants of strap handles, are represented in the assemblage. Examples of pottery sherds from Spasovine are illustrated in Figure 8B–G. The condition of the sherds is consistent with surface material from later Bronze Age sites and single-period Eneolithic sites in the area south of the Danube. Such sites are shallow, usually consisting of a single cultural layer covered by active humus. They are easily destroyed by plowing, especially under modern machine-aided agriculture. The Jadar sites, usually located on the terraces above the river bottoms, are especially prone to surface erosion. The river bottoms themselves are flat and vary in width from <100 m to several hundred meters. They are fertile and arable but subject to flooding under the present climatic regime. The unsuitability of the river bottoms and the erosion of the terraces may partially explain the scarcity of known Bronze Age sites in the area.

## DISCUSSION

Tin is unevenly distributed around the Mt. Cer pluton, with concentrations significantly higher in the Milinska River than in all other streams, but grade decreases downstream toward the Lešnica. The Cernica River, with its tributaries (Čavinac and Lipovac), is a secondary site of cassiterite accumulation. Tomić (1991) found that tin

grades in the Milinska and Cernica Rivers were approximately equal. However, the results of this study indicate that the Cernica River may be of somewhat lower grade than the Milinska River, with 0.5% and 0.4%, respectively, and significantly higher concentration in upstream grab samples. Lesser cassiterite accumulations occur in the Drinska River. These results refine and expand the initial report by Durman (1997), and emphasize the importance of the Milinska River as a potential site of Bronze Age tin mining. The high concentrations of tin within the sediments of the Milinska River are likely a combination of a broad catchment area with multiple ore-bearing tributaries, and the topographic profile of the river. The Lešnica normal fault juxtaposes the southern margin of Mt. Cer against limestones and argillites of the Jadar Block. This planar granite-sedimentary contact has produced a sharp bend and decrease in gradient of the Milinska River, thereby providing an ideal setting for the development of accumulation placer deposits at the bend.

Tin distribution data, coupled with Geographic Information System (GIS)-based watershed delineation constrains the bedrock source of cassiterite to the south-central and eastern side of the pluton (Figure 6). Most streams whose headwaters flow from the S-type, peraluminous, TMG phase of the pluton are tin-barren, as are streams within watersheds that host tourmaline granite bodies on the eastern side of the pluton (Figure 6). Therefore these intrusive phases cannot be hosts for the bedrock ore source. The I-type, metaluminous QMZD would be an unlikely source for the tin ore based on the metallogenetic characteristics of this metal. Therefore, the tin ore must be associated with an unmapped intrusive

phase hosted by the QMZD. The most likely source for cassiterite in the Milinska, Cernica, and Drinska Rivers would be broadly distributed pegmatitic bodies associated with late-stage crystallization of the peraluminous phase of magmatism, and which are too small to have been mapped at the scale of available geological maps of Mt. Cer (1:100,000) (Mojsilović et al., 1975). A pegmatite source for cassiterite in most tin-bearing Mt. Cer streams is consistent with the documented heavy mineral assemblages of spessartine (Mn) garnet, columbite, and euxenite, the lack of F-rich minerals in the stream sediments, and existing descriptions (e.g., Janković, 1990). Furthermore, tin was documented in boulders of tourmaline-garnet bearing pegmatites used as building stones within the remains of a Roman tower at Trojanov Grad on the peak of Mt. Cer. Pegmatite-hosted tin ores are associated with deep-seated plutons, and are most common in Precambrian terrains where there has been extensive erosional denudation. However, such ores would be consistent with the local geological setting in which Tertiary regional extension associated with the Pannonian Basin resulted in rapid uplift of the Mt. Cer pluton.

Mineral assemblages in the cassiterite-bearing Kamenica River are distinct from streams further to the east; the heavy mineral fraction of cassiterite-bearing sands from the Kamenica River contain low abundances of garnet and lack the variety of ore minerals associated with the Milinska, Cernica, and Drinska Rivers (columbite, euxenite, rutile). Therefore, it is likely that placer cassiterite in the Kamenica weathered from a distinct source rock. The lack of complex mineral assemblages suggests a greisen-type ore source.

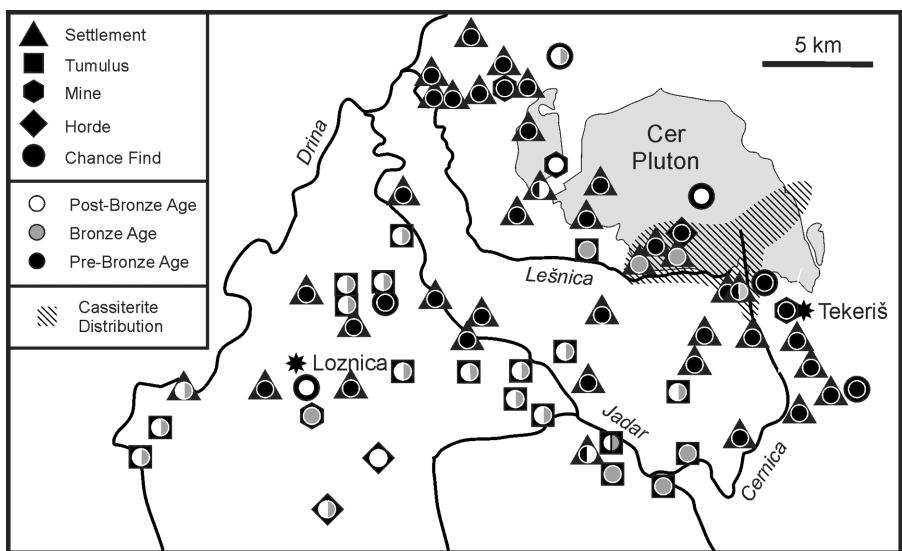
Although the archaeological survey in this study is a small sample, it is striking that Bronze Age sites with traces of occupation were found only adjacent to the richest placer tin ores which lie along the Milinska and Cernica Rivers; the largest Bronze Age site (Spasovine) coincides with the bend in the Milinska River where the greatest concentrations of cassiterite were documented (Figure 6). It should be noted that neither soil maps nor field observation of the Jadar area indicate any significant difference in the soil types that might provide another reason for the observed location of these Bronze Age sites. The current ground cover, forest, cropland (essentially wheat, corn, and soy), and pasture does not differ significantly along the Milinska and Cernica from other parts of the region. The sites are all situated within a short walk (~100–200 m) from the rivers and tributaries that dot the landscape. One can speculate that these waterways might well also have served for transport of goods downstream via the Jadar and the Drina, but the Milinska, Lešnica, and Cernica are not uniquely situated in this regard. Therefore, based on today's landscape, there

is no obvious reason for preferential settlement at these locations (e.g., arable land, communication routes, viewsheds) other than the concentration of cassiterite. However, we have little information about the Bronze Age landscape, which may have differed from the present. Pollen from cores currently being analyzed as part of the Jadar Project may provide a better picture.

As mentioned above, archaeological survey and mapping of the southwestern border of Mt. Cer uncovered pre- and post-Bronze Age sites. However, Bronze Age settlements were not found in the flood plains and terraces in this cassiterite-barren to cassiterite-poor area at the western end of the pluton. A map compiled in 2007 by the Jadar Museum in Loznica shows approximately 20 Bronze Age sites across the region (Figure 10). All but one of these sites that lie outside of the Milinska Valley constitute chance finds or tumuli, in contrast to the Bronze Age sites along the tin-bearing streams of Mt. Cer. Thus the Milinska Valley is archaeologically distinct from the remaining Jadar region.

No Bronze Age settlements were documented in previous research, which concentrated on the Bronze Age tumulus burials around Bela Crkva in the southern part of the Jadar region of West Serbia. The usual explanation for this dearth of occupation considers the whole Middle to Late Bronze Age population in the area to be nomadic or seminomadic, thus lacking in permanent settlements (Garašanin, 1983d, 1983g; also see Garašanin et al., 1994). Given the sites found on survey, this seems less likely at this point (also see Porčić, 2008). It is notable that the distribution of settlements and apparently contemporaneous tumulus burials are essentially mutually exclusive. Occupation sites occur in the north of the Jadar area, where the cassiterite could be exploited, while the tumuli occur in the cassiterite-poor south of the area. It is uncertain whether settlement was transient, possibly seasonal ore-extraction sites, or longer term habitation sites.

Like the geologically similar small Alpine tin deposits of Kestel and Deh Hosein, the Cer tin deposit potentially correlates with Bronze Age archaeological sites. The apparent correlation between Bronze Age site locations and the richest placer tin deposits in the area suggests that the sites might have been situated to exploit these ores. Similar reasoning has been used to infer Bronze Age placer mining in the Erzgebirge based on the co-location of placer ore and a Bronze Age camp site (Bouzek et al., 1989). Neither kilns nor incontrovertible processing implements have been found on these sites, except for the possible stone hammers and crucible fragments found on the surface at Spasovine, which lack context. It may be that, as at Göltepe, the smelting and casting were done elsewhere, perhaps in the lower Drina



**Figure 10** Distribution of archaeological sites and placer cassiterite in the Jadar region.

Valley, where ores of copper and tin, and fuel could have been brought down the rivers to a convenient processing site. The placer mining in the cassiterite-rich Milinska region may thus represent only the first step in a regional bronze production network. This possibility remains to be clarified by future work, including chemical and isotopic characterization of the tin and copper ores, and the metal artifacts in which they may have been used.

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