

1 COPPER PRODUCTION LANDSCAPES OF THE SOUTH CAUCASUS

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14

15 **Abstract**

16

17 Studies of metal production frequently show a correlation between scale and organizational
18 complexity. The remarkably rich landscapes of metal-producing sites of late 2nd-early 1st
19 millennium BC Colchis provide an unprecedented opportunity to reexamine this apparent
20 correlation. Investigations of copper smelting sites show that industries with a large aggregate
21 output can be the result of numerous small groups of metalworkers acting independently. Spatial
22 data on site distributions, estimates of productive output, and archaeometric data on ore
23 procurement patterns were integrated to reconstruct the organization of production. Judicious use
24 of a portable X-ray fluorescence spectrometer (pXRF) showed that not only were smelting sites
25 highly dispersed, but also that metalworkers at different sites were using ores from geologically
26 distinct deposits. This innovative approach helped to reconstruct the organization of production
27 in a distinctive metal production landscape, bridging an enduring divide between landscape-scale
28 and microscopic investigations of craft production.

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34 Early Iron Age; GIS; Black Sea

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36 **1. Introduction**

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38 Metal production systems are complex enterprises shaped by both natural and
39 anthropogenic factors (Hardesty, 2010: 109). Geological realities constrain where ore deposits
40 are located, and ecological factors determine where suitable fuel sources can be found. Often
41 these areas are located in mountainous regions or in other areas of marginal agricultural
42 potential, meaning that ore deposits are removed from both sources of labor and consumer
43 markets. Many metallurgical technologies require specialist knowledge gained over long periods
44 of time. These twin issues—the complexity of the production process and the spatial distribution
45 of resources—have invited a range of different solutions, from emergent systems organized from
46 the bottom up (Morse, 2003: 4), to highly organized expeditions by centralized authorities
47 (Shaw, 1998).

48 In Western Asia, the organization of metal production, particularly bronze and iron, has
49 figured prominently in discussions of social and technological change in the Late Bronze and
50 Early Iron Age (LBA-EIA) (Mirau, 1997; Sherratt, 1993; Zaccagnini, 1990). The overwhelming
51 geographical focus of research on LBA-EIA metal production and trade is the eastern
52 Mediterranean and the Levant (Kassianidou, 2012; Knapp, 2012; Knapp and Kassianidou, 2008;
53 Liverani, 2003; Liverani, 2008; Pulak, 2008; Sherratt, 1993, 1998). Much of the scholarly debate
54 has centered on the degree of state control over trade and (to a lesser extent) production (Bell,
55 2012; Routledge and McGeough, 2009). However, though it is clear that economic activity was
56 organized by both merchant families independent of the palace and “men of the king” working
57 for the crown, the pervading viewpoint is that much trade, especially long-distance large-scale
58 movements of materials, was organized from the top down.

59 Studies of LBA-EIA copper production have uncovered landscapes that bear the mark of
60 a highly centralized system of control over production. There is ample evidence of New
61 Kingdom (LBA) Egyptian presence in major copper producing areas (Rothenberg, 1987, 1988),
62 even if the nature of that presence is unclear. Despite new Early Iron Age dates from Timna Site
63 30, a site previously thought to be Late Bronze Age in date (Ben-Yosef, 2010: 567; Ben-Yosef et
64 al., 2012), it is highly likely that Egyptians exploited copper in the Timna area (Yagel et al.,
65 2016). By the Early Iron Age, large fortified smelting camps were constructed at Timna and
66 Faynan (Bachmann and Rothenberg, 1980; Hauptmann, 2007; Levy et al., 2012; Levy et al.,

67 2014; Rothenberg, 1990; Weisgerber, 2003). These smelting sites attest to both the centralization
68 of production and the efforts to control and protect valuable resources and labor—a remarkable
69 feat if, as has been suggested, significant portions of the population remained mobile (Levy,
70 2009).

71 Evidence of Late Bronze copper production on Cyprus is substantial, but there are some
72 important gaps (Knapp, 2012). While copper slags are commonly found in urban LBA contexts
73 on the island (Courtois, 1982; Kassianidou, 2012; South, 2012; Stech, 1982; Tylecote, 1982),
74 LBA evidence of copper smelting and mining in the rural hinterlands near ore deposits is more
75 scarce (Kling and Muhly, 2007; Knapp and Kassianidou, 2008). This is almost certainly due to
76 modern mining, as well as the presence of large slag heaps of pre-modern, post-Bronze Age date
77 (see Shaar et al., 2015). There is ample speculation that, especially in the Late Bronze Age,
78 Cypriot mining and smelting was a highly organized enterprise directly administered by elites in
79 coastal centers (Knapp and Kassianidou, 2008: 144), though the ubiquity of metal production at
80 different sites suggests centralized island-wide control is less likely (Stech, 1982: 113). It is
81 certainly possible coastal elites directed mining and smelting activities in the interior, but the
82 small body of evidence for LBA metallurgical activities in inland mining regions leaves open
83 other possibilities.

84 Outside of the Eastern Mediterranean, very few studies have looked at the spatial and
85 social organization of LBA-EIA copper production in Southwest Asia. Investigation of copper
86 production landscapes in the western regions of the South Caucasus reveals an industry that
87 defies traditional models of how large metal production industries were organized. Data from
88 field survey and test pitting of smelting sites, coupled with a detailed reconstruction of the
89 technology of copper production (Erb-Satullo et al., 2014; Erb-Satullo et al., 2015), provide a
90 fundamental basis for considering questions about the spatial and social organization of copper
91 production. The large number of metal production sites, and the large quantities of production
92 debris found at each of them, allow us to merge spatial and archaeometric data in new ways. This
93 approach not only illuminates the dynamics of a metal production landscape, it also demonstrates
94 how archaeometric data can contribute to a broader understanding of social and economic
95 processes. The picture that emerges is one that differs from traditional notions about the links
96 between organizational complexity and scale of production, demonstrating that industries with

97 large-scale aggregate output can emerge though the actions of numerous independent, small-
98 scale producers.

99

100 **2. Space and Social Organization in Production Landscapes**

101

102 Any attempt to reconstruct the organization of copper production must begin with a
103 discussion of the spatial parameters of the industry. Where are the ores coming from? What do
104 the spatial distribution of smelting camps and the kinds of activities taking place at them tell us
105 about the organization of production? How is metal distributed and where are artifacts made?

106 The synthesis of spatial and archaeometric data allows us to approach more complex
107 social questions about the coordination of production. Was metal production organized from the
108 top-down or were small groups of people exploiting many different deposits? The degree to
109 which production was controlled (and if so, by whom) is a fundamental issue. The concepts of
110 coordination and control are related to the concept of attached production (Costin, 1991; Earle,
111 1981). However, the above terms, particularly “coordination,” do not assume that the producer
112 no longer retains the “rights of alienation” (i.e. the ability to dictate how the product is
113 distributed), a key element of some definitions of attached specialization (cf. Clark and Parry,
114 1990: 298). As an index of production, coordination refers to the degree to which metal
115 production was carried out by a large group of people acting in concert towards a single goal.
116 High levels of coordination encompass a range of different types of social organization,
117 including both communal pooling of labor resources, as well as highly regimented mining and
118 smelting expeditions organized from the top down (e.g. Shaw, 1998).

119 The extent of coordination and control has a direct impact on the spatial organization of
120 production activities (Rochette, 2009; Zori et al., 2013). Highly concentrated smelting camps are
121 easier to monitor. Direct visual oversight of production allows those organizing and controlling
122 production to ensure compliance and obedience in the labor force, monitor the distribution of
123 raw materials to workers, and increase organizational flexibility through easy communication
124 between work parties. In the archaeological record, there are numerous instances where the
125 concentration of production is correlated with other evidence of increased control (Levy et al.,
126 2014; Olivier and Kovacic, 2006). Following Arnold and Munns (1994), one analytical approach
127 for assessing the degree of control is to identify “choke-points,” or key nodes along the chaîne

128 opèratoire where a small minority could exert an outsize influence over production. In the case of
129 Arnold and Munns, while Channel Island bead production was not directly monitored by elites,
130 the importance of elite-owned canoe transportation for bead distribution meant that they exerted
131 *de facto* control over the industry. In the sequence of activities required to produce bronze
132 objects, there are many possibilities for this kind of horizontal integration. Rich deposits of
133 copper ores may be located deep underground, requiring significant labor to cut through
134 overlying rock. This circumstance might result in the construction of just a few, easily controlled
135 mines. On the other hand, ore may occur in numerous outcrops close to the surface, making
136 control of access more difficult. The primary smelting stage of production offers another chance
137 to exercise control over production, especially if this activity, which requires specialist skills,
138 occurred in nucleated workshops close to centers of political authority.

139 Spatial nucleation of production activities and top-down control by political elites are not
140 strictly connected, however (Campbell et al., 2011; Costin, 2011: 112ff.). Some ecological
141 factors may push for a more dispersed pattern of production, even if it falls under the control of a
142 regional authority. A large smelting camp will quickly exhaust fuel in its immediate vicinity, so a
143 more dispersed landscape of smelting sites might reduce the amount of work required to bring
144 fuel to the furnace. Lack of external threats may result in a centrally administered production
145 system that is nevertheless somewhat dispersed (e.g. Yagel et al., 2016). A cellular model of
146 production (see Martín-Torres et al., 2014) also permits spatial dispersion of workshops even
147 within the context of a tightly controlled industry. Conversely, Stark's (1991) study of
148 community specialization among Kalinga potters reveals how production can be concentrated in
149 certain areas, but without administrative control.

150 For these reasons, it is not sufficient merely to look at the spatial distribution of smelting
151 sites and their relative sizes. In addition, the patterns of behavior at these sites must also be
152 examined. Distance unavoidably attenuates the ability to control both end products and labor,
153 and increases the cost of maintaining that control (Costin, 1996: 212). However, it is conceivable
154 that controlled, or at least coordinated, enterprises might be scattered in different locales.
155 Spatially dispersed yet highly controlled production landscapes may show a high degree of
156 coordination in production activities, such as the types of ores used, the standardization of tools,
157 or a homogeneous set of production practices. Highly organized, tightly controlled industries
158 may be dispersed for some stages of production, but it is very unlikely that they would be

159 dispersed at *all* stages of production. It is also crucial to consider the possibility that loose
160 networks of independent metalworkers may share techniques and practices (through
161 apprenticeship or other informal forms of knowledge sharing), producing a common
162 technological style in an industry where daily activities were nonetheless carried out
163 independently.

164 With few exceptions (Thornton, 2009a, 2009b), typical treatments of metal production in
165 the Near East have focused on situations where there is a high degree of correlation between
166 concentration, top-down organization, and scale (e.g. Ben-Yosef, 2010: 889). In contrast, there is
167 little investigation of cases in which scale, nucleation, intensity, and elite oversight are not
168 correlated. The following analysis of Colchian bronze production closely examines the
169 relationship between the spatial distribution of activities, and other evidence of top-down
170 coordination. Integrating chemical and spatial data, this approach not only examines spatial
171 proximity of sites, but also considers coordination through the lens of ore procurement networks.

172 This data integration overcomes a long-standing challenge for archaeometallurgical
173 research. Spatial and chemical/mineralogical data are rarely integrated on a large scale in the
174 study of metal production. In large part, this is due to a mismatch between the two types of data.
175 Chemical and microscopic analyses identify patterns on the micron scale. The mode of analysis
176 is often intensive by necessity—chemical and microscopic analyses require significant time and
177 money to prepare. Moreover, the destructive nature of some analyses discourages large sample
178 sizes. Large robust datasets, such as in lead-isotope studies of Mediterranean copper ores and
179 bronze artifacts, take years to produce (Gale, 1999; Gale and Stos-Gale, 1982; Stos-Gale et al.,
180 1997). In addition, the ephemeral nature of some production activities and the difficulties of
181 correctly identifying production debris in the field contribute to small sample sizes from most
182 excavations. As a result, these kinds of data are rarely synthesized to address broad systemic
183 questions (for excellent exceptions to this general pattern, see Bray et al., 2015; Bray and
184 Pollard, 2012; Perucchetti et al., 2015).

185 In contrast, studies of ancient landscapes are by definition extensive. Scales are measured
186 in meters and kilometers, six to nine orders of magnitude greater than the scale of slag
187 microscopy. Integration of intensive and extensive datasets at wildly differing scales poses a
188 serious challenge. However, overcoming the tyranny of (very small) distances offers a chance to
189 examine previously invisible patterns of behavior and address questions of broad anthropological

190 relevance (i.e. questions at the human scale). Despite its enormous potential,
191 archaeometallurgical research has largely failed to do this (Killick, 2015; Martín-Torres and
192 Killick, in press).

193 The exceptionally rich metal production landscapes of the South Caucasus present an
194 opportunity to integrate micro-scale and macro-scale datasets, answering key questions about the
195 spatial and social organization of production. Building on an essential foundation of microscopic
196 and chemical analyses (Erb-Satullo et al., 2014; Erb-Satullo et al., 2015), we used rapid
197 qualitative chemical analyses to generate large sample sizes, revealing spatial patterns in the ore-
198 use taking place at different sites, and reconstructing the organization of production.

199

200 **3. Survey and Analysis of Copper Smelting Sites in Ancient Colchis**

201

202 Between 2010 and 2014, a series of surveys were carried out to explore metal production
203 landscapes in western Georgia, a region known to the Greeks as Colchis, and possibly Kulkha to
204 the Urartians (see Melikishvili, 1962). Soviet-period survey and excavation uncovered a large
205 number of metal production sites (Gzelishvili, 1964; Khakhutaishvili, 1976, 1977, 2009 [1987]),
206 but without the benefit of modern GPS, mapping capabilities were limited. In the densely-
207 vegetated subtropical landscape, traditional systematic survey techniques were ineffective at
208 locating small smelting sites, so the knowledge of local villagers and Soviet-period field
209 notebooks were the primary tools for relocating known sites and find new ones. Both copper and
210 iron smelting sites were located, though the earliest dated iron smelting site in our current project
211 dates to the mid-late 1st millennium BC (see Erb-Satullo et al., submitted). This paper focuses on
212 the copper smelting landscapes of the Late Bronze and Early Iron Age (c. 1500-600 BC). Copper
213 smelting sites were mapped in all the areas investigated during the Soviet period, illustrating the
214 broad regional extent of the industry (figure 1). Late Bronze and Early Iron Age copper smelting
215 was likely carried out in a more or less continuous band through the foothill regions of the
216 Greater and Lesser Caucasus range. This complex of sites almost certainly extends eastward
217 along the southern shore of the Black Sea, as the Eastern Pontides are also extremely rich in
218 metal deposits (Lutz et al., 1994; Seeliger et al., 1985).

219 Because mapping a few sites in a number of different areas reveals little about the local
220 spatial organization, survey efforts were concentrated in the Supsa-Gubazeuli area, in order to

221 examine the spatial organization of copper production in detail (figure 1). Three seasons of
222 fieldwork (2010, 2012, and 2014) identified 49 metal production sites. Radiocarbon dating of the
223 sites shows that this landscape was active for a period 300-500 years between about 1300 and
224 800 BC (Erb-Satullo et al., submitted). While not all previously known sites were relocated, the
225 distribution likely represents a good approximation of the actual smelting landscape within the
226 areas investigated. The two most striking features of the smelting site distribution are the density
227 of smelting sites within the area surveyed, and the lack of clustering. This distribution alone
228 suggests that any attempt to coordinate or control production on this scale would have faced
229 serious challenges. Sites are scattered across numerous small ravines and ridges, making travel
230 between them challenging. Given the extent of modern vegetation and topography, it is rare to be
231 able to see one site from another unless they are very close. It is difficult to estimate the level of
232 vegetation in the LBA-EIA, given that most paleoecological research in the area has focused on
233 coastal zones (Connor et al., 2007; Janelidze, 2007; Janelidze and Tatashidze, 2010). The thick
234 forests, which today are found slightly higher in the foothills immediately to the south of the
235 survey area, probably extended to lower elevations in the Bronze Age. Large-scale land
236 clearance for tea plantations dates to the 20th century. Even when modeling a landscape with no
237 vegetation, intervisibility of sites is low for sites that are so close together (figure 2). Of the 1128
238 possible site pairings¹, only 105 pairings are intervisible (9%), assuming an observer and target
239 height of 2 m above the ground surface. When one excludes site pairings that are over 1 km
240 apart, the proportion of intervisible sites is only 49 of 281 (17%). Many pairs of proximate sites
241 are not intervisible (e.g. Sites 20, 40 and 41; Sites 45 and 46; Sites 25 and 47; Sites 25 and 24). If
242 one assumes that it is easier to control dispersed labor parties if nearby sites are intervisible and
243 within shouting distance, it follows that the topography of the Supsa-Gubazeuli production area
244 inhibits coordination between dispersed groups. In other words, it is not only the dispersed
245 distribution of the sites that makes them more difficult to control, it is their arrangement within
246 the specific topographic and ecological environment of the Caucasus foothills. It is nonetheless
247 important to recognize that intervisibility and proximity are not direct indices of coordination
248 and top-down organization. Lack of intervisibility between smelting parties does not preclude

¹ Site 34, located in the Vakijvari gorge, was excluded from this analysis since it is far removed from the other sites. This analysis assumes that all sites are contemporary. While there is good evidence that virtually all these sites date to the LBA-EIA (Erb-Satullo et al., submitted; Khakhutaishvili, 2009 [1987]), they were probably not all in operation at the same time.

249 coordination—after all, the distances in question are not large. However, the distribution of these
250 sites within the landscape would have imposed challenges for any attempt to manage production,
251 ensure compliance, and maintain control over a dispersed workforce.

252 It is worth comparing the Colchian site distribution with that of Late Bronze Age copper
253 smelting in the Timna Valley (Yagel et al., 2016). Like the Colchian case, LBA smelting sites in
254 Timna are small (relative to later EIA sites) and somewhat dispersed. However, Yagel et al.
255 argue that the spatial positioning and character of Timna Site 3 suggest that it served as an
256 administrative center for other sites in the vicinity. None of those elements are present at
257 Colchian sites, which are remarkably homogeneous in character.

258 In addition to their spatial distribution, the second main feature of the sites is their small
259 size. No excavated site in the Supsa-Gubazeuli region contained more than two furnaces, and
260 slag heaps are generally only 10-20 m in diameter. Data collected from test pits can be combined
261 with earlier, more extensive excavations during the Soviet period to approximate the scale of
262 production at each site. As quantities of slag are proportional to the amount of labor involved,
263 such calculations also put rough constraints on the number of people involved in production and
264 the duration of occupation.

265 Published details from earlier Soviet projects (Khakhutaishvili, 2009 [1987]) provides
266 usable information about the total size of slag heaps at a number of sites. Often, the excavator
267 reported the approximate area of the waste dump and the maximum depth of the slag heap. In
268 addition, the excavator sometimes reports the number of cubic meters of slag recovered during
269 excavation. Gilmour (2009) assumes about 10 tonnes of slag for every 6.6 cubic meters of slag
270 (~1500 kg/m³) as reported by David Khakhutaishvili. An alternative method involves calculating
271 the volume of the slag heap from reported area and maximum depth figures (approximating its
272 shape as a generalized cone), then multiplying that volume by the empirical value of
273 approximately 470 kg of slag per cubic meter of slag heap calculated during testing of Site 43 in
274 2012.² Both of these methods provide only coarse approximations, but their roughly equivalent
275 results are encouraging (table 1). Averaging the slag quantities at all sites for which the whole
276 slag heap is quantified (i.e. excluding those figures, such as Mziani III,1 where information is

² Note that this is not comparable to the other figure of 1500 kg per cubic meter of slag. The higher figure refers to the density of slag only, while the lower one refers to the density of unexcavated slag heap, which includes sediments and voids in the slag heap matrix.

277 only available for one part of the slag heap), gives values of roughly 13,000 kg (calculation 1)
278 and 17,000 kg (calculation 2).

279 Estimates of total slag quantities can be used to estimate how many cycles of copper
280 production took place at each site. Technological reconstructions of the copper smelting process
281 (Erb-Satullo et al., 2014; Erb-Satullo et al., 2015) have shown that slag was produced in two
282 distinct stages of production. One (probably earlier) stage produced dense slag cakes left to cool
283 in the furnace, while the other (most likely later) stage of production produced spongy masses of
284 slag formed from scraping or pouring molten slag from smaller reaction vessels. Each slag cake
285 therefore corresponds to one furnace firing. The average diameter of measured slag cakes was
286 about 24 cm (n=28). Thickness was more difficult to measure because full sections of slag cakes
287 were rarely preserved, but one example measured 7 cm. Slag cake densities were measured
288 empirically on four samples, with an average density of 4.1 g/cm³. Modeling the shape as a
289 cylinder, and assuming that roughly 10% of the slag cake volume consists of gas bubbles, gives a
290 cake mass of about 12 kg. Estimating the mass fraction of slag cakes as a proportion of total slag
291 at a site is difficult. Attempts to quantify this figure using data from small test pits yielded wildly
292 varying values, from less than 0.1 to greater than 0.9, reflecting the simple fact that spongy slags
293 and dense slags were often deposited in different parts of the site. An intermediate value of 0.6
294 was chosen for this analysis, meaning that a site with an estimated 15,000 kg of slag would
295 represent about 770 slag cakes and an equivalent number of furnace firings.

296 If one speculates that these smelting sites were in use for at least a generation of 20-25
297 years, this amount of slag represents an upper bound of 30-40 firings per year. Even accounting
298 for time taken for the production of charcoal, mining, and the stages of production that produced
299 spongy slag, this represents a fairly modest undertaking well within the capabilities of a small
300 group of metalworkers smelting for only part of the year. These final calculations of annual
301 output involve substantial assumptions, but the figures suggest that the labor required to produce
302 the amount of slag at each site would not have required a large expedition.

303 Quantities of slag at individual sites can also be used to make very approximate estimates
304 about the aggregate output of the industry. Assuming an average of about 15,000 kg (15 metric
305 tons) of slag per site, the 49 sites identified in the Supsa-Gubazeuli area represent about 735 tons
306 of slag. The reported 400 sites mentioned by Khakhutaishvili (2009 [1987]: 17) in the four areas
307 he studied would be roughly equivalent to 6000 tons of slag. But as we have already discussed,

308 the small size of the sites, and the densely vegetated landscape probably means that this figure is
309 a gross underestimation of the total number of sites. Anecdotal evidence (e.g. Site 34) strongly
310 suggests that the landscape of copper smelting sites extends up into the densely wooded copper-
311 rich mountains immediately to the south of the study area. Mountainous areas of southwestern
312 Georgia are almost totally unexplored in this regard, and the same is true of the Greater Caucasus
313 regions of Svaneti, Abkhazia, and Racha. Nevertheless, work conducted by local archaeologists
314 in these regions unequivocally shows that they were also major centers of metal production
315 (Chartolani, 1989: 158-166; 2001; Chernykh, 1992: 275-276; Iessen and Degen-Kovalevskiy,
316 1935; Maisuradze and Gobedzhischvili, 2001; Mudzhiri, 2011; Sulava, 2001). While the
317 individual output of any particular smelting site was rather small, the aggregate output of the
318 Colchian copper smelting industry was quite extensive.

319 These figures allow order-of-magnitude comparisons with contemporary sites.
320 Excavation of Politiko Phorades, an early LBA (1650-1500 BC) site in Cyprus, recovered more
321 than 3.5 tons of plano-convex slag cakes, or roughly equivalent to 3200-3500 kg (Knapp and
322 Kassianidou, 2008: 142). These values are on the same order of magnitude as many individual
323 slag heap size estimates for the Supsa-Gubazeuli area. The excavators argue that the scale of
324 production at Politiko Phorades does not support a centralized enterprise, but note that such
325 organization probably existed in the later part of the LBA (Knapp and Kassianidou, 2008: 144).
326 Total values in the range of about 4 million tons of slag (Constantinou, 1982: 22; Kassianidou,
327 2013: 37) do not distinguish between Bronze Age slag heaps and later pre-modern exploitation
328 (Ben-Yosef, 2010: 87; see also Shaar et al., 2015).

329 In contrast to the somewhat ambiguous evidence on Cyprus, Early Iron Age smelting
330 sites in the southern Levant show clear evidence for large-scale production. By one estimate,
331 100,000 to 130,000 tons of slag were produced in just four Iron Age sites in Wadi Faynan
332 (Hauptmann, 2007: 147), with 50,000-60,000 tons at Khirbet en-Nahas alone (Levy et al., 2004:
333 867). The quantity of early Iron Age production debris on the western side of the Arabah is
334 smaller, through still substantial (Ben-Yosef, 2010: 617). Smelting camps at Bir Nasib in the
335 Sinai, dated to the LBA and possibly earlier, contained as much as 100,000 tons of slag
336 (Rothenberg, 1987). More recent work has suggested that early estimates of slag quantities might
337 be an overestimate, since slag heaps, at least at Khirbet en-Nahas, are only about 40% slag by
338 volume (Ben-Yosef, 2010: 338). Nevertheless, the scale of production at the larger sites in the

339 Southern Levant is three orders of magnitude greater than any single contemporary Colchian
340 smelting site. Accurate comparisons of aggregate output of all smelting sites in the two regions
341 are challenging, because the Southern Levant has been the subject of more intensive research,
342 and the arid landscape makes large sites easier to find. By comparison, the small site size, less
343 intensive research, and lush subtropical landscape would all suggest an underestimation of the
344 Colchian bronze industry relative to the Southern Levant. It is conceivable that, in aggregate, the
345 actual scale of production was comparable in both areas.

346 The previous discussion has intentionally used slag rather than metal as the proxy for
347 industrial output. It is very difficult to move from quantities of slag to quantities of metal
348 produced, especially for copper smelting operations. The composition of the ore and
349 technological decisions (such as fluxes used) will significantly affect these ratios. For the Faynan
350 region, which contains mostly copper oxide ores, estimates run on the order of 10:1 for
351 slag:metal ratios (Hauptmann, 2007: 253). Similar ratios are used to estimate the quantity of
352 metal produced at Politiko Phorades (Knapp and Kassianidou, 2008). However, different ratios
353 of slag:metal have been suggested, from 3.75:1 (Maldonado and Rehren, 2009: 2004) to the
354 radically different ratio of 1:6 (Shalev et al., 2006). While there is relatively good qualitative
355 information about the ore sources used in Colchis, there is simply not enough quantitative data to
356 estimate slag:metal ratios.

357 It is worth asking how much fuel, and correspondingly, how much woodland, would have
358 been required to support this industry. Calculating the acreage of trees required to produce a
359 given quantity of slag is challenging, and depends on the richness of the ore, metal production
360 technologies, charcoal-making practices, wood harvesting strategies, and local ecologies (Straka,
361 2014; Wertime, 1983: 451). As a result, the following calculations should be treated as very
362 approximate. Wertime, calculating the area of forest cut to produce 1 ton of slag, estimates 0.5 to
363 1.5 acres per ton for Mediterranean metal production, with Cyprus on the upper end of that range
364 due to its relatively low-grade ores (Wertime, 1982: 357; 1983: 451-452). Given the wetter
365 climate and denser vegetation of the Eastern Black Sea region, 1.5 acres per ton of slag seems to
366 be a reasonable upper bound for the Colchian case. Assuming an average of 15,000 kg (16.5
367 tons) of slag per site, these calculations yield about 25 acres of forest per site, equivalent to an
368 area with a radius of about 175 m. For all the sites mapped in the Supsa-Gubazeuli area, the total
369 forest area required is just under 5 km². If the wetter climate resulted in higher productivity in

370 terms of charcoal per acre of forest, and 0.5 acres of trees per ton of slag is closer to the true
371 figure, then the 49 sites of the Supsa-Gubazeuli region correspond to the clearance of just 2.5
372 km². Both figures are significantly less than the roughly 8-9 km² over which the sites are
373 distributed, and forest regeneration may have significantly reduced the total amount of land
374 cleared during the period that these sites were active. The fuel demands of the industry
375 undoubtedly impacted the local ecology, and exhaustion of adjacent stands of trees may have
376 prompted the relocation of smelting sites, as has been documented ethno-historically in Anatolia
377 (Yener, 2000: 78). Indeed, environmental records from settled areas near the coast show
378 evidence of anthropogenic burning and land clearance around the 1st millennium BC, though in
379 this case, metallurgy is not directly implicated (Connor et al., 2007: 31-33). However, these
380 calculations make it reasonably clear that the fuel demands of this smelting landscape did not
381 exceed the capacity of the immediately surrounding forest, and most fuel could have been
382 brought from very nearby, perhaps less than 200 m away. This means that the labor requirements
383 for procuring and transporting fuel were far less than for a large centralized site operating over a
384 long period, which would have quickly exhausted the closest stands of trees.

385

386 **4. Ore supply and the Organization of Mining**

387

388 The size and distribution of smelting sites suggest a lack of coordination and top-down
389 control of production activities. However, leaping immediately to this conclusion risks casually
390 conflating lack of concentration with lack of coordination and control. As discussed above, there
391 are circumstances where an industry organized from the top down might still have a high degree
392 of dispersion. Indeed, a cursory examination of production remains shows broad similarities in
393 technological style between sites. Are these commonalities indicative of large-scale coordination,
394 or are they merely reflective of a common technological style among independent producers?

395 In order to address the question of whether metalworkers at each site were acting
396 independently, it is necessary to take a closer look at the activities taking place at each site. Are
397 metalworkers smelting ore mined from a single location, or are they using ores gathered from
398 multiple sources? The former case would indicate a greater degree of coordination and perhaps
399 control of the metal production sequence, even if smelting sites were highly dispersed. Iron
400 mining by the Toro of Uganda provides a fitting ethnographic example of such an arrangement

401 (Childs, 1998). Iron mines were controlled by their discoverers, who allotted mining rights to
402 family members and other associates. The iron ore was processed in different smelting
403 workshops, but the original discoverer of the mine held considerable power over access to the
404 deposit. Could such a model apply to the Colchian case? Fortunately, the chemical and
405 mineralogical composition of the slag reflects variations in the original ore sources (Erb-Satullo
406 et al., 2014), making it possible to distinguish ores gathered from different mines.

407 This approach naturally requires a strong understanding of the ore sources, their
408 compositional variation, and their parageneses (formation of associated non-ore minerals). The
409 Eastern Pontic and Lesser Caucasus mountains are known for a wide variety of metallic deposits,
410 including porphyry, volcanogenic massive sulfide and vein-type deposits (Gugushvili et al.,
411 2010; Moon et al., 2001). In Southwestern Georgia, copper and other polymetallic deposits are
412 typically associated with syenitic and dioritic intrusions in andesitic host rock (Erb-Satullo et al.,
413 2015: 272-273; Nazarov, 1966). The deposits in the Merisi region, consisting primarily of
414 copper, silver, lead and molybdenum, have been best recorded (Gugushvili et al., 2010: 339), as
415 they were briefly exploited during modern times (Ghambashidze, 1919: 88; Nazarov, 1966: 117).
416 The likely source of the ores smelted at the Supsa-Gubazeuli sites is the stock batholith intrusion
417 in the upper reaches of the Bzhuzhi and Vakijvari gorges, some 10-15 km away. This massive
418 intrusion into andesitic host rock probably opened up numerous fissures in the host rock,
419 allowing ore bearing fluids to form numerous small, but potentially rich metal veins. This pattern
420 is confirmed by Soviet-period geological surveys of nearby copper deposits (Gabunia, 1933:
421 556-557) (figure 3). Ore bodies such as this may vary chemically and mineralogically, a
422 phenomenon known as zonation. Evidence of zonation is reflected in Gabunia's descriptions,
423 with some copper deposits listed as having associated sphalerite ((Zn,Fe)S), galena (PbS), pyrite
424 (FeS), and hematite (Fe₂O₃).

425 Laboratory analysis of the smelting slags showed that paragenetic mineral and chemical
426 variation was translated to the slag in the smelting process (Erb-Satullo et al., 2014; see also
427 Tylecote et al., 1977) (figure 4). Differences in zinc, deriving from sphalerite, were clearly
428 observed in both chemical and mineralogical analyses.

429 New trace element analyses of slag via powder WDS-XRF suggest that zinc-bearing
430 sphalerite was not the only paragenetic mineral that varied between different ore deposits (table
431 S1 in online supplementary material). The plot of molybdenum vs. cobalt, both of which are

432 elements commonly associated with copper deposits, illustrates this point effectively (figure 5).
433 High cobalt content tends to correlate with low molybdenum, and vice versa. In addition,
434 chemical compositions are relatively consistent within sites. Samples from Site 5 have up to
435 2939 ppm Co, but never more than 630 ppm Mo. Likewise, samples from Site 3 have up to 1449
436 ppm Mo, but never more than 705 ppm Co. The linear spread in samples from the same sites
437 (most obvious for Sites 3, 5, and 38) is likely due to volatilization or admixture of other material
438 during the smelting process. Importantly, none of these samples have appreciable Zn content.
439 High Zn samples from Site 8 all cluster together with very low Co and Mo. These results
440 demonstrate that there were likely many different types of ore deposits being exploited, with
441 varying combinations of Zn, Mo, Co, and probably other elements.³ Not all ore differences
442 translate to the slag as well as zinc, but that does not mean that they did not exist.

443 Despite the clear evidence that differences in slag chemistry and mineralogy reflect
444 differences in ore sources, there are some challenges to this analysis. These deposits were not
445 mined in modern times, and many are located in steep, densely forested gorges with no modern
446 settlement and no easy means of access. Thus, it was not possible to locate and sample ancient
447 mines directly to demonstrate that the differences are *between* mining sites rather than *within*
448 mines. However, several lines of evidence point to the former case. Geological surveys do report
449 paragenetic variation between nearby copper deposits, mentioning sphalerite ((Zn,Fe)S) as an
450 accessory mineral in some but not in others (Gabunia, 1933: 556-557). Moreover, the consistent
451 chemical and mineralogical differences between slags from different smelting sites (figure 5)
452 (Erb-Satullo et al., 2014: 153-156) also suggest these major ore variations were mostly between
453 mines, not within them. Otherwise, we would expect to see more homogenous assemblages of
454 slag compositions at different sites. Thus, while some variation within mines is possible, the
455 large differences in the presence and absence of key elements almost certainly reflect the
456 exploitation of distinct deposits.

457 Still, there are limits on the extent to which mines can be distinguished. Nearly all
458 textural and mineralogical information about the ores, which might have allowed more fine-
459 grained differentiation, has been destroyed or severely compromised by the high temperatures of
460 the smelting process. Similarly, more subtle chemical differences have also been obscured.

³ Ag, Pb, and Cr are additional possibilities. Minute inclusions of lead and silver sulfides were noted in one or two slags. Trace lead and chromium concentrations do vary somewhat by site. Silver content was not measured.

461 These circumstances place limitations on the ability to distinguish different ore sources. For
462 instance, there may have been many different deposits of zinc-rich ores that were exploited, but
463 distinguishing between them using slag analysis is challenging.

464 Keeping in mind these limitations, careful use of the portable X-ray fluorescence
465 spectrometer (pXRF) permitted the rapid qualitative analysis of a large number of slags, making
466 it possible to map spatial patterns in ore acquisition and assess to what extent metalworkers were
467 acting in concert to acquire ore. 691 slag samples were analyzed from 39 of the 49 sites
468 surveyed. Analysis of the spectra focused on two elements clearly associated with paragenetic
469 mineral variation in the original ore deposits, Zn and Mo. Spectra were classified as having large,
470 small, or no peak in the X-ray spectrum, corresponding to high, low and no quantities of Zn and
471 Mo. For additional information about the pXRF methodology, especially the methods of
472 classifying peaks, see Appendix A (supplementary material).

473 Qualitative pXRF analysis permits testing of two distinct models of ore acquisition
474 (figure 6). In the coordinated mining model, mining expeditions were organized by local elites,
475 and then ores were smelted in separate camps. If this were the case, we would expect
476 contemporary sites to have used the same types of ores, and exploitation of multiple types of ore
477 at a single site should be fairly minimal. If multiple types of ore are exploited at single sites, one
478 should expect the ore-use profile to be broadly consistent between contemporary sites.

479 On the other hand, in the independent mining model, multiple groups of miners extracted
480 ore from a constellation of mining sites. In this case, contemporary sites would have dramatically
481 different ore-use profiles. This model encompasses both situations where metalworkers at a
482 particular smelting site exploited ores from one source, and cases where metalworkers used ores
483 from multiple deposits. The latter case might indicate that the people carrying out the smelting
484 received ores from multiple groups of miners, or, if the miners and the smelters are the same
485 people, that different ore deposits were exploited during different mining campaigns.

486 The results of a large pXRF survey show some intriguing patterns on both an intra- and
487 inter-site level. For sites where samples were taken from a number of different contexts, the data
488 show a general consistency between different contexts on the same site (figure 7). This is
489 especially clear for the zinc data. Generally, if a site has a high proportion of zinc-rich slags (e.g.
490 Site 28), that high frequency is seen across a range of contexts. On the other hand, some sites
491 have no high zinc slags, despite the fact that multiple contexts were sampled (e.g. Sites 5 and

492 46). Only Site 43 showed a marked difference between surface collected slags and those from
493 test pit contexts, suggesting that multiple ore sources were exploited by metalworkers at the site.

494 The data for the presence and absence of molybdenum show the same relative
495 consistency between different contexts at the same site. Compared with the data for zinc,
496 however, the patterns are less clear. Several explanations may account for this difference. Even
497 in high molybdenum samples, the absolute concentration of molybdenum is less than that of
498 zinc, meaning that the tripartite categorization signifies a finer scale of differentiation (see
499 Appendix A in online supplementary material). The smaller absolute quantities of molybdenum
500 in the slag (and, correspondingly, the ore), mean that smaller variations are required to shift the
501 sample to another qualitative category and obscure the translation of the ore pattern to the slag. It
502 is also unclear how molybdenum content is affected by smelting, since available experimental
503 data does not discuss that element (Tylecote et al., 1977). Interestingly, very few samples had a
504 high content of both molybdenum and zinc. Among the samples with low or no zinc, however,
505 there are large numbers of samples both with and without high molybdenum.

506 These intra-site comparisons point to several conclusions. The results suggest that
507 variability found in surface collected slags are reasonably good approximations of the range of
508 ores being smelted at the site, though surface collections likely contain a wider range of variation
509 than small test pits. The data on molybdenum variation may point to the same conclusion, though
510 the smaller absolute variation and outstanding questions about partitioning make this dataset
511 somewhat less reliable. The likely use of ores from distinct mining locales could be the result of
512 exploiting different outcrops in different years of seasonal work.

513 Maps of ore-derived variations in slag chemistry reveal significant patterns. Maps were
514 produced based on zinc data alone, molybdenum data alone, and a combination of the two. The
515 zinc map reveals striking differences in the use of zinc-rich ores between different sites (figure
516 8). A number of sites with large sample sizes (e.g. 5, 46, 25, and 41) have no high-zinc slags,
517 indicating that they were exploiting ore deposits with little to no zinc. This is a striking contrast
518 to other sites (e.g. 8, 14, 24, 28, and 29), where the majority of slag samples are rich in zinc.

519 Moreover, there is very little spatial correlation between sites using zinc-rich ores and
520 sites using zinc-poor ores. High-zinc slags are found at slightly higher frequencies in the
521 southwest portion of the survey area, while low and no-zinc slags are slightly more common in
522 the northeastern part, but this is not a sharp distinction. This slight pattern is likely a reflection of

523 proximity to ores of different types. Zinc-rich ore deposits may be closer to the smelting sites in
524 the southwestern area, while zinc-poor ores are probably more common in areas closer to the
525 northeastern part of the survey area.

526 Remarkably, different ore types were often used at sites in very close proximity to one
527 another. For instance, metalworkers at Site 14 exploited large amounts of high-Zn ores (15 of 16
528 samples), while neighboring Site 36, located about 100 m away, apparently did not (0 of 8
529 samples). The data are even more compelling for Site 27 and 28, which have larger sample sizes
530 and are about 90 m from one another. Only 1 sample of 46 at Site 27 was categorized as zinc-
531 rich, while 31 of 47 samples were zinc-rich at Site 28. These comparisons strongly suggest that
532 these proximate sites were *not* part of a larger, coordinated mining expedition. Spatial proximity
533 of sites using the same ore sources is a key prediction of the coordinated mining model. The lack
534 of this spatial patterning is further indication that mining and smelting were conducted by
535 multiple independent groups of miners and metalworkers. Some of these pairs of proximate sites
536 may have been occupied sequentially. Metalworkers probably did not build new workshops
537 every season, but they may have shifted sites of production between different generations. At
538 that point, the veins or outcrops exploited by the earlier generation of metalworkers may have
539 been exhausted, prompting a change in ore source.

540 Radiocarbon dating supports the independent mining model, showing that sites exploiting
541 zinc-rich and zinc-poor ores were in operation at about the same time (for detailed discussion of
542 chronology, see Erb-Satullo et al., submitted). Two wood charcoal samples from Site 28 were
543 dated to 996-842 calBC (95% confidence) and 1026-836 calBC (95% confidence), while a single
544 charcoal sample from Site 27 produced a date of 1016-839 calBC (95% confidence). Sites 5 and
545 8 also date to the same period, yet have dramatically different ore-use profiles. Two charcoal
546 samples from Site 5, which had no high zinc slags among the 46 analyzed, yielded dates of 970-
547 961; 935-822 calBC (95% confidence) and 908-812 calBC (95% confidence). Two samples from
548 Site 8, a site with abundant zinc-rich slags, were dated to 915-815 calBC (95% confidence), and
549 1086-903 calBC (95% confidence). These dates do not prove that metalworkers were operating
550 these sites at exactly the same time, as each site was probably not occupied continuously for
551 100+ years. Nevertheless, the dating does show that the exploitation of zinc-rich and zinc-poor
552 ores were not separated by hundreds of years. Importantly, these results contradict the
553 predictions of a coordinated mining model.

554 The spatial patterning of molybdenum-rich samples reveals generally similar patterns
555 (figure 9). There are some inter-site differences in the molybdenum content (compare Sites 5, 8,
556 27, and 29), but these differences are not as sharp as in the zinc data. Mapping patterns of zinc
557 and molybdenum data together (figure 10) revealed additional patterns, suggesting a greater
558 diversity of mining sites. While zinc-rich slags are slightly more common in the southwestern
559 parts of the survey area, zinc- *and* molybdenum-rich slags, though rare overall, are more
560 common in the northeast. Similarly, the combined dataset suggests that there may be different
561 kinds of zinc-poor deposits, as evidenced by the differing molybdenum content in zinc-poor
562 slags at Sites 5 and 41. In conjunction with the WDS-XRF trace element analyses on the more
563 limited sample, these results hint that the number of mining sites almost certainly exceeds the
564 capacity of the available methods to distinguish them. It is highly likely that zinc-rich ores from
565 one site likely came from a different mine than zinc-rich ores from another site.

566 Results from the large-scale qualitative pXRF analysis of slags have crucial implications
567 for the spatial and social organization of mining and smelting. Combined with the spatial
568 dispersion of the smelting sites, the evidence that metalworkers were using ores from different
569 mining sites points to the conclusion that primary production was carried out independently by
570 different groups of people (figure 11). Though they may have shared technological practices,
571 evidence for more sustained coordination or top-down organization in raw copper production is
572 minimal. Still, questions remain about the organization of production elsewhere in the *chaîne*
573 *opèratoire* of bronze production. Is there evidence that artifact production was nucleated and
574 perhaps controlled by certain social groups? Answering this question requires an analysis of
575 secondary production sites.

576

577 **5. The Organization of Secondary Production**

578

579 Archaeological evidence shows that raw copper, and in some cases alloyed bronze, was
580 transported from smelting sites to settlement sites for casting and forging into artifacts.
581 Numerous bronze hoards have been found in the region (Lordkipanidze, 2001: Fig. 1). The
582 hoards include both finished artifacts as well as pieces of raw metal in the form of ingots, ingot
583 fragments, or amorphous lumps of metal. Mostly, the unformed metal is unalloyed copper
584 (Abesadze and Bakhtadze, 2011 [1988]: 362-365). These analyses suggest that most copper was

585 alloyed in the later stages of production, just before casting into metal. This data conflicts with
586 the clear evidence that some alloying did happen at primary smelting sites, earlier in the
587 production sequence (Erb-Satullo et al., 2015). Perhaps metalworkers followed different
588 production sequences, depending on whether they had immediate access to alloying materials.
589 Ingot sizes tend to vary, and there is little evidence for standardization. It is difficult to track the
590 exact pathways of metal from smelting sites to casting foundries in settlements. However, there
591 is certainly nothing comparable to the fortified Cypriot sites that some interpret as way stations
592 for copper travelling from the mines to the coast (Kassianidou, 2012: 97; Peltenburg, 1996: 35).
593 Metalworkers may have brought the raw metal from smelting sites to the more densely settled
594 areas themselves. The only evidence for the consolidation of metal resources comes from
595 examples of very large ingots, which are found in many museums in western Georgia (e.g.
596 Ozurgeti Museum, Dadiani Museum in Zugdidi, Kutaisi State Historical Museum). Their size in
597 relation to the crucibles found at smelting sites suggests that these ingots may be metal
598 consolidated from several different smelting episodes. One example in the Kutaisi State
599 Historical museum is only partially fused, and many different artifacts are visible. Since most of
600 these very large examples have no detailed contextual information, it is difficult to know whether
601 the metal was consolidated as part of a non-retrievable offering or as a means of amassing
602 metallic wealth.

603 The highly dispersed pattern of production found in smelting activities also extends to
604 secondary production—the process of making finished goods out of raw metal (figure 12).
605 Mikeladze notes “the presence of bronze casting molds at all Colchian settlements beginning at
606 least from the end of the 3rd millennium BC, despite their strictly agricultural character”
607 (Mikeladze, 1990: 26) (NES translation). Many of these settlements are in lowland coastal areas
608 somewhat removed from the foothill zones where smelting sites are concentrated. At Ispani, an
609 Early Bronze Age settlement found beneath peat deposits near the modern resort town of
610 Kobuleti, several tuyères and casting molds were found (Mikeladze and Khakhutaishvili, 1985:
611 Pl.4). The settlement has been dated by radiocarbon to the 3rd millennium BC (Burchuladze et
612 al., 1976: 359; Burchuladze and Togonidze, 1987: 244). Other early evidence for casting and
613 shaping of artifacts comes from the central tell settlement at Pichori and Anaklia II, in layers
614 dated to the late 3rd and early 2nd millennia BC (Apakidze, 2009: 334, 337, Tf . 339-311;

615 Baramidze et al., 2002; Mikeladze, 1990: Pl. 4). These include molds for hoes and axes, as well
616 as other implements.

617 Evidence for secondary metal production is equally abundant in later periods that are
618 contemporary with the Supsa-Gubazeuli smelting sites. The tell settlement of Namcheduri has a
619 stratigraphic sequence spanning the Late Bronze Age to the Classical period (Mikeladze and
620 Khakhutaishvili, 1985). Casting molds are found in many levels (VI, V, and III, dated by the
621 excavators to the mid-second millennium BC, the 12th-11th c. BC, and no later than the 7th c.
622 BC, respectively), and include those for making jewelry, miniature and full-size axes, and a
623 dagger or spear (Mikeladze and Khakhutaishvili, 1985: Pl. 36). Tuyères were found in
624 construction fill between Namcheduri levels III and IV, and were interpreted by the excavators
625 as originating from an earlier workshop at the base of the mound (Mikeladze and
626 Khakhutaishvili, 1985: 26-27). A broad range of metallurgical implements, including tuyères,
627 crucible fragments, ladles, and a wide variety of molds, were found at Choloki, another site in
628 the immediate vicinity (Apakidze, 2009: 340-341; Chavleishvili, 1991). Architectural remains at
629 Choloki are relatively well preserved, and show that metal production was carried out in a small
630 circular building with a single furnace. Namcheduri and Choloki were probably part of a mosaic
631 of patchy, low density settlement, located on drier ground within a marshy landscape (Connor et
632 al., 2007; Mikeladze and Khakhutaishvili, 1985: 4, Pl. 1; Tsetskhladze, 1999: 31-35). The
633 presence of metalworking debris in two places suggests that artifact production may not have
634 been restricted to a single area within this low density settled area.

635 Metal production debris has been found at numerous other LBA-EIA settlements in
636 Colchis. Recent excavations at Kulevi have yielded a casting crucible, tuyères, numerous axe and
637 jewelry molds (Papuashvili and Jibladze, 2014), as well as a bronze ingot and a possible iron
638 bloom (personal observation, Poti Museum of Colchian Culture), which the excavator dates to
639 the 8th-7th centuries BC (Papuashvili, personal communication). A dagger mold was found
640 along with “pre-antique” (roughly 8th-early 6th c. BC) ceramics at Pichori, Mound 4, another
641 smaller tell settlement 35-40 m from the Pichori settlement discussed above (Apakidze, 2009:
642 335). Crucibles, ingot fragments, and a possible furnace were discovered near the top of
643 Sukhumi Hill and dated to the turn of the 1st millennium BC on ceramic evidence (Kalandadze,
644 1953: 89-91). The description of the finds and the accompanying drawings suggest the
645 possibility that this furnace was intended for melting copper to produce large ingots

646 (Kalandadze, 1953: figs. 28-30, Pls. II, XXII). At Dablagomi near Vani, molds, crucibles, and
647 copper-alloy ingots were found (Tolordava, 1977). Farther inland, crucible fragments have been
648 found near Itkhvisi, a site with occupation spanning the 1st millennium BC (Apakidze, 2009:
649 354, Tf. 395). A mold for inlay was discovered in excavations at Tskheta and dated to the 8th-5th
650 c. BC (Sulava, 2008).

651 Assessing the social contexts of craftspeople who made bronze artifacts is challenging,
652 since detailed contextual information is often lacking, and the predominantly wooden
653 architecture of the period typically does not preserve well. The pyrotechnological feature on top
654 of Sukhumi Hill may be significant, since bringing fuel and metal up to the top of a steep hill
655 seems unnecessary in the absence of an explicit desire to control and/or protect the products of
656 metal production. Whatever this decision signifies about the control of this particular workshop,
657 the ubiquity of secondary production debris at a wide range of sites suggests that, as a whole,
658 copper and bronze production was not controlled, even if bronze was a valued material used for a
659 range of prestige and agricultural items. The lack of centralization, coupled with a general lack
660 of evidence for extreme hierarchy until well into the 1st millennium BC (see Kacharava and
661 Kvirkevelia, 2009), shows that local elites probably did not exercise exclusive control over the
662 production of artifacts from raw metal. Coupled with the ubiquity of ore deposits and the
663 dispersed distribution of smelting sites, the evidence of secondary production suggests that
664 efforts at direct control over production of raw copper and most types of artifacts were bound to
665 be futile.

666

667 **6. Conclusion: The Social Organization of Bronze Production**

668

669 Detailed examination of the production of copper alloys, from mining and smelting in the
670 foothill and mountain zones, to casting and forging workshops in lowland coastal areas, reveals
671 an industry whose defining feature at nearly every stage is dispersion. Mining was carried out on
672 a small scale at numerous different outcrops, as evidenced by the chemical analysis of a large
673 sample of slags. Smelting was equally dispersed, and any putative attempt at coordination would
674 have had to confront serious challenges posed by the rough topography and dense vegetation of
675 the sub-tropical landscape. Casting and forging of artifacts did not take place at the smelting
676 sites, but the distribution of secondary production debris shows a similar lack of spatial

677 concentration. Molds, tuyères and casting crucibles are found at numerous sites, but never in
678 quantities that suggest massive centralized production. There are some ambiguous hints (e.g. the
679 hilltop workshop at Sukhumi) that metal resources were deemed worthy of protection, and the
680 ubiquity of Late Bronze Age hoards suggests some accumulation of metal wealth, but there is no
681 evidence that control of production was in any way exclusive. This situation contrasts with shell
682 bead production in the Channel Islands (Arnold and Munns, 1994). In the latter case, elites
683 maintained exclusive control over a key node in the production and distribution chain, giving
684 them effective control over bead production, even if it did not take place under their direct
685 supervision. In ancient Colchis, the ubiquitous evidence for both primary and secondary
686 production, the modest quantities of metallurgical debris found at any individual site, and the
687 broad range of metal uses all point to a single conclusion: exclusive control of the metal supply
688 was impossible.

689 Many lines of evidence, though indirect, point to seasonal smelting carried out by
690 metalworkers moving between lowland areas and foothill/mountain zones. First, climatic factors
691 would have made it difficult to carry out smelting year-round. Some areas of western Georgia
692 receive more than 2500 mm of precipitation per year, with significant seasonal variation (Connor
693 et al., 2007: 32-33; Lydolph, 1985: 280). Snow would have prevented access to mines at higher
694 elevations in the winter. If the metalworkers also engaged in agriculture, smelting would have to
695 have been scheduled around the harvest and planting seasons. Second, there is little evidence of
696 permanent habitation at smelting sites in the Supsa-Gubazeuli region, given the almost
697 exclusively metallurgical character of the finds. With few possible exceptions (Khakhutaishvili,
698 2009 [1987]: 95), settlement sites have not been found in the vicinity of smelting sites. This may
699 reflect a real absence of habitation in these areas, or it may reflect the difficulty of finding
700 settlements in such a densely vegetated landscape. Third, intra-site chemical variation (see
701 discussion of Site 43 above) and the small size of the sites are consistent with intermittent
702 smelting episodes in which different ore outcrops were exploited at different times.

703 Based on the current evidence, it is not possible to say whether metalworkers lived
704 permanently within a few kilometers of their smelting camps and travelled back and forth every
705 day, or whether they lived tens of kilometers away in the more densely settled coastal lowland
706 areas and stayed at the smelting sites only for the duration of a seasonal smelting campaign.
707 Whether or not the metalworkers themselves moved between these different topographic zones,

708 the evidence clearly demonstrates the regularized movement of people and materials between
709 these areas. Considering the output of each smelting site and the modest distances involved,
710 however, the balance of evidence favors a model where people producing metal were also
711 involved with its transport to more populated areas. The smelting sites, therefore, served as
712 intermediate nodes between the areas where coastal/lowland raw materials, labor, and markets
713 were located and the ore-bearing zones located somewhat further up in the mountains.

714 In this light, the spatial segmentation of different stages of production should not be seen
715 as evidence for horizontally specialized production. In other words, *spatial* segmentation of
716 production does not require *social* segmentation of metalworkers by production stage.
717 Metalworkers probably moved between lowland and foothill areas as part of a regular pattern of
718 movement. If different people were involved in secondary production, primary smelting, and ore
719 mining, it is likely that these groups would have been closely connected socially, probably by
720 kinship relations. The ubiquity of small-scale production debris suggests that metallurgical
721 knowledge was fairly widespread in Colchian society. Yet at the same time, the complex, multi-
722 stage process of copper-sulfide smelting would have required significant time to learn, and a
723 relatively structured system of apprenticeship probably existed.

724 There is much discussion in the literature about the formation of a specialized group of
725 craftspeople, especially in the 1st half of the 1st millennium BC (Khakhutaishvili, 1981;
726 Khakhutaishvili, 2009 [1987]: 123-125; Khakhutaishvili, 2008; Khakhutaishvili and Khalvashi,
727 2010). Given the considerable elasticity of the term “specialization” (Clark and Parry, 1990;
728 Costin, 1991; Flad and Hruby, 2007; Muller, 1984), it is worth examining how it has been
729 applied in the Colchian case. Significant emphasis has been placed on textual descriptions in
730 Appolonius of Rhodes’ *Argonautica*, linking these accounts to ethnographic descriptions of
731 metalworkers in Georgia (Khakhutaishvili, 2009 [1987]: 125). Passages in the *Argonautica* seem
732 to present a textbook case of specialization defined as an activity undertaken at the expense of
733 subsistence pursuits: “[The Chalybes] do not use the ploughing ox. They not only grow no corn,
734 but plant no vines or trees for their delicious fruit and graze no flocks in dewy pastures. Their
735 task is to dig for iron in the stubborn ground and they live by selling the metal they produce. To
736 them no morning ever brings a holiday. In a black atmosphere of soot and smoke they live a life
737 of unremitting toil.” (*Argonautica* 2.1002-1008, tr. E.V. Rieu).

738 Interpretations of this vivid passage, composed sometime in the 3rd century BC (Murray,
739 2014), must be undertaken with caution. The fact that the passage refers to iron production
740 makes its relevance to the organization of copper smelting as much as 1000 years earlier
741 somewhat questionable. Though the accuracy of external descriptions of peoples and places is
742 itself uncertain, the Chalybes and the Colchians are distinguished in the narrative, with the land
743 of the Chalybes situated somewhere to the south and west of Colchis (Tsetskhladze, 1995: 321;
744 Tsetskhladze and Treister, 1995: 18). Conservatively, one may conclude that late 1st millennium
745 BC descriptions of metal producers in the southeastern Black Sea region simply reflect the long-
746 standing tradition of metallurgical expertise in the region. Earlier archaeologists studying these
747 metallurgical landscapes have not simply taken the reports of extreme specialization (i.e. the
748 complete abandonment of agriculture in favor of metal production) at face value. Rather, they
749 present a picture of seasonal metal production mostly in line with the new data presented here
750 (Khakhutaishvili, 2009 [1987]: 123-125), with the exception that earlier hypotheses of
751 centralized administration are no longer tenable.

752 This detailed examination of the copper and bronze industry in western Georgia provides
753 no evidence that metal production was organized and controlled by a single unified authority.
754 Yet metalworkers at these sites constructed workshops with similar layouts, built similar
755 furnaces, and used similar smelting techniques. If these similarities were not the product of
756 imposed top-down organization, they nonetheless require explanation in the context of the
757 proposed model of dispersed mining and smelting carried out by independent groups of
758 metalworkers.

759 Evidence of homogeneity in technological practice does not necessarily indicate the
760 existence of a centralized, highly organized, tightly controlled mode of production. A better way
761 of explaining these shared characteristics is through reference to the concept of a “community of
762 practice” (Stöllner et al., 2016; Wenger, 1998, 2000). This term refers to a group of craftspeople
763 who interact and exchange ideas in both structured and unstructured ways. “Communities of
764 practice” include both tightly connected, constantly interacting groups and more loosely joined
765 associations (Wenger and Snyder, 2000: 139-140). As a whole, the metalworkers on the
766 southeastern coast of the Black Sea probably fall on the more loosely connected end of that
767 spectrum, though smaller, kin-related sub-groups within this larger community likely had more
768 regularized contact. Dispersed groups and irregular contact are by no means insurmountable

769 barriers to community formation, nor is the fact that metal producers were engaged in
770 independent mining enterprises. Ethnographic and historic studies of mining and craft production
771 have shown that metalworkers maintain social ties over long distances, even in spite of high
772 levels of mobility and transience (Douglass, 1998). Ideas and techniques developed by some
773 members of the group may be transferred to others through apprenticeships or less structured
774 modes of communication (Minar and Crown, 2001; Wendrich, 2013). Regular movements of
775 people and materials between centers of settlement and marginal foothill zones would facilitate
776 these contacts, as areas rich in metal deposits drew in craftspeople living in different lowland
777 areas. These kinds of social relations create a defining feature of communities of practice: their
778 “shared repertoire” for approaching and solving particular problems (Wenger, 2000: 229). This
779 concept not only explains why, with minor variations, copper smelting sites are remarkably
780 similar, it also explains how this homogeneity can occur without accompanying evidence for top-
781 down organization.

782 This reconstruction of the organization of Colchian metal contrasts sharply with other
783 well-documented contemporary metal production systems in Southwest Asia (Ben-Yosef et al.,
784 2012; Levy et al., 2014; Weisgerber, 2003: 85-86). Despite the recognition that craft production
785 indices are theoretically independent, many of the better documented case studies show strong
786 correlations between scale, concentration, and organizational complexity. The smelting
787 landscapes of the southeastern Black Sea region provide a clear counterexample. In aggregate,
788 the copper production industry was large-scale, as evidenced by the quantity of both metal
789 artifacts and production debris found in the region. Yet individually, sites are quite small, and
790 many lines of evidence point to an industry composed of numerous small groups of
791 metalworkers who, though they employed similar technologies and probably had at least
792 intermittent contact with one another, did not coordinate activities in any systematic way. While
793 the Colchian case is remarkable for the number of sites recovered in such a small area, this
794 model of production was probably not unique to the South Caucasus. The Colchian smelting
795 landscape has some intriguing parallels in Central Europe (Stöllner, 2003: 433-435; Stöllner et
796 al., 2016), and if more small smelting sites like Politiko Phorades (Knapp and Kassianidou,
797 2008) are found, the organization of LBA Cypriot mining and smelting may require re-
798 evaluation.

799 The Colchian copper mining and smelting landscape might be compared to a slow-
800 motion gold rush. The rates of production surely did not approach those of the Californian or
801 Yukon gold rushes; Colchian production landscapes formed over several hundred years. There is
802 no evidence that Colchian mining operations followed the claim systems of the western gold
803 rushes, but as with the Toro of Uganda (Childs, 1998), there were probably local norms and
804 practices governing mining rights. The pattern of numerous small groups of miners, smelters,
805 and craftspeople exploiting metal deposits in an uncoordinated manner applies to both situations.
806 The model of loose networks of mining communities in the American West (Douglass, 1998),
807 involving exchange of ideas, competitive behaviors, and fairly high levels of mobility, is
808 applicable to the Colchian copper industry. Fundamentally, these cases show how production
809 taking place at individually small-scale sites can, in aggregate, play a major role in shaping the
810 landscape.

811 This discussion of the Colchian copper industry adds a new dimension to recent
812 discussions of technological development and social organization of craft production. Recent
813 work on the emergence of metallurgy on the Iranian plateau has argued that technological
814 developments do not always follow a predictable linear sequence according to the so-called
815 “Levantine Paradigm” (Thornton, 2009a, 2009b). Thornton demonstrates the co-existence of
816 production in both domestic spaces and specialized workshop areas at the same site (Thornton,
817 2009a: 189-198). Similar evidence has emerged even in the Southern Levant. Copper smelting
818 debris in Timna, originally assigned to the Chalcolithic due to its simpler technology, has been
819 re-dated on the basis of paleomagnetic intensity measurements to the Early Iron Age, roughly
820 contemporary with the large fortified smelting camp at Site 30 (Ben-Yosef et al., 2010). Copper
821 production landscapes in the South Caucasus are remarkable for their combination of small site
822 sizes, dispersed distribution, and large aggregate scale of production. The Colchian metal
823 production industry shows that large industries with high aggregate output using complex
824 technologies need not be centralized, nor must they be coordinated on a large scale.

825

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827

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842

843 **Figure Captions**

844

845 Figure 1. Map of Late Bronze-Early Iron Age copper smelting sites in Western Georgia, mapped
846 by the authors in 2010-2014. Contours in the largest-scale map are at 5 m intervals.

847

848 Figure 2. Lines of sight between smelting sites in the Supsa-Gubazeuli area, assuming a 2 m
849 target and observer height. Contours are at 5 m intervals.

850

851 Figure 3. Geological map with approximate locations of known copper deposits. Information on
852 base geology from Nazarov (1966). Each circle indicates approximate location of a deposit
853 mentioned in Gabunia (1933: 556-557). Information about exact locations is variable, hence the
854 variable sizes of the circles. Contours are at 100 m intervals.

855

856 Figure 4. Schematic representation of how paragenetic mineral variation in ore veins is translated
857 into the chemical composition of the slag. The example shown is for zinc-bearing minerals such
858 as sphalerite. Similar processes may also apply to other elements, though partitioning and
859 volatilization may affect how well these variations translate from ore to slag.

860

861 Figure 5. Plot of molybdenum versus cobalt trace element content in copper smelting slags, as
862 measured by powder WDS-XRF.

863

864 Figure 6. Alternative models of copper ore mining and distribution to smelting sites.

865

866 Figure 7. Intra-site variation in slag composition as determined by pXRF. Each bar represents a
867 single context. Site numbers are given before the "-". Surface collections (-S) are treated as a
868 single context. Broken vertical lines divide contexts from different sites.

869

870 Figure 8. Map of the presence of Zn at smelting sites in the Supsa-Gubazeuli production area. Pie
871 charts show the proportion of samples at each size which have no Zn, low Zn, and high Zn. The
872 size of the pie chart is related to the number of samples analyzed (see figure A1 in online
873 supplementary material). Pie charts are labeled with site numbers.

874

875 Figure 9. Map of the presence of Mo at smelting sites in the Supsa-Gubazeuli production area.

876 Pie charts show the proportion of samples at each size which have no Mo, low Mo, and high Mo.

877 The size of the pie chart is related to the number of samples analyzed (see figure A1 in online

878 supplementary material). Pie charts are labeled with site numbers.

879

880 Figure 10. Map of the combined presence of Zn and Mo at smelting sites in the Supsa-Gubazeuli

881 production area. The size of the pie chart is related to the number of samples analyzed (see figure

882 A1 in online supplementary material). Pie charts are labeled with site numbers.

883

884 Figure 11. Model showing independent groups of metalworkers exploiting multiple ore deposits

885 in a zoned ore body.

886

887 Figure 12. Map of sites in western Georgia where evidence of secondary production

888 (casting/melting crucibles, tuyères, casting molds) has been found.

889 **Tables**

890

891

Site Number	Khakhutaishvili Site Name	Collected Slag Pile (Cubic Meters)	Slag (kg) (Calculation 1)	Area (m ²)	Thickness (m)	Slag (kg) (Calculation 2)	Notes
8	Askana II,1	8	12000	80	1	13000	
8	Askana II,2	10	15000	100	1.2	19000	
15	Askana III,1	8	12000	600	0.4	38000	
18	Mziani I	10	15000	300	n/a	n/a	Slag heap damaged by agricultural activities
19	Mziani II	4	6000	n/a	n/a	n/a	
20	Mziani III,1	4	6000	200	0.3	9000	Slag heaps associated with other furnaces at Mziani III too heavily disturbed
21	Mziani IV	2	3000	100	n/a	n/a	Slag heap partially damaged.
14	Mshvidobauri I	n/a	n/a	400	0.4	25000	
—	Mshvidobauri IV	10	15000	400	n/a	n/a	Slag heap partially damaged.
16	Nagomari I,1	5	8000	200	0.25	8000	
—	Charnali I,1	6	9000	60	1	9000	Two slag heaps of Charnali I are reported as overlapping
—	Charnali I,2	3	5000		n/a	n/a	Two slag heaps of Charnali I are reported as overlapping
—	Jikhanjuri I,1	4	6000	30	0.55	3000	Text mentions 4 cubic meter in one place and 5 in another.
—	Jikhanjuri I,2	4	6000	20	0.35	1000	
—	Jikhanjuri I,3	5	8000	40	0.4	3000	
—	Jikhanjuri III	5	8000	40	0.35	2000	
—	Jikhanjuri IV	10	15000	60	0.4	4000	
55	Tsetskhauri I	10	15000	600	0.5	47000	

possibly 56	Tsetskhlauri II	10	15000	300	0.45	21000	
—	Tsetskhauri III	6	9000	200	0.4	13000	
54	Leghva I,1	5	8000	100	0.5	8000	
54	Leghva I,2	6	9000	n/a	n/a	n/a	
74	Chogha I	5	8000	n/a	n/a	n/a	

892

893

894 Table 1. Rough calculations of slag at previously excavated sites, using two independent
895 methods. Calculation 1 uses the cubic meters of slag reported in Khakhutaishvili (2009 [1987]),
896 and density estimated by Gilmour in the foreword to that book. Calculation 2 takes
897 Khakhutaishvili’s report of the area and depth of the slag heap, and approximates the volume of
898 the slag heap (dirt included), modeling it as a generalized cone. Estimated measurements of slag
899 mass per cubic meter of (unexcavated) slag heap (from testing of Site 43 in 2012) were then used
900 to estimate the total slag mass. All estimates were rounded to the nearest 1000 kg. Note:
901 Khakhutaishvili often subdivided sites, using with Arabic numerals following the Roman
902 numerals to refer to different furnaces and their associated slag heap. Those slag heaps with
903 Arabic numerals are therefore only part of the total quantity of slag at a site. For example, while
904 dimensions of the slag heap and quantities of slag are reported for Mziani III,1, no values are
905 given for Mziani III,2 and Mziani III,3.

906

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1 **Appendix A (Supplementary Material). pXRF Methodology for Rapid Qualitative Analysis**
2 **of Slag**

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Qualitative portable X-ray fluorescence (pXRF) analysis of a large number of slags was used to track patterns of ore acquisition and demonstrate lack of coordination in copper mining activities. The analysis focused on measuring the zinc and molybdenum content of the slags as a means of approximating variation of those elements in different ore deposits. While WDS trace element analysis showed cobalt also varies between ore sources, the overlap between the large Fe K_{β} and the Co K_{α} X-ray peaks complicated measurement of Co by pXRF.

While quantitative analyses by pXRF are possible in certain well-controlled circumstances (Mass and Matsen, 2012; Shugar and Mass, 2012), doing so in this case is both inappropriate and unnecessary. Slags contain significant quantities of low-atomic weight elements, which the pXRF is ineffective at detecting, and standards for the two primary elements of interest, zinc and molybdenum, were unavailable. Moreover, rigorous quantification is unnecessary: the variation in the elements of interest is large and easily detected by qualitative methods alone.

Where possible, the samples were taken from a range of different contexts in order to maximize the likelihood that the sample assemblage reflects many different smelting episodes. Slags from sites with radiocarbon dates were particularly heavily sampled, with 10 sites having 25 or more analyses (Figure A1). Samples were analyzed using a Bruker Tracer III-V with the yellow Ti-Al filter at 40 kV without any vacuum attachment. Current was adjusted to keep counts under about 10,000 cps. Counting times were a minimum of 100 seconds. Where possible the analysis was done on a freshly broken edge or polished section, but for some samples (such as thin slag glazes on ceramics) only surface analyses were possible. Comparison of spectra gathered from a broken edge and the corroded surface of the same sample showed that in qualitative terms, the choice of where to analyze the sample made little difference. In most cases, only a single measurement was necessary, as repeat measurements usually yielded similar results. However, if spectra were qualitatively anomalous or unusual in some way, repeat measurements were done.

Qualitative pXRF analysis produces an energy spectrum with peaks corresponding to specific elements. The size of the peak is proportional to the amount of that element present in

32 the sample. Spectra were examined visually and given a preliminary assignment to one of three
33 categories—no peak, a small peak, or a large peak. The primary distinguishing feature was the
34 relative heights of zinc and molybdenum peaks to the copper peaks in the characteristic X-ray
35 spectrum. Classification was made on a relative basis with respect to the peak sizes of that
36 element in the assemblage as a whole, meaning that a sample with “high” Mo was high with
37 respect to the Mo content of the assemblage as a whole. “High” zinc peaks, were generally much
38 larger than “high” molybdenum peaks, as the absolute Zn content of the slags was much greater
39 than the absolute Mo content. Following this initial categorization, a more consistent method of
40 categorization was developed by calculating area-under-the-curve ratios using Artax 7 software.
41 The deconvolution method included the following elements: K, Ca, Ti, Mn, Fe, Co, Ni, Cu, Zn,
42 As, Rb, Sr, Zr, Mo, Rh, Sn, Ba, W, and Pb. Area-under-the-curve ratios between Zn/Cu and
43 Mo/Cu were calculated, correcting for variable count times and rates between samples. Cu was
44 chosen as the reference, since that element also derived exclusively from the ore source.

45 Next, by reexamination of a number of different spectra and referring back to their
46 original preliminary visual categorization, sharp cut-offs were fixed between categories. This
47 created a rigorous classification system that eliminated any creep in the definition of the
48 categories between spectra collected over a period of several months. In the minority of cases
49 where multiple spectra were measured for a single sample, peak ratios were averaged prior to
50 classification. For the Zn/Cu area-under-the-curve categorization, 0.02 was cutoff between “no
51 zinc” and “low zinc,” while 1 was the cutoff between “low zinc” and “high zinc.” For the Mo/Cu
52 area-under-the-curve categorization, 0.06 was cutoff between “no molybdenum” and “low
53 molybdenum,” while 0.2 was the cutoff between “low molybdenum” and “high molybdenum.”

54 The sharp and somewhat arbitrary cut-offs for such qualitative classification may invite
55 some skepticism. What if a particular slag was corroded in such a way that it was incorrectly
56 classified? What if the boundaries between categories were incorrectly placed? The coarse
57 qualitative categorization and large sample size mean that the “erroneous” classification of a few
58 borderline samples will not obscure the broader pattern. In any event, the smelting process itself
59 is an imperfect translation of ore mineralogy to slag chemistry, so minor variations have no
60 significance for understanding broader patterns of ore acquisition. Anomalous single
61 measurements were not given great interpretive weight, especially not without reference back to

62 the original spectra and any accompanying notes taken during analysis. Adjusting of the cut-offs
63 does shift a few samples between categories, but the overall pattern does not change.

64

65 **List of Figures**

66

67 Figure A1. Sample sizes for pXRF analysis.

68

69 **Caption for table of WDS-XRF chemical analyses included as online supplementary** 70 **information**

71

72 Table S1. Trace element WDS-XRF analyses of copper production slags. Values above 10,000
73 ppm (1 %) are outside the calibrated range of the instrument, and may not be accurate. Slag types
74 include amorphous spongy slags (A) dense slag cakes (D) and more fluid tap slags (TS). See
75 Erb-Satullo et al. (2014; 2015) for a more detailed discussion of slag types and the technology of
76 production. An entry of “nm” means that the element was not measured for that sample.

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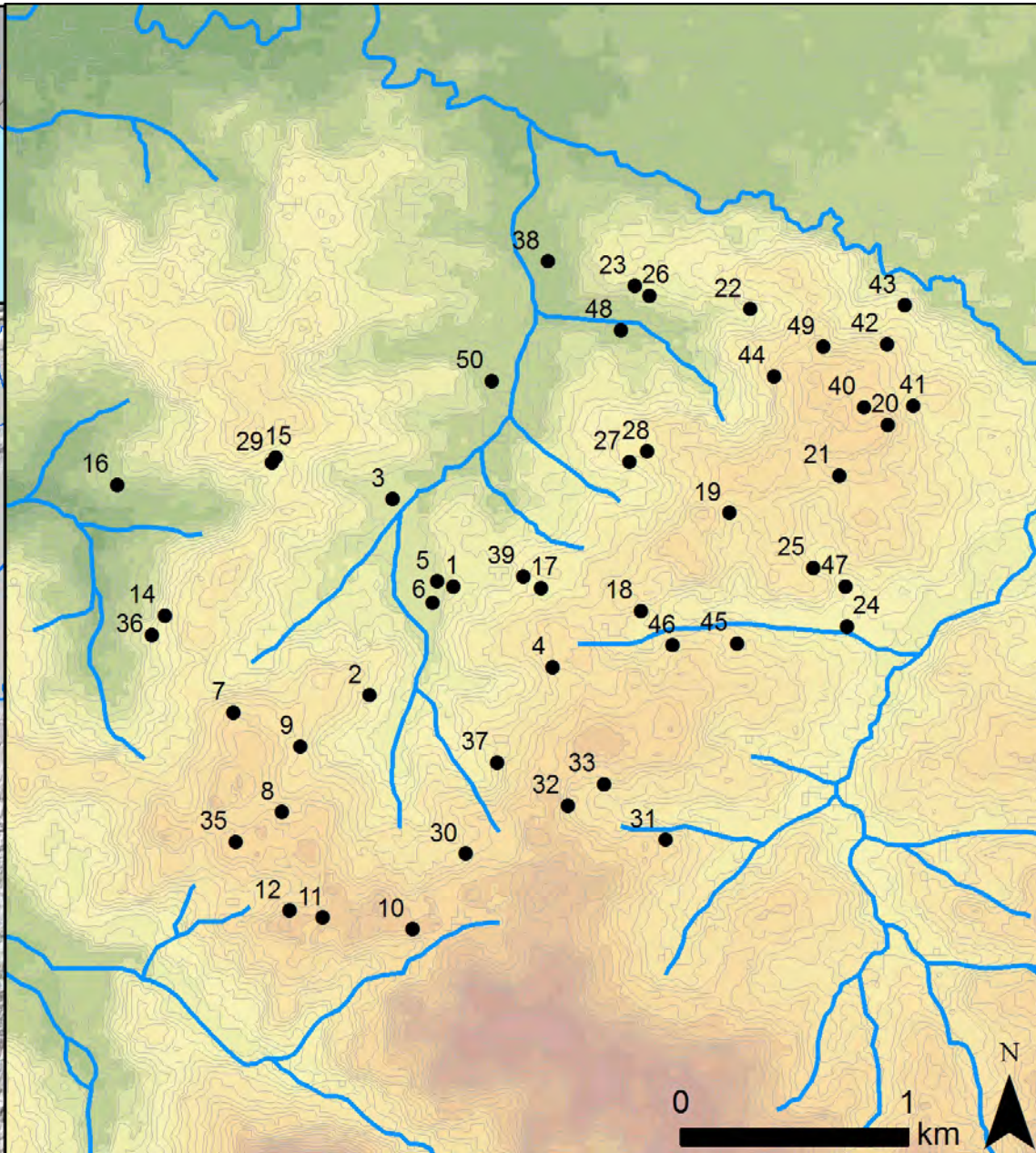
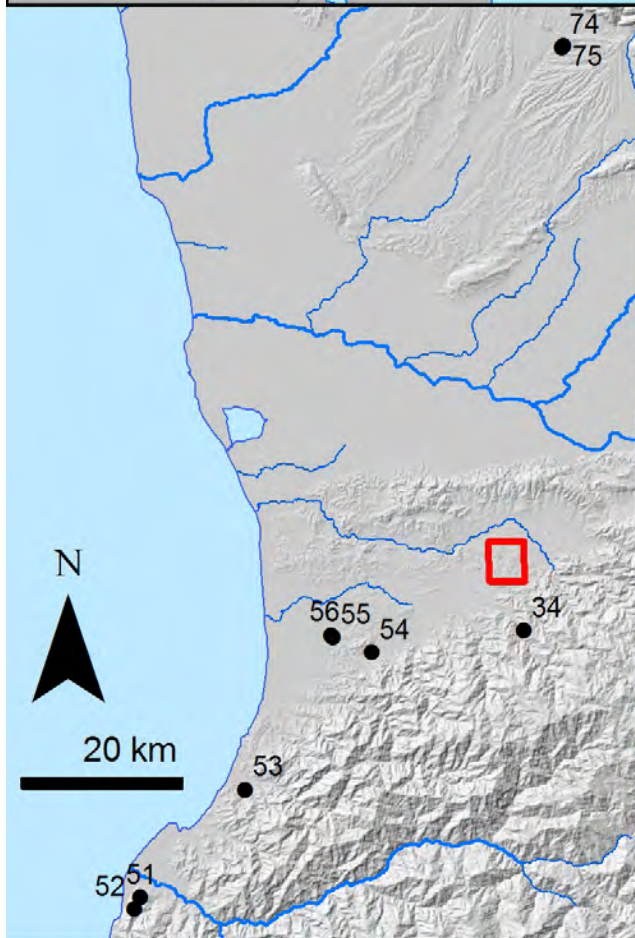
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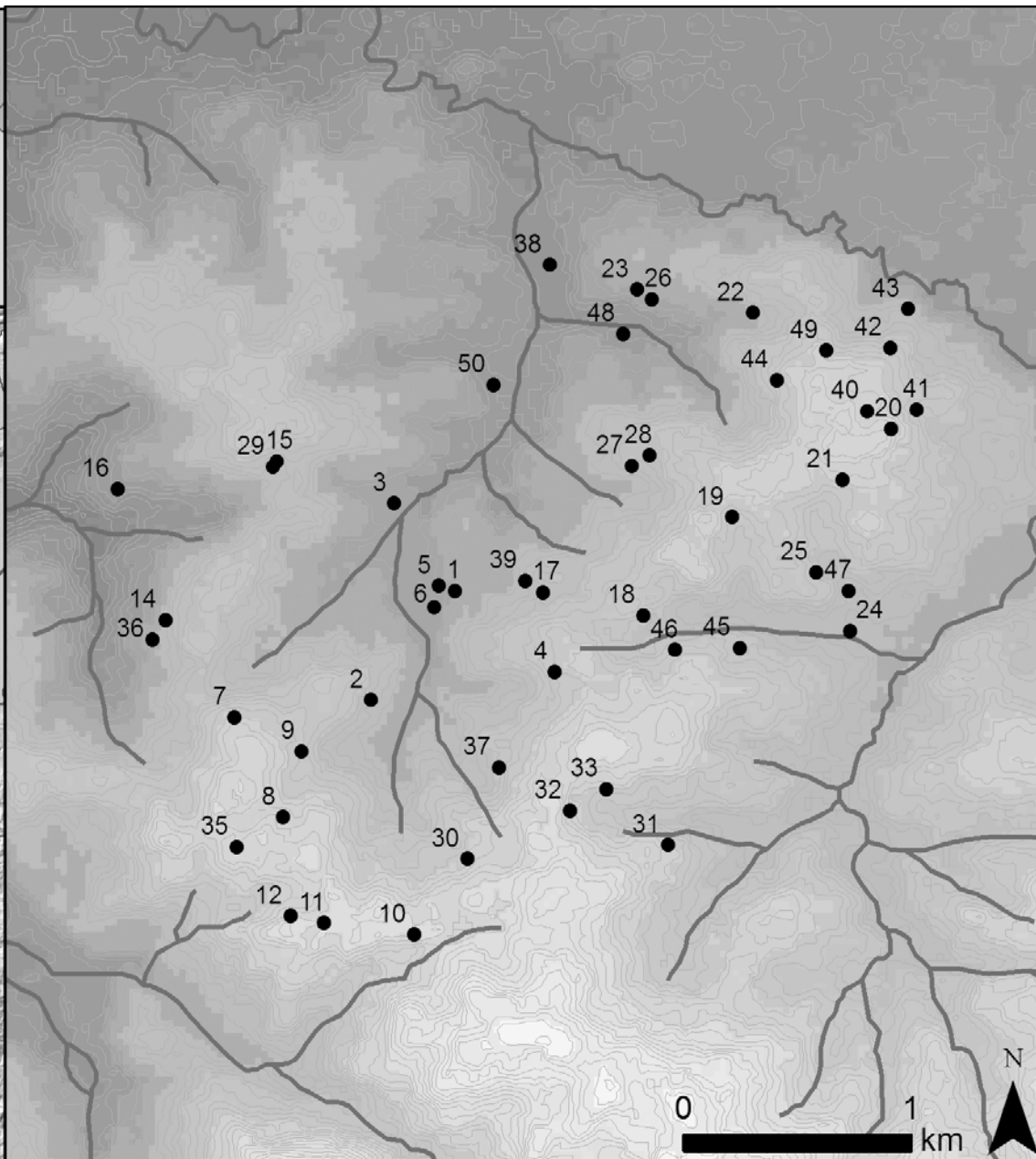
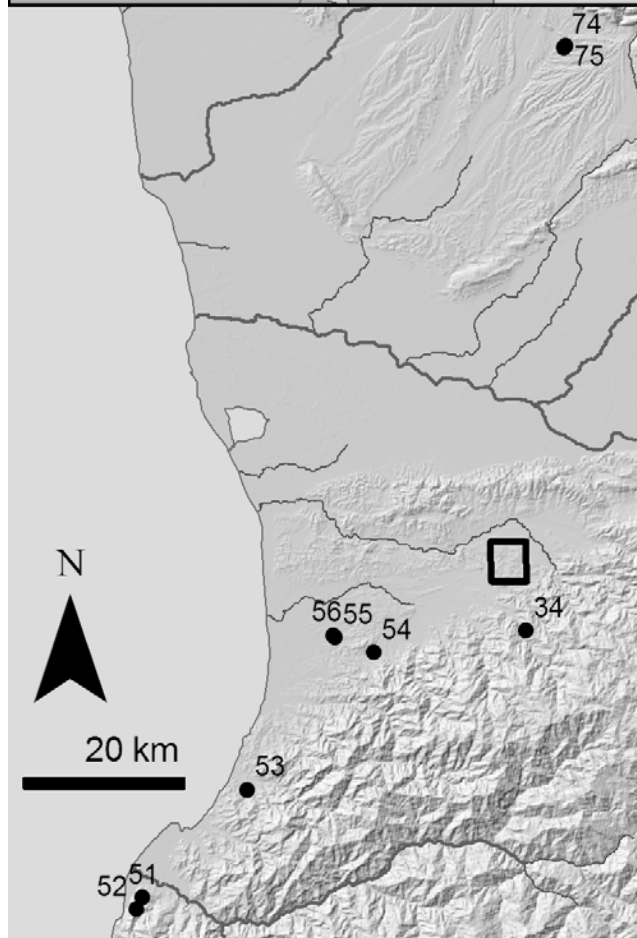
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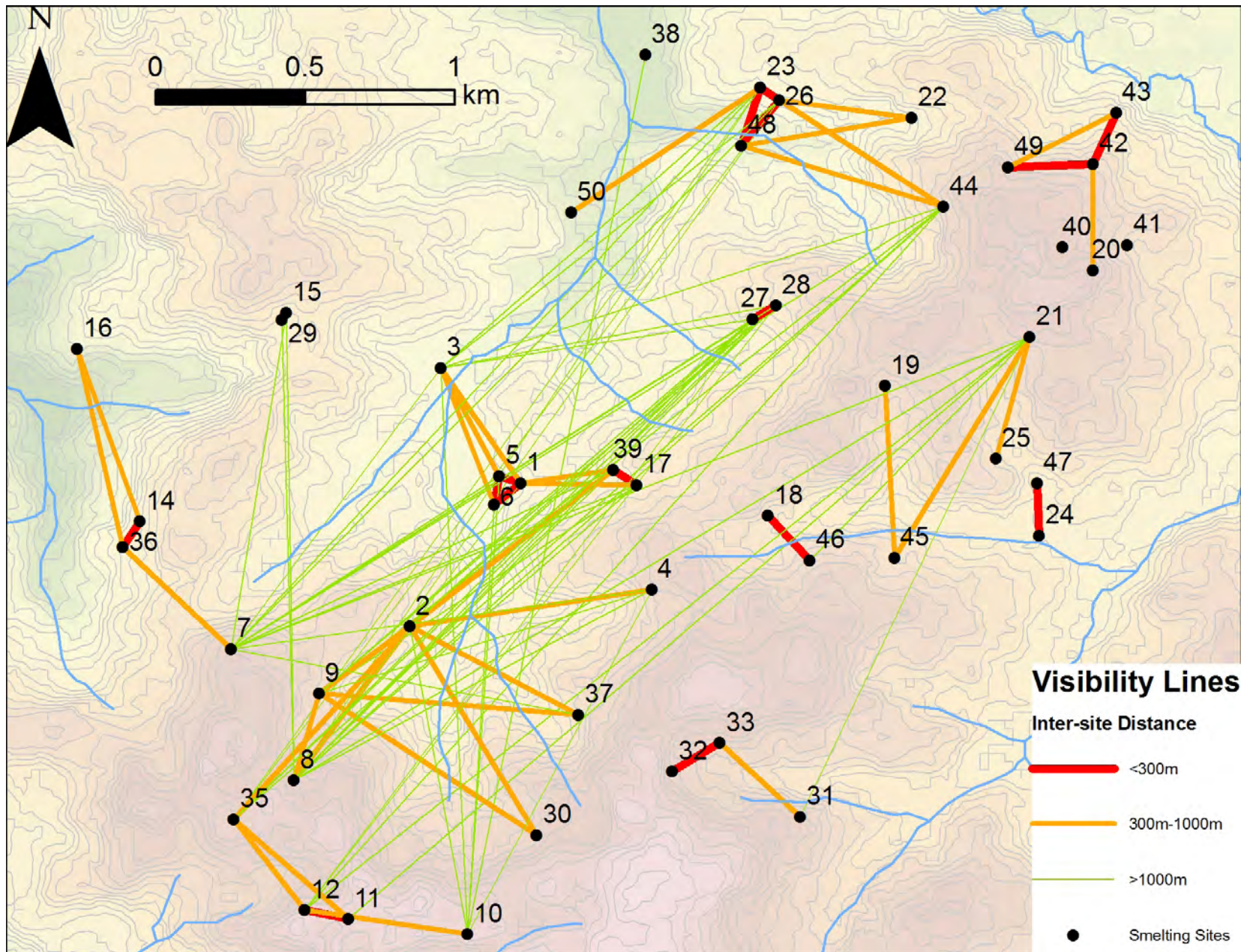
93 Shugar, A., Mass, J.L., 2012. Introduction, in: Shugar, A., Mass, J.L. (Eds.), *Handheld XRF for*
94 *Art and Archaeology*. Leuvan University Press, Leuven, Belgium.

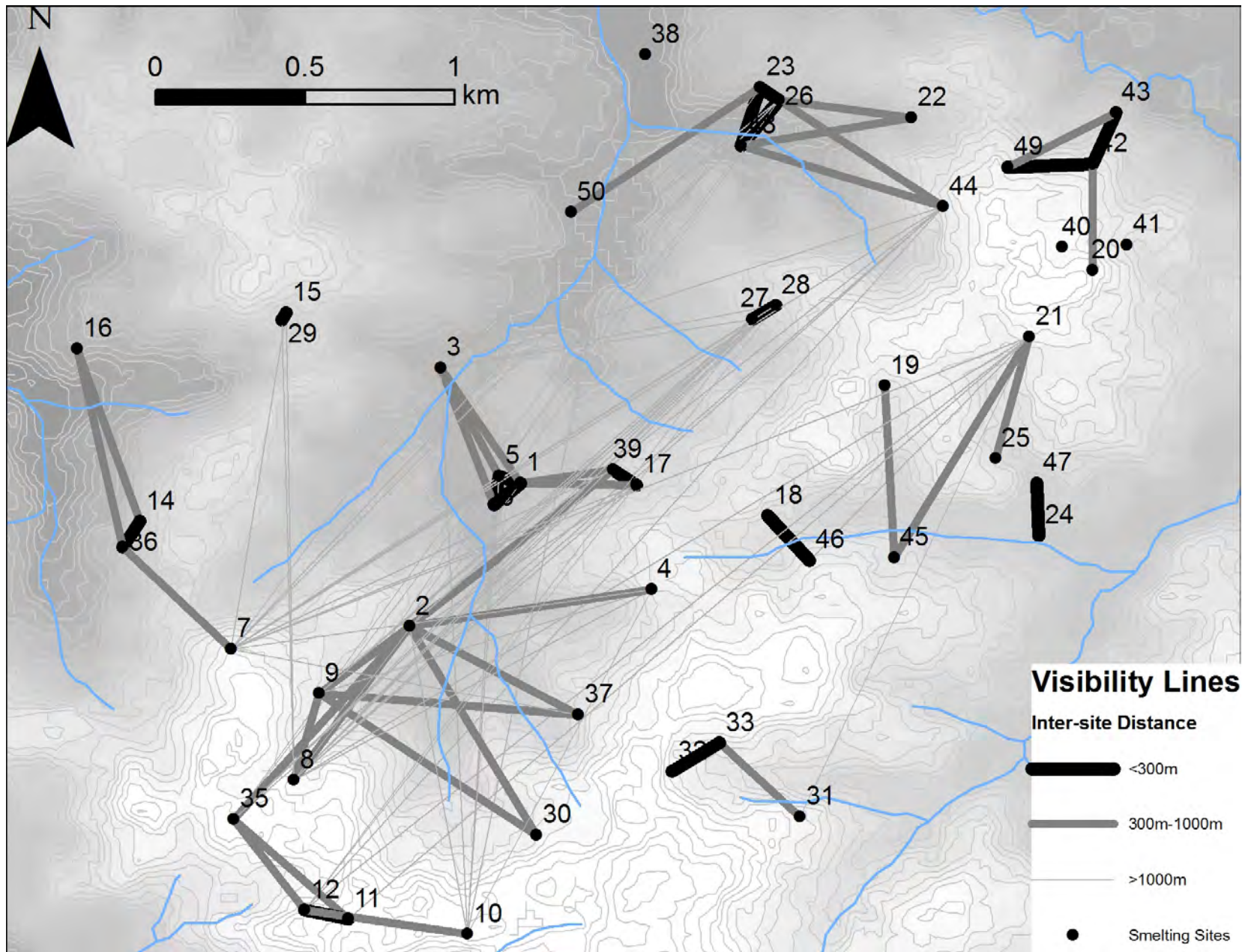
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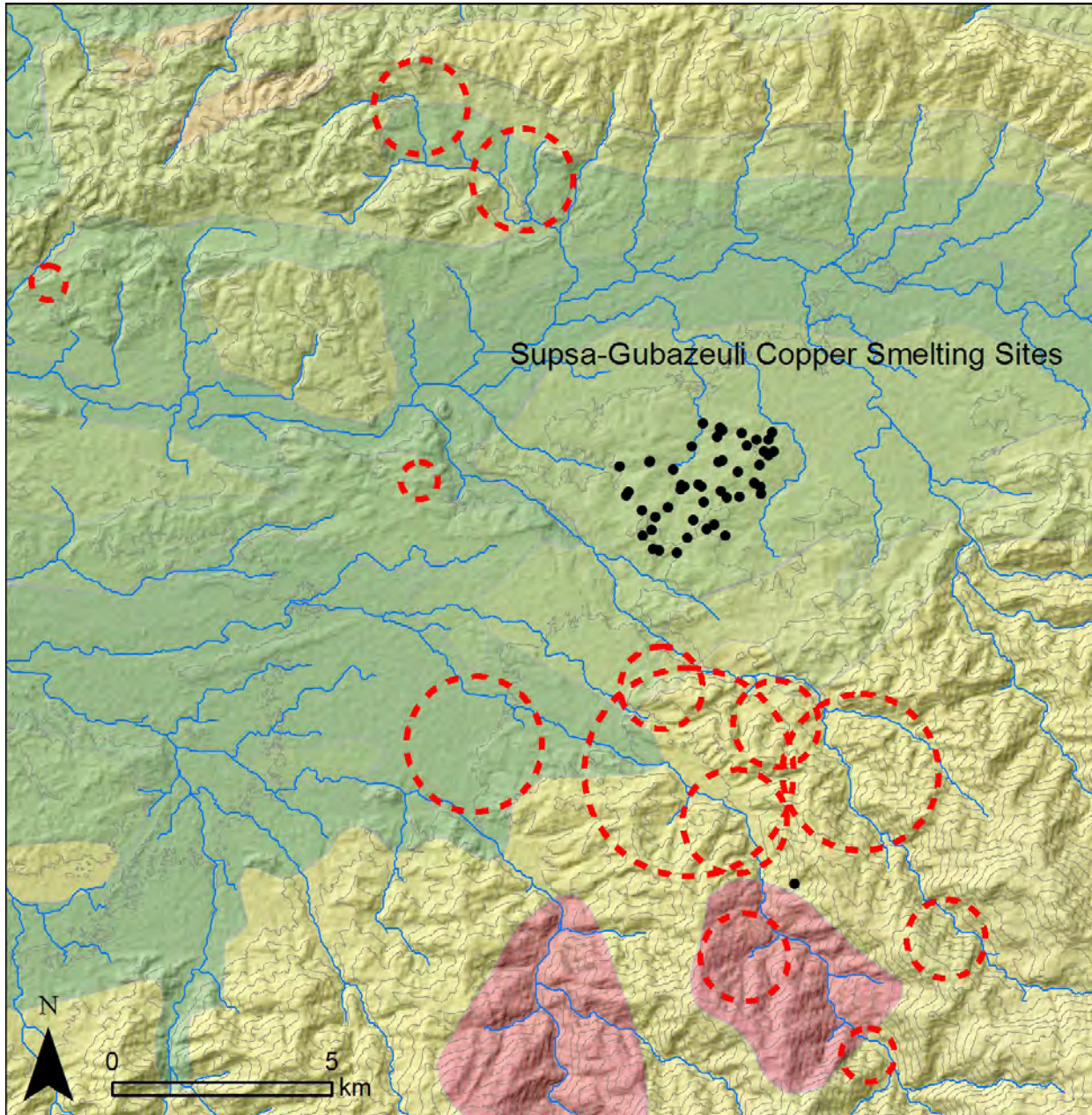
96











- Approximate Locations of Known Cu Deposits

- Quaternary Deposits

- Upper-Miocene to mid-Quaternary lavas and terrigenous deposits

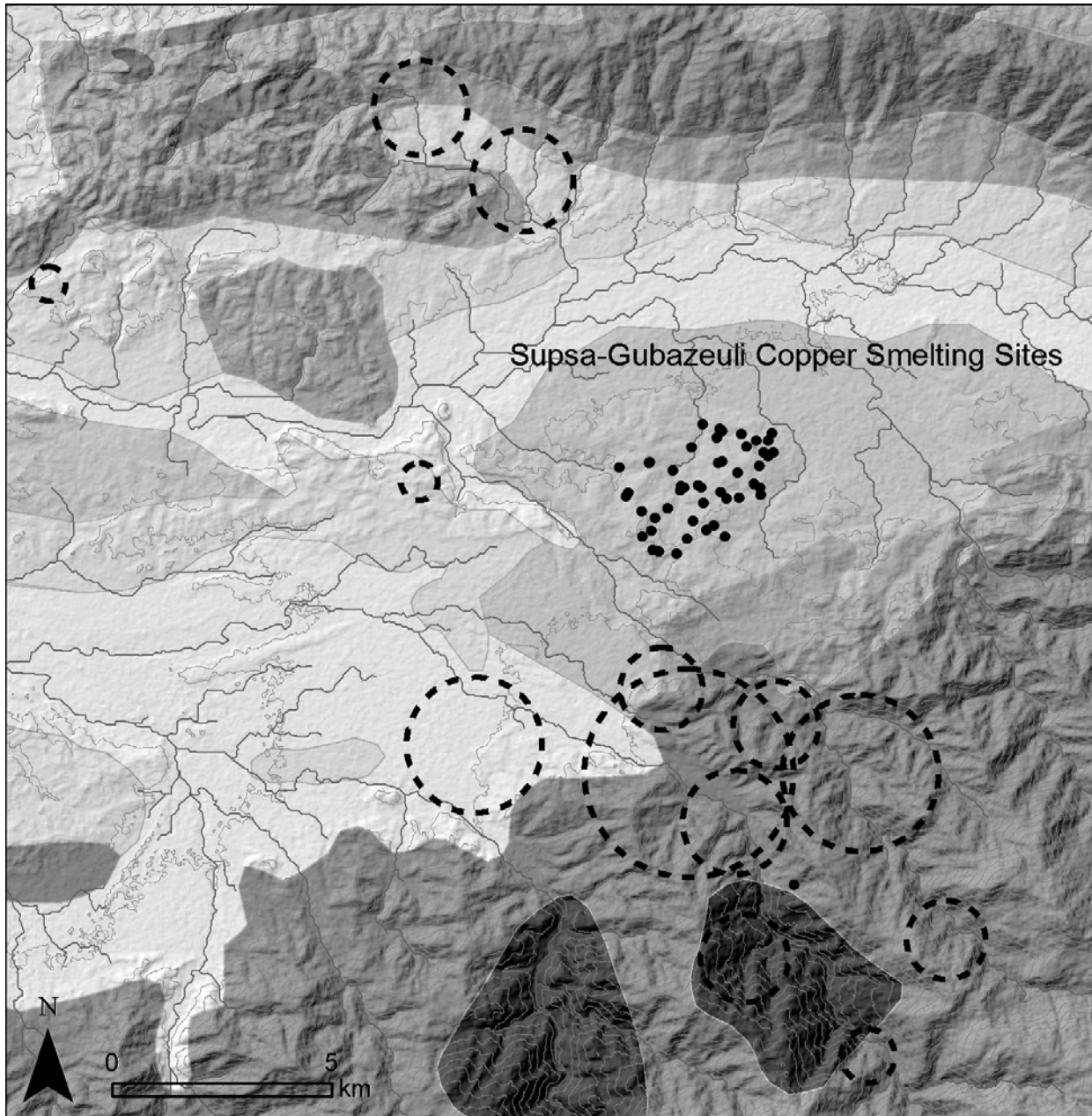
- Oligocene-Lower Miocene sandy-clayey deposits

- Upper Eocene volcanogenic sedimentary deposits

- Middle Eocene Andesites

- Paleocene-Lower Eocene sedimentary volcanogenic formations

- Stock batholith intrusions (generally syenites-diorites; Trialeti Phase)



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Ore Deposits

Copper ore vein with associated zinc minerals

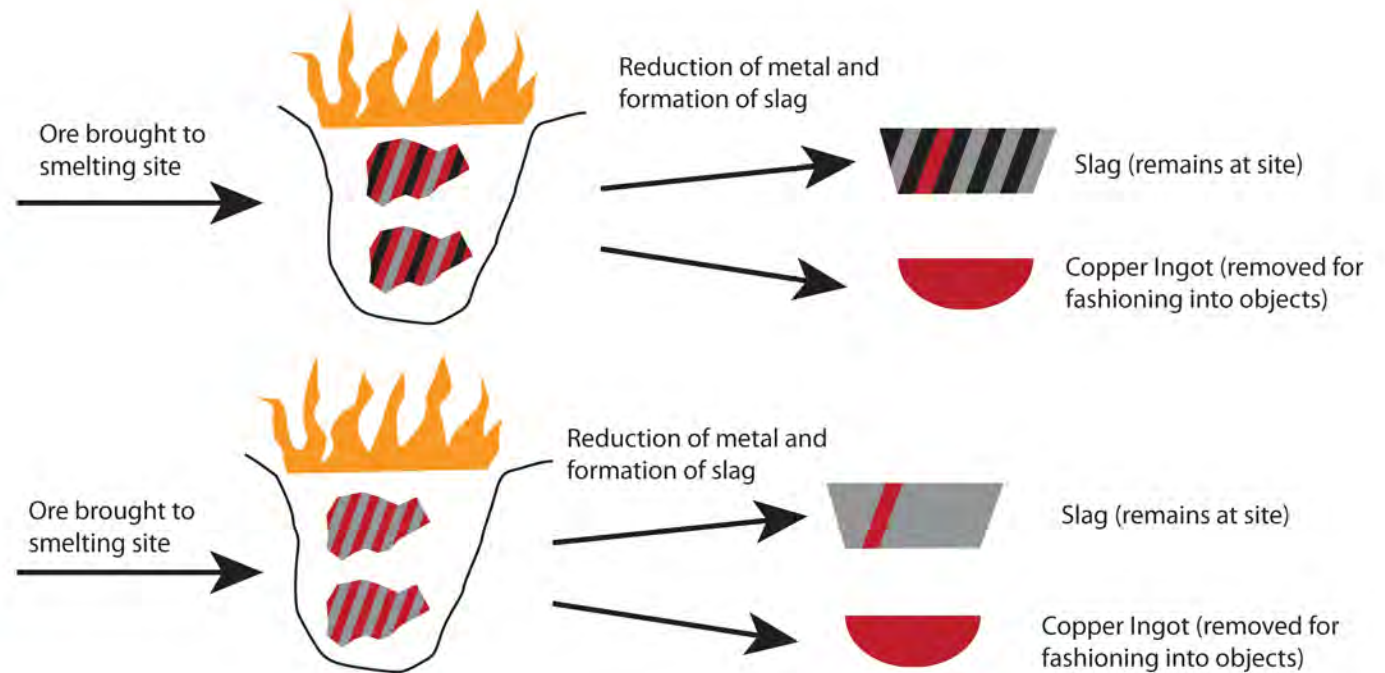


Copper vein without associated zinc minerals



-  Copper
-  Zinc
-  Other ore impurities (mostly silicon, iron, oxygen, sulfur)

Smelting in Pit Furnace



Ore Deposits

Copper ore vein with associated zinc minerals



Copper vein without associated zinc minerals



■ Copper

■ Zinc

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Smelting in Pit Furnace

Ore brought to smelting site



Reduction of metal and formation of slag

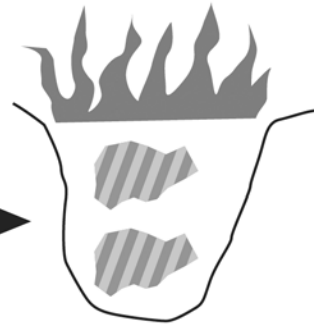


Slag (remains at site)



Copper Ingot (removed for fashioning into objects)

Ore brought to smelting site



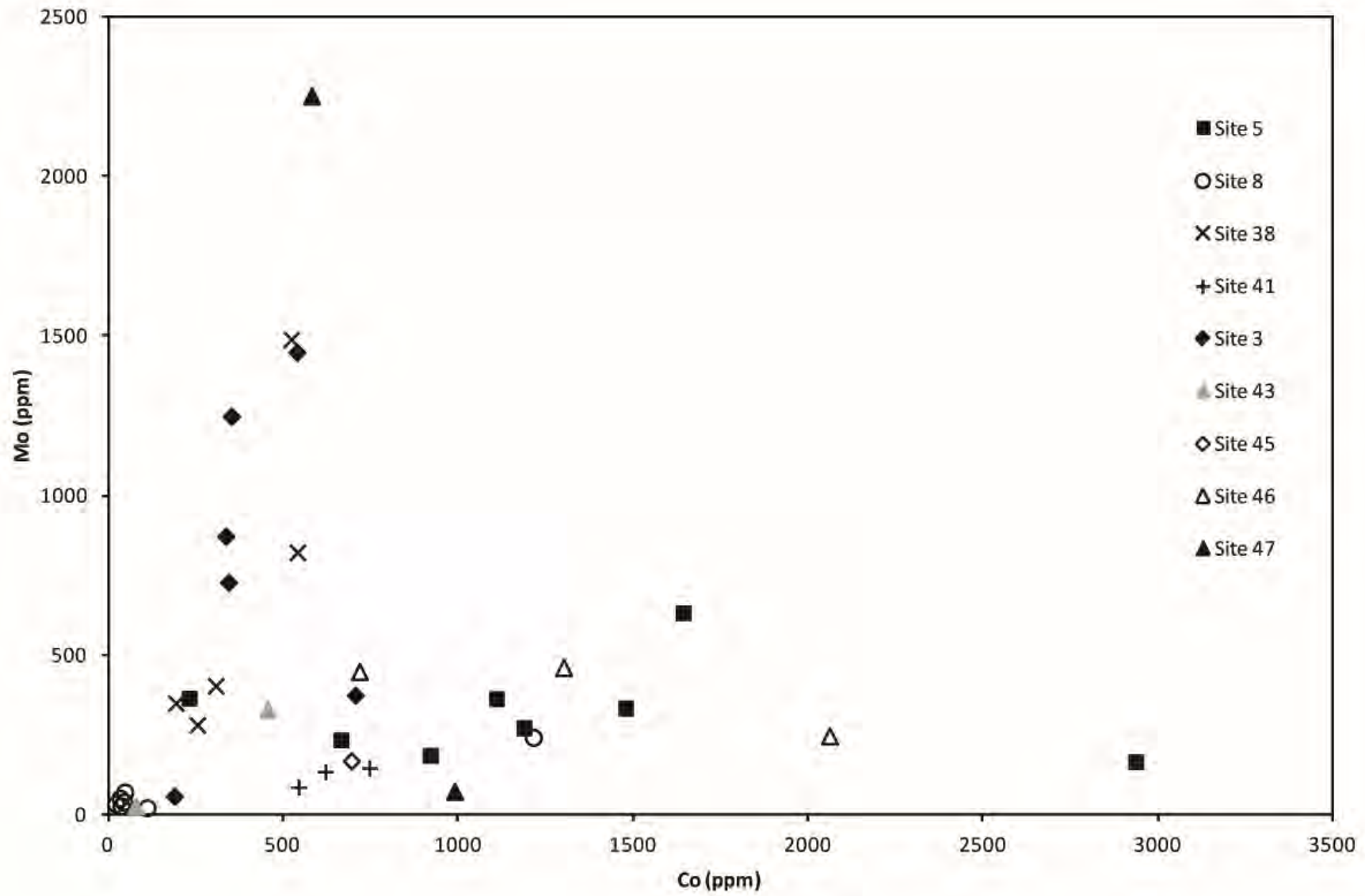
Reduction of metal and formation of slag



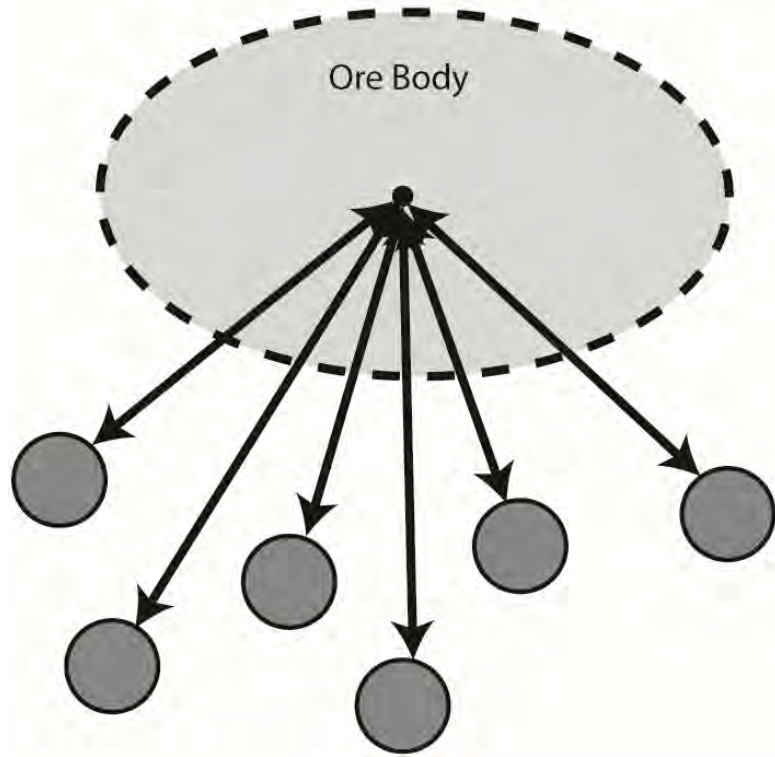
Slag (remains at site)



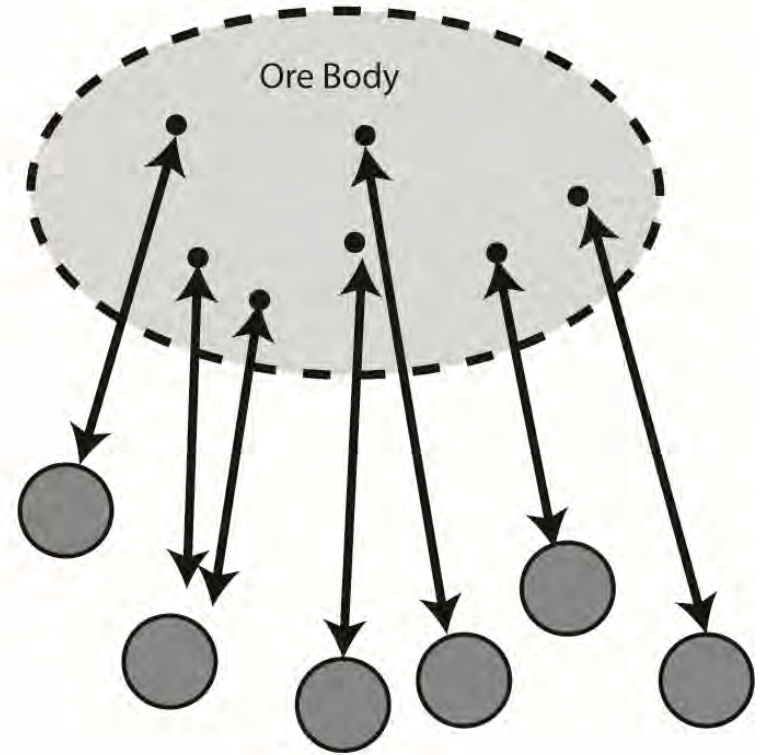
Copper Ingot (removed for fashioning into objects)



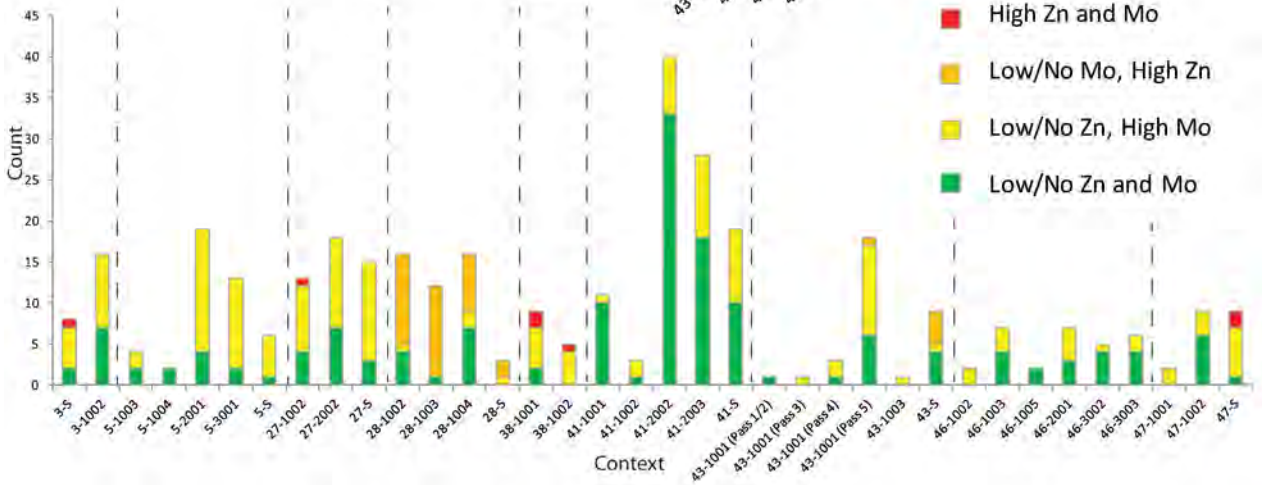
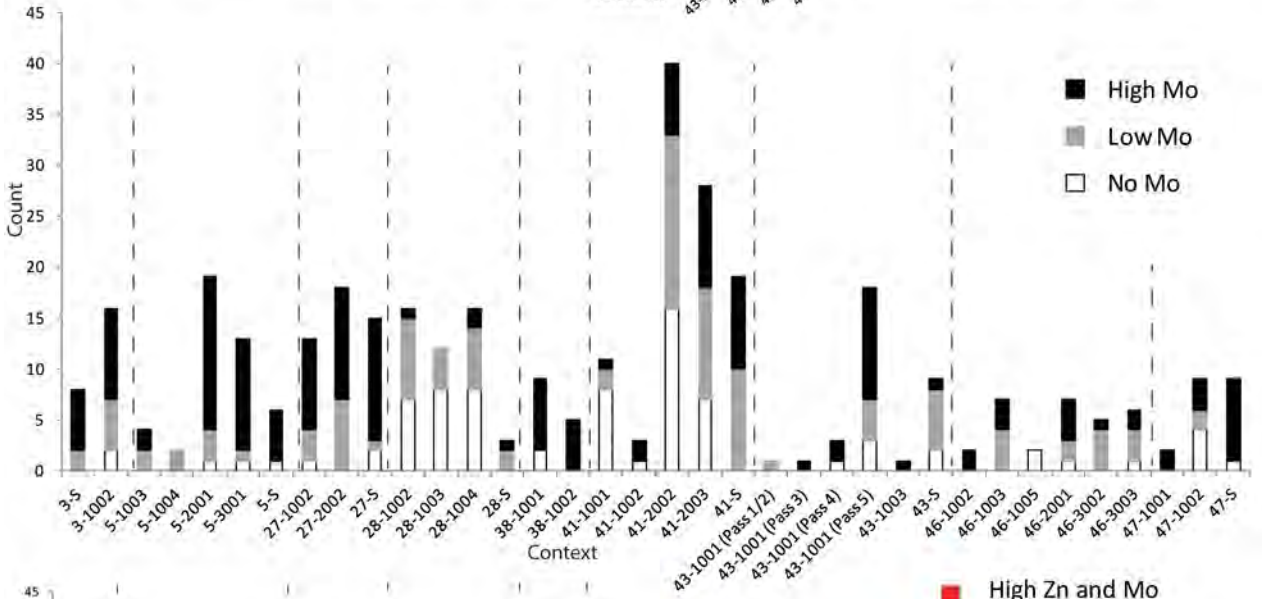
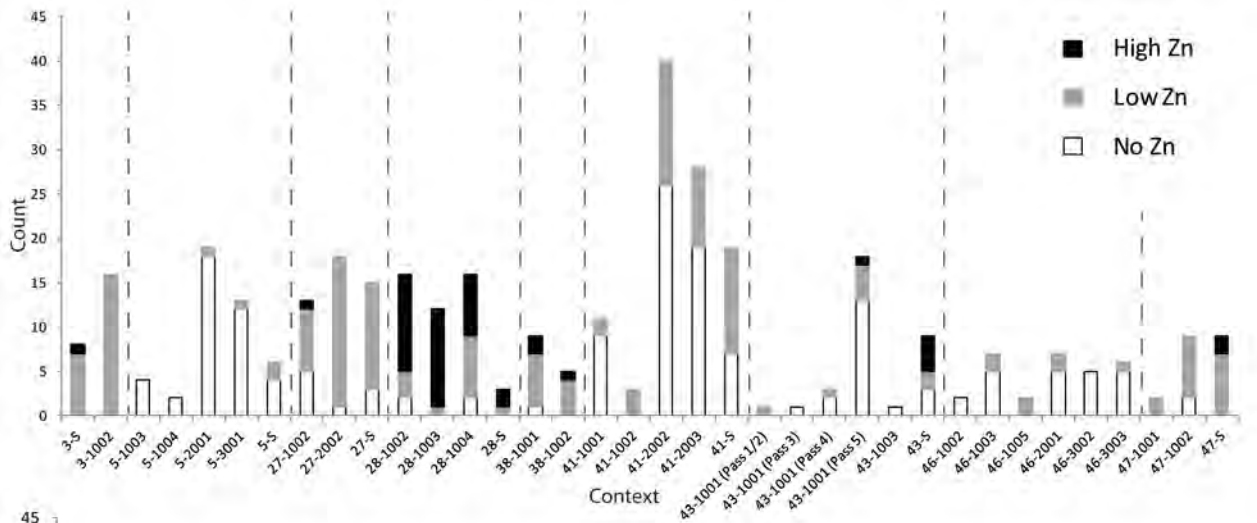
Coordinated Mining Model

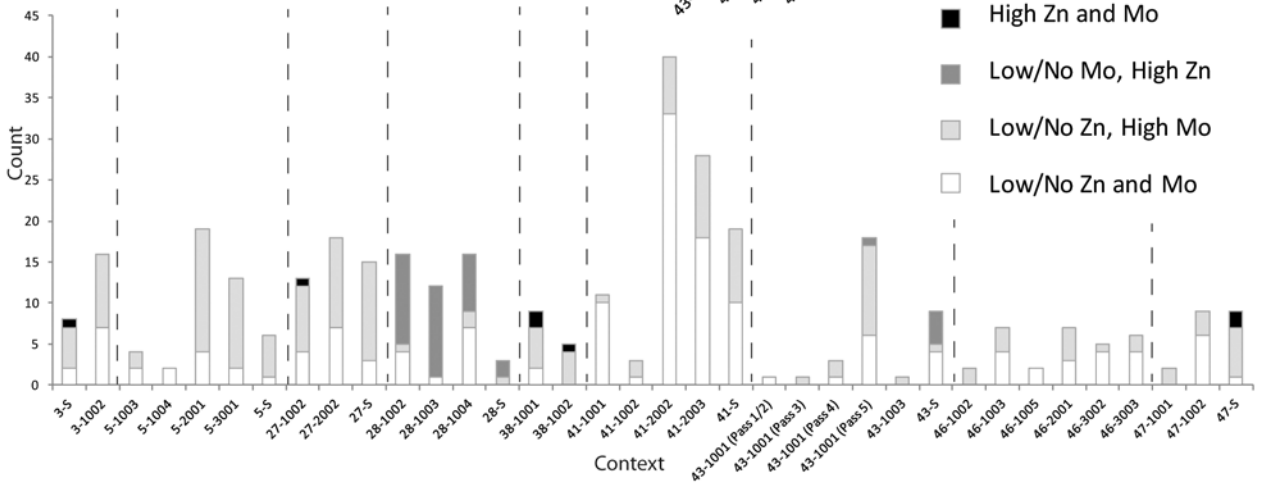
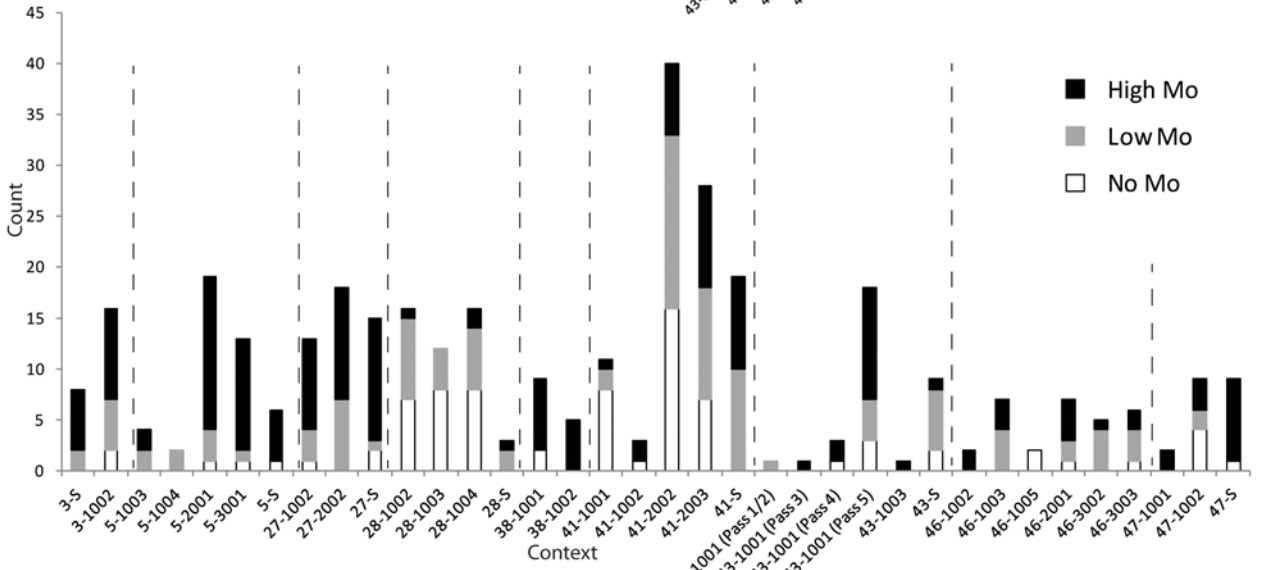
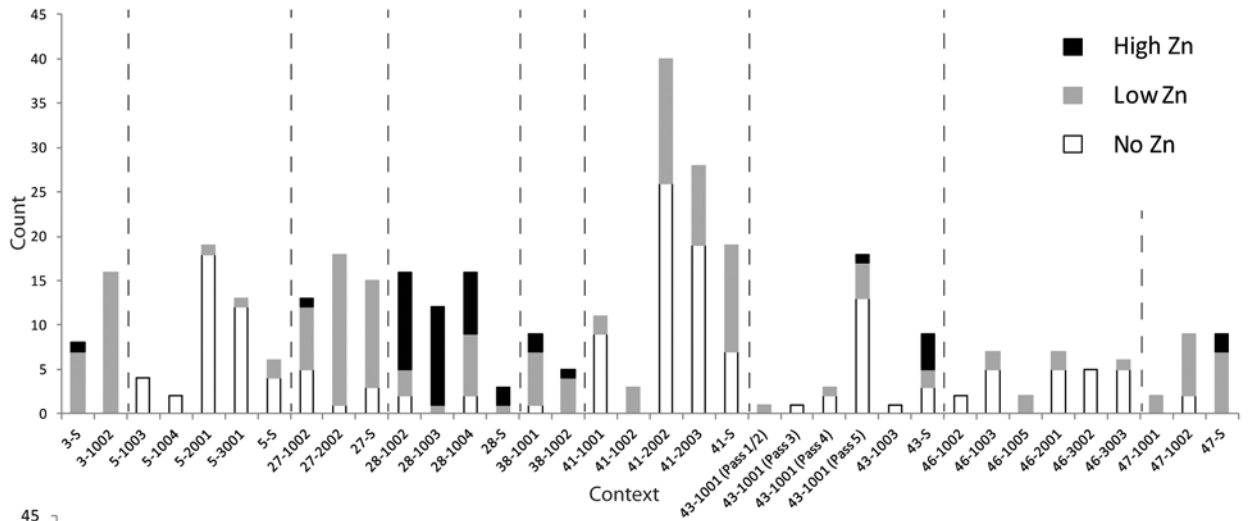


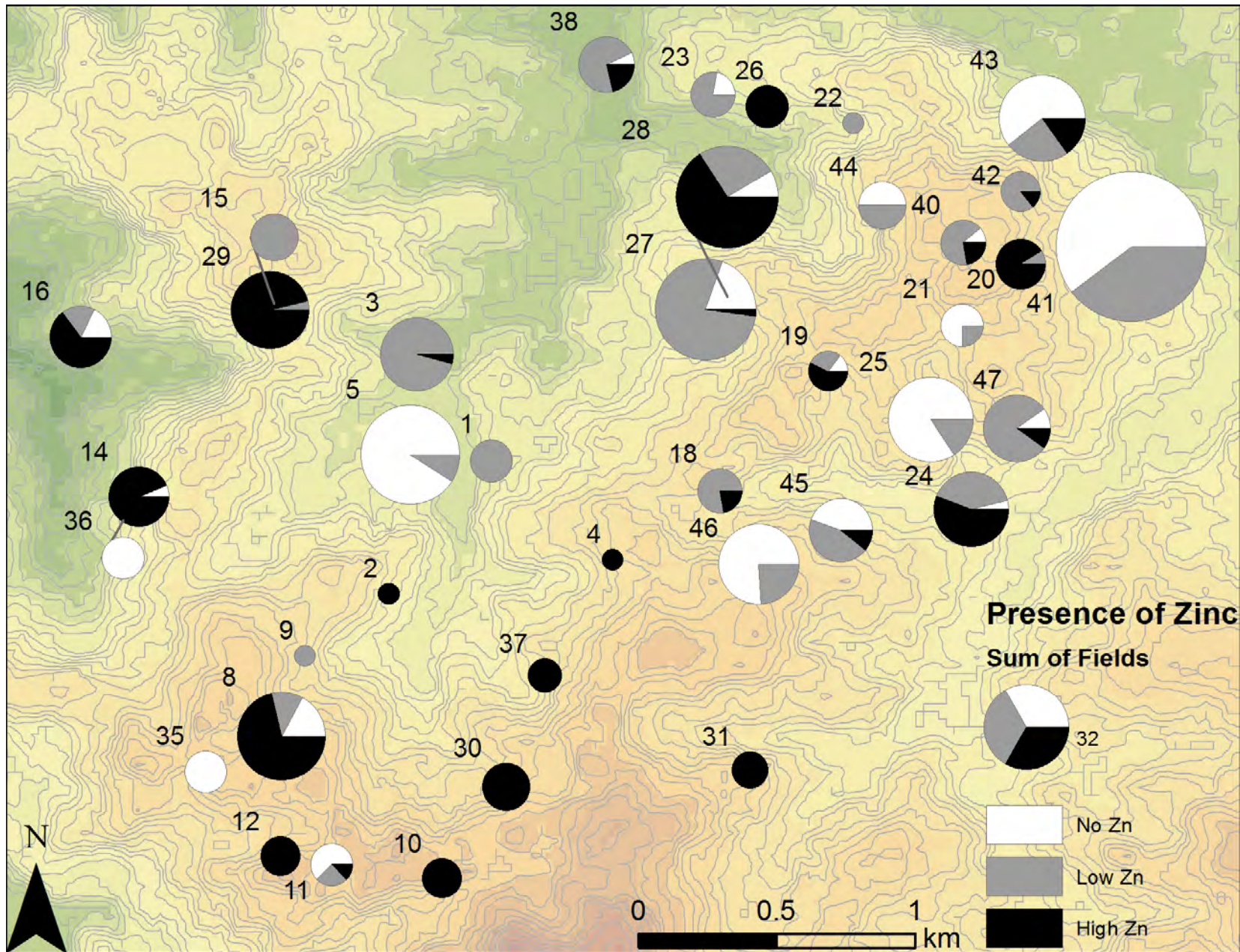
Independent Mining Model

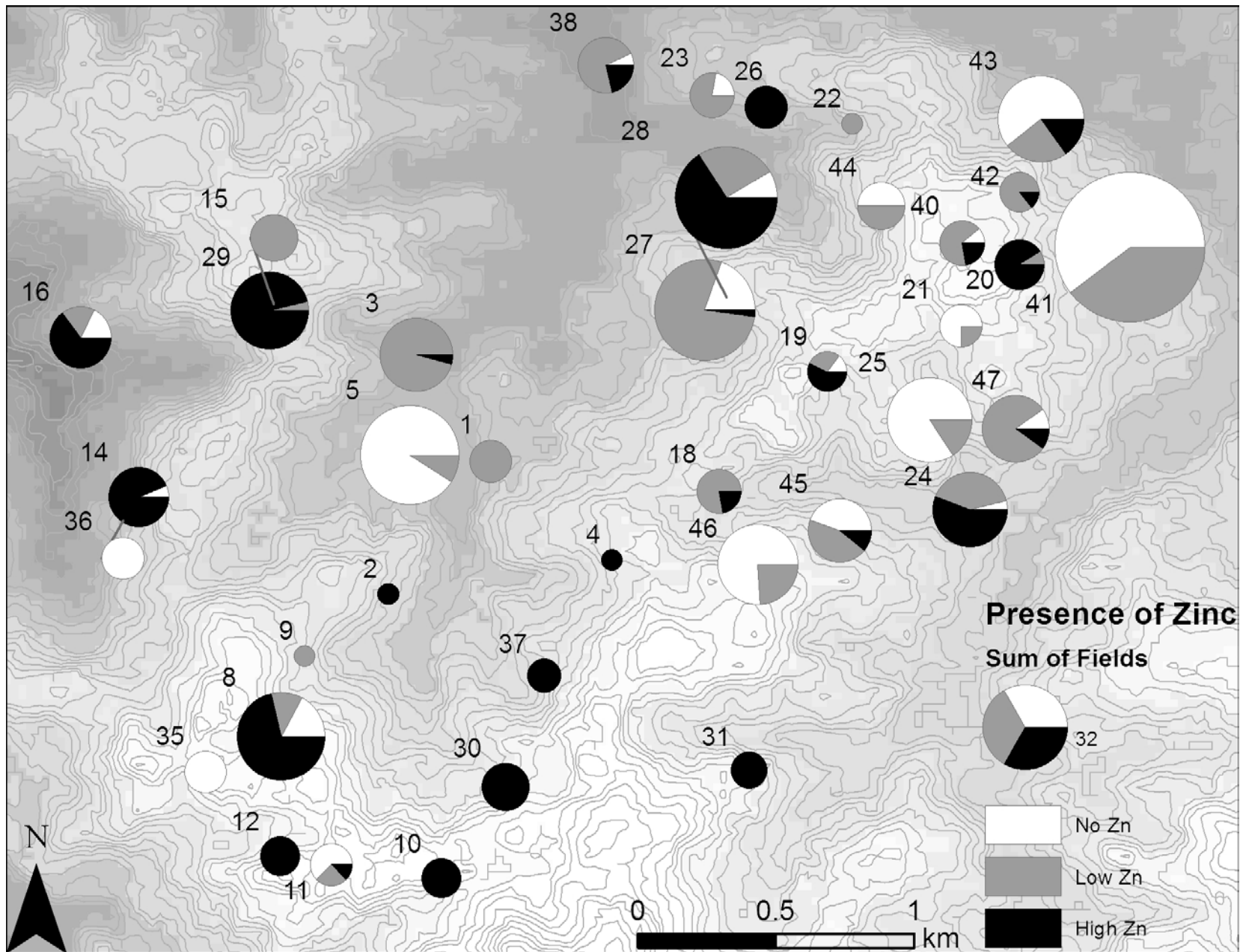


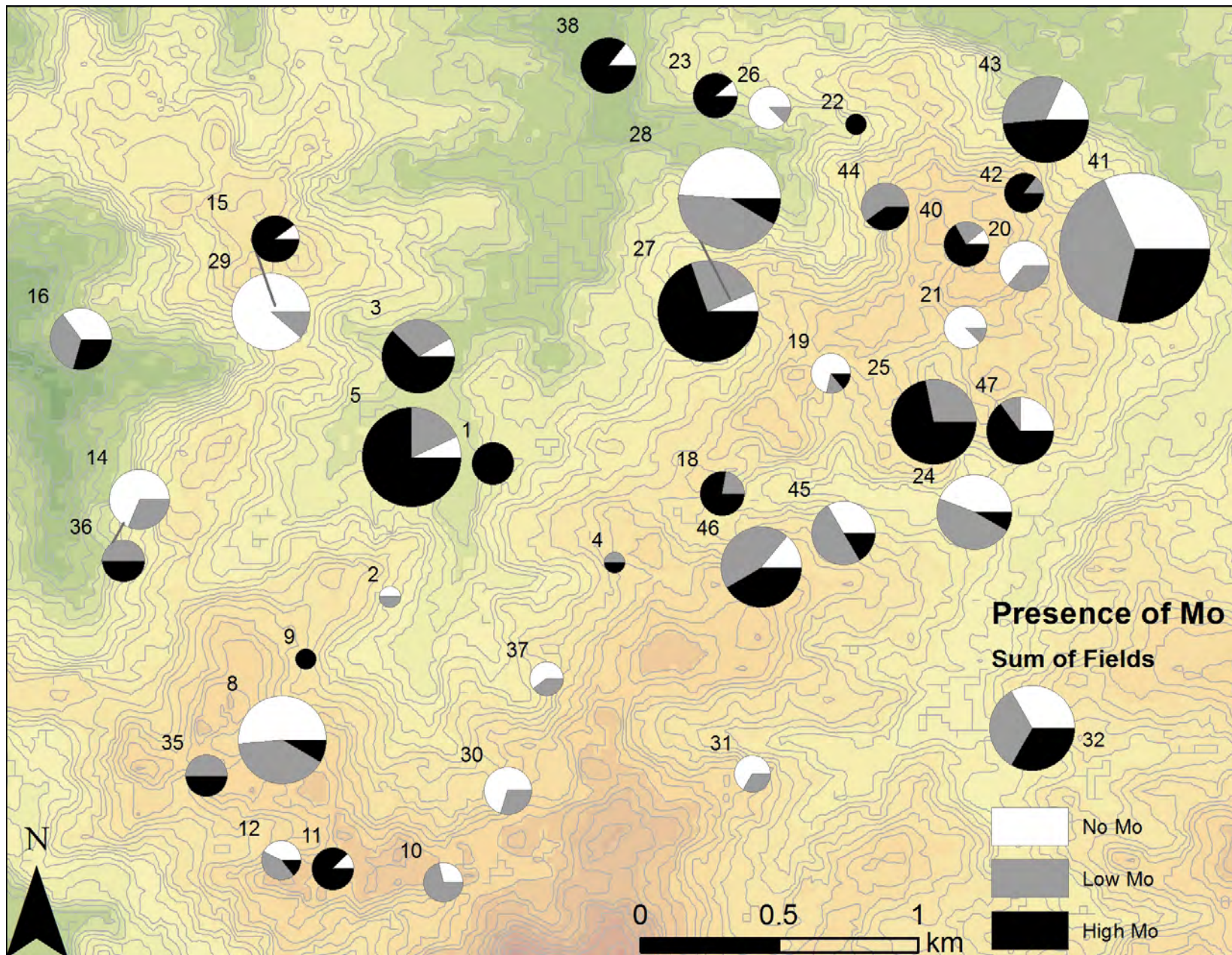
- Mining Site
- Smelting Site

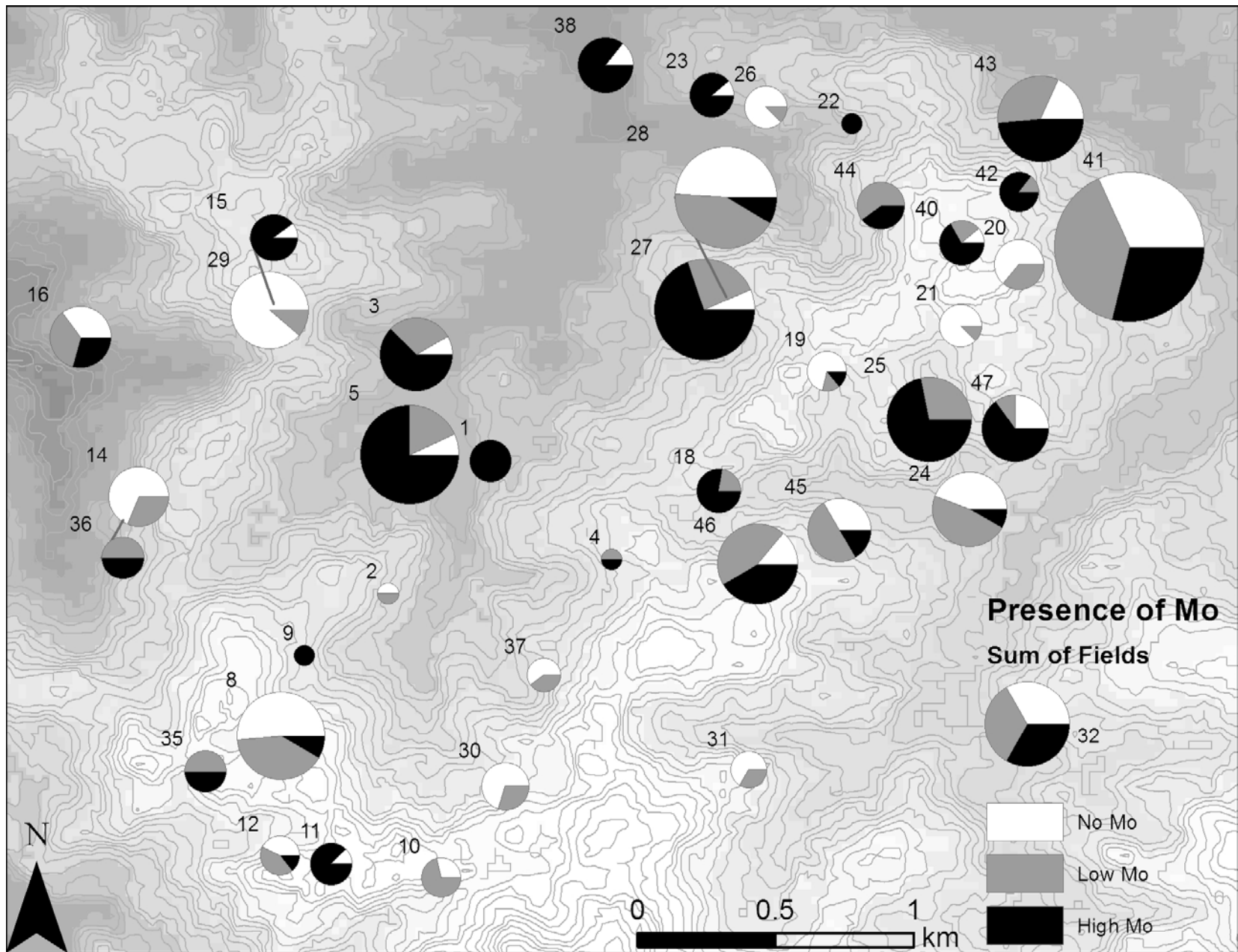


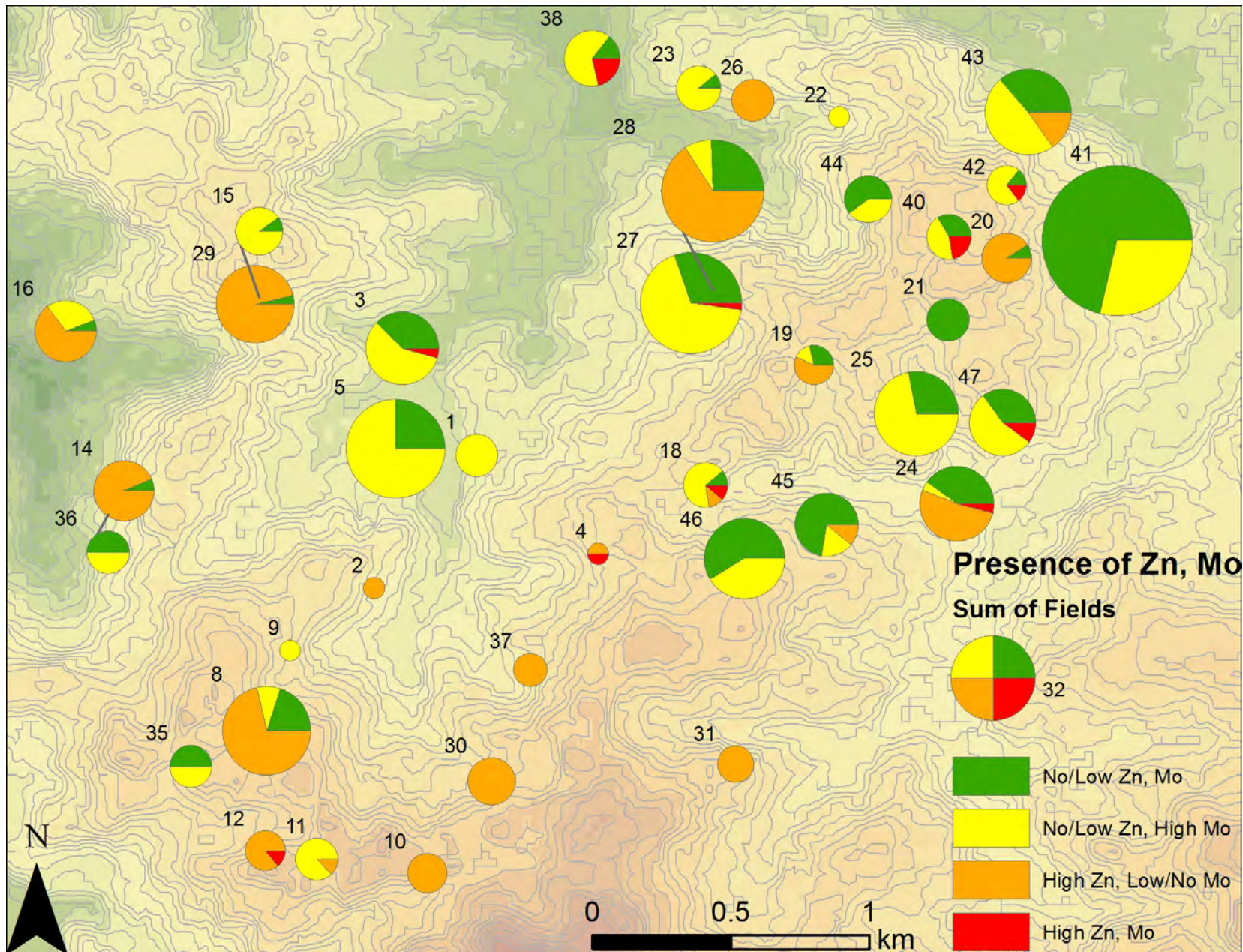
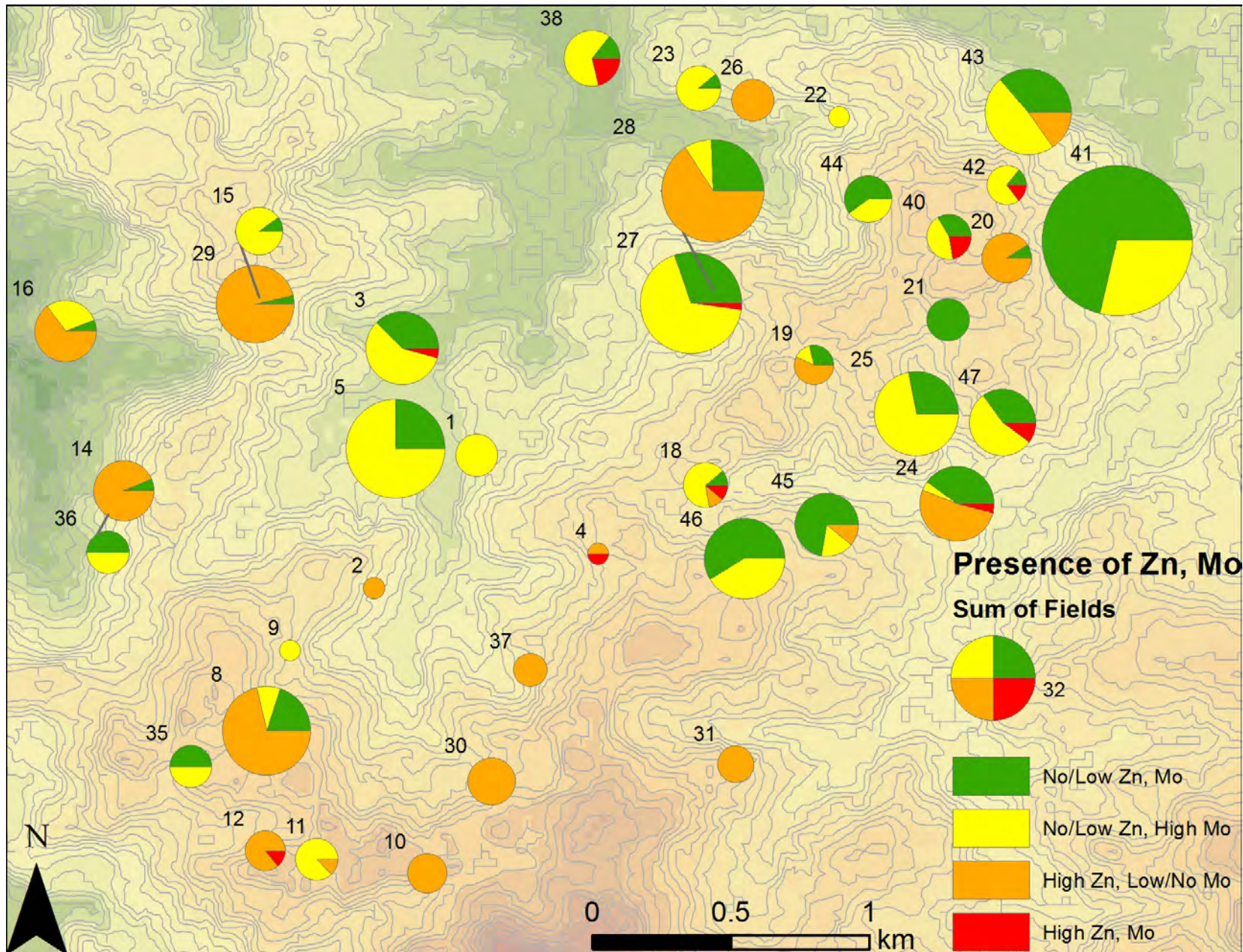


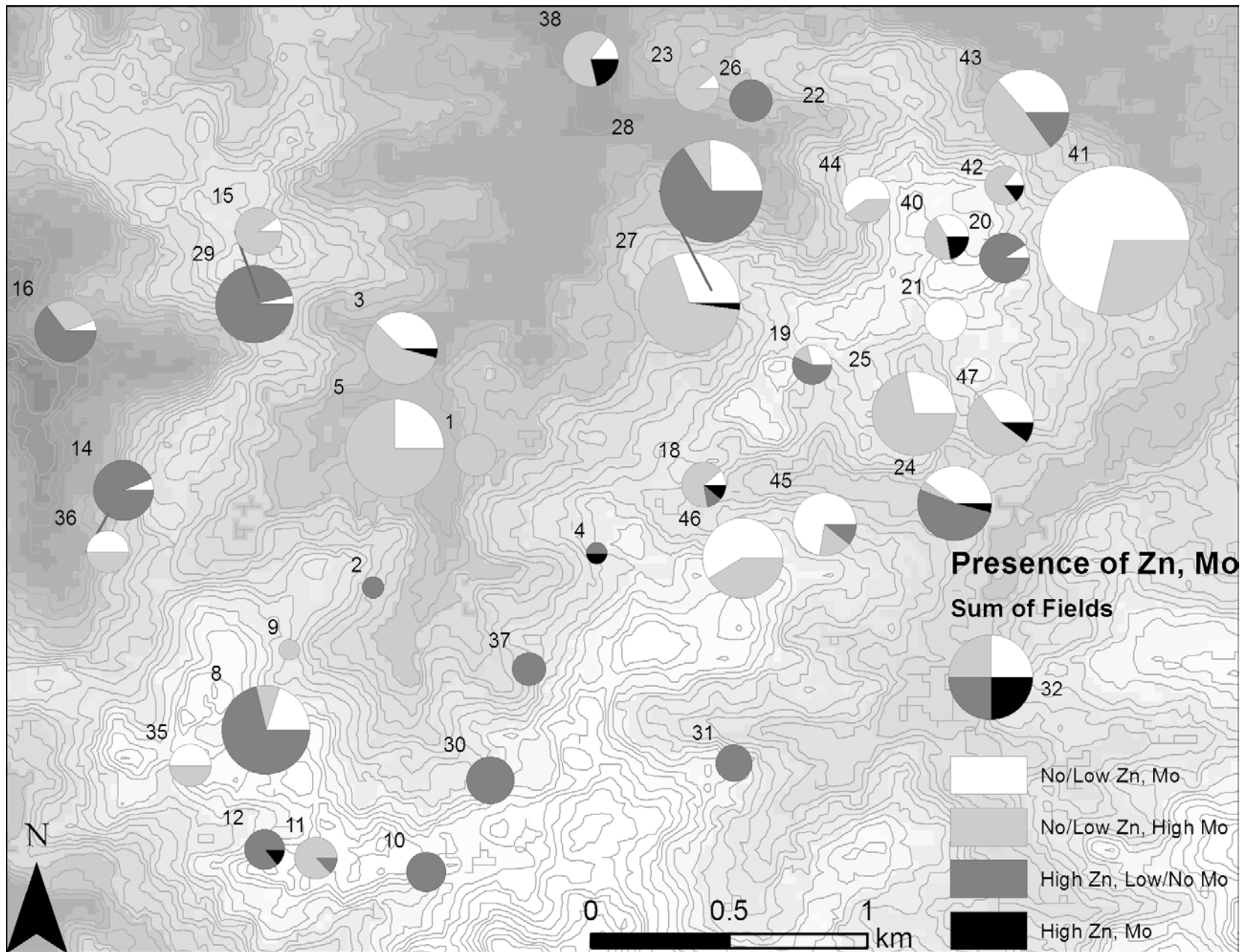


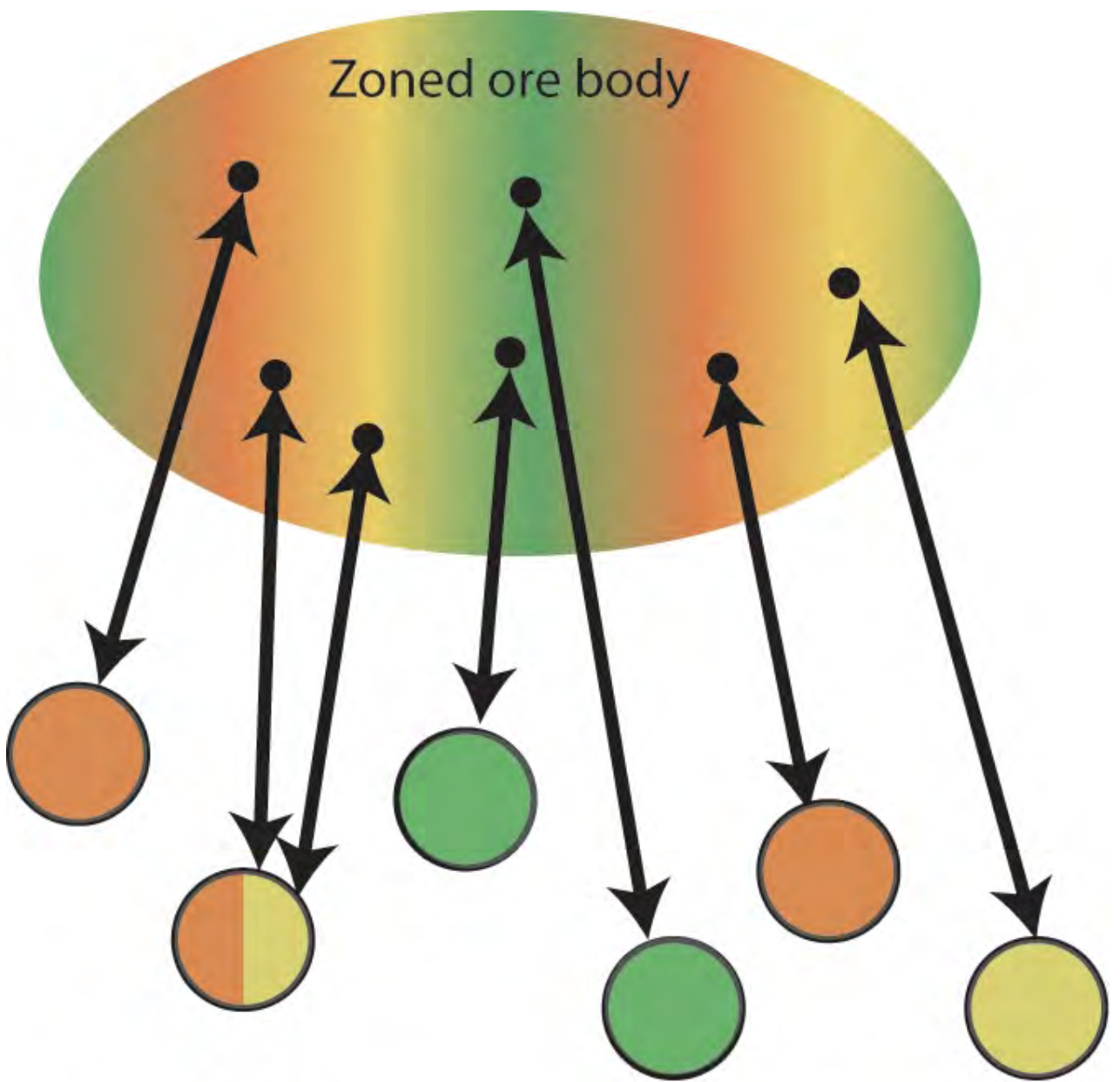








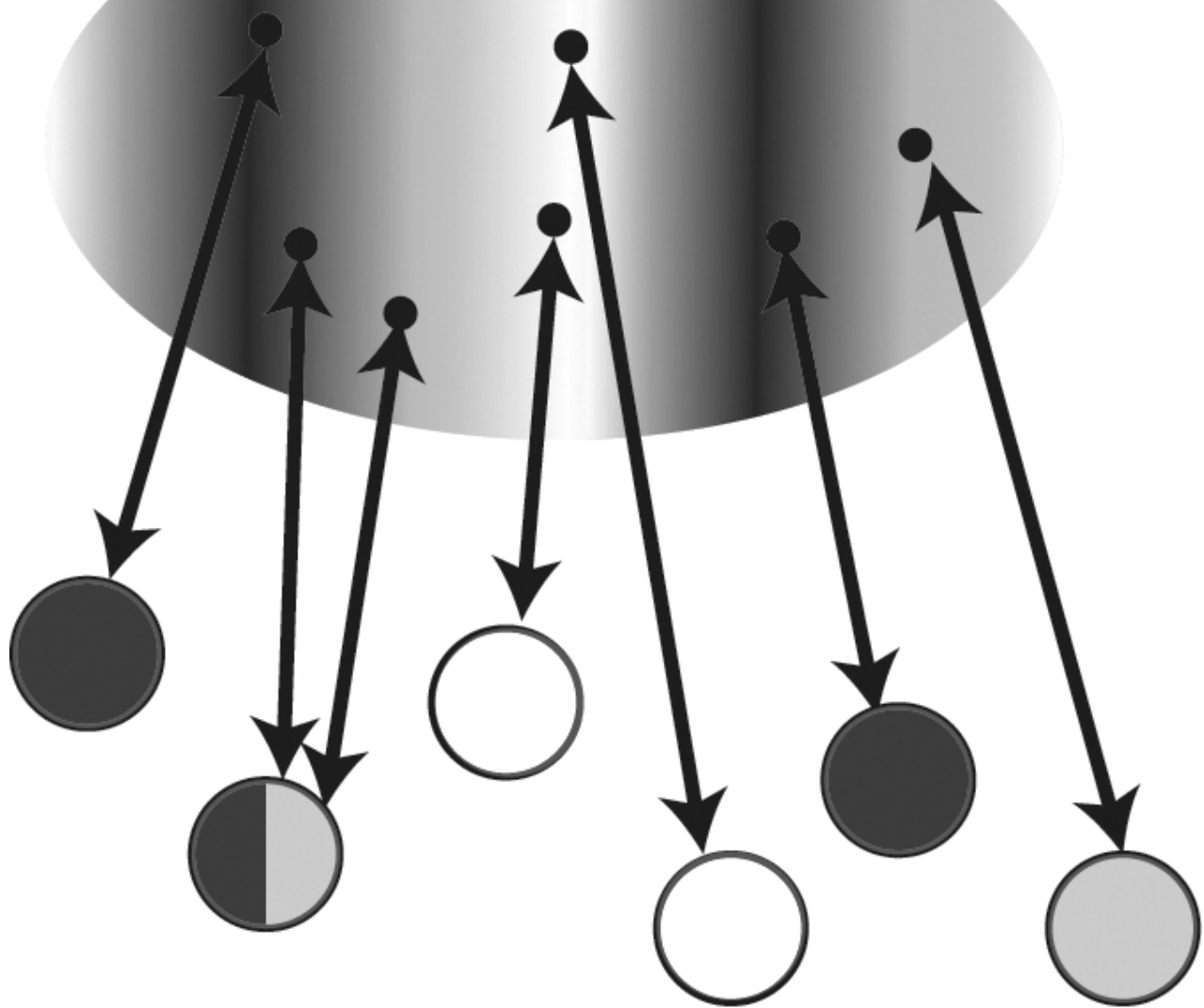




● Mining Site

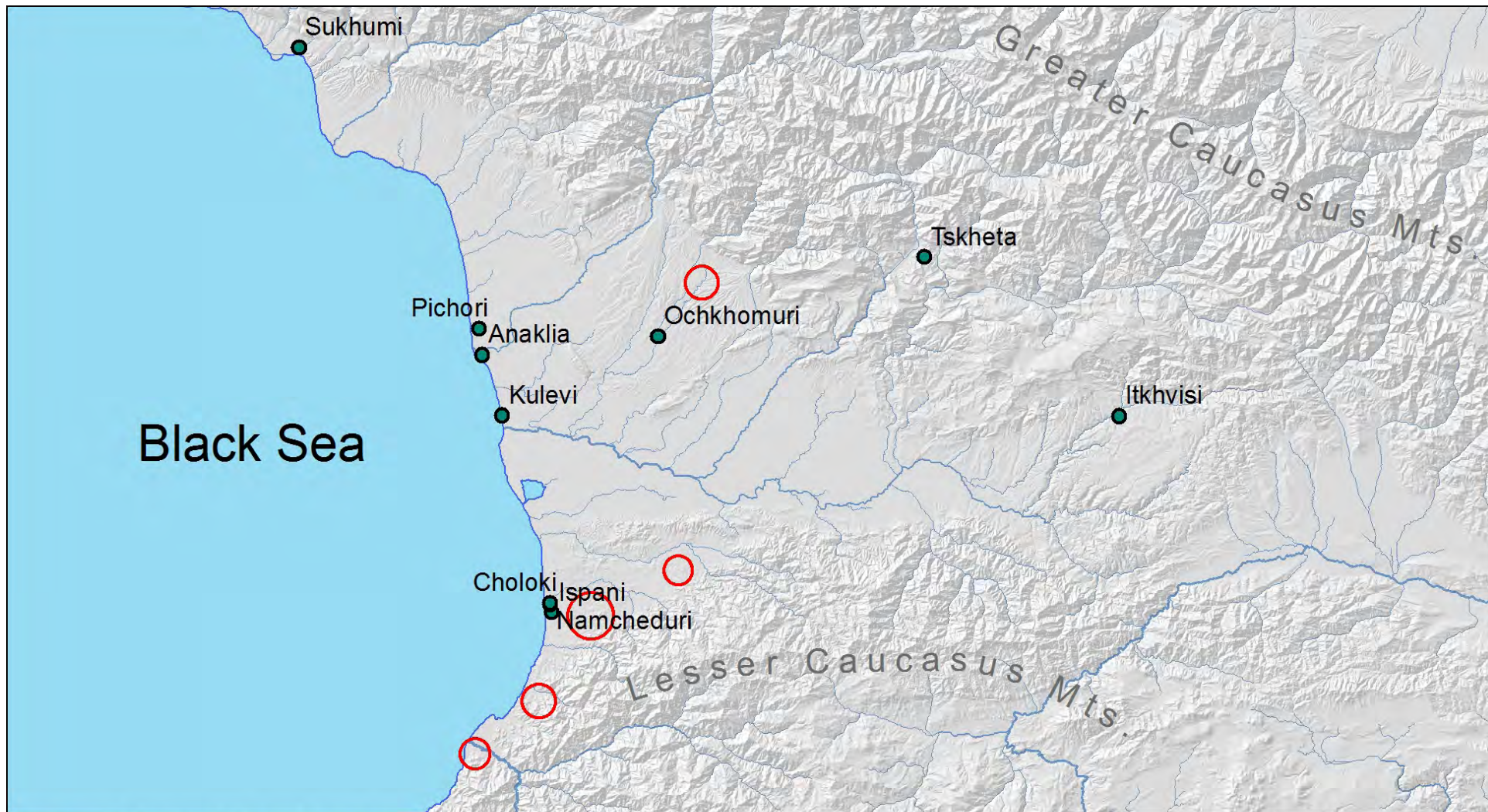
○ Smelting Site (colored according to ore type used)

Zoned ore body



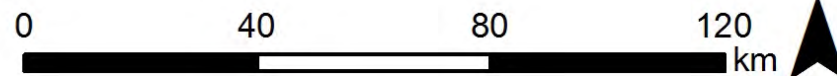
● Mining Site

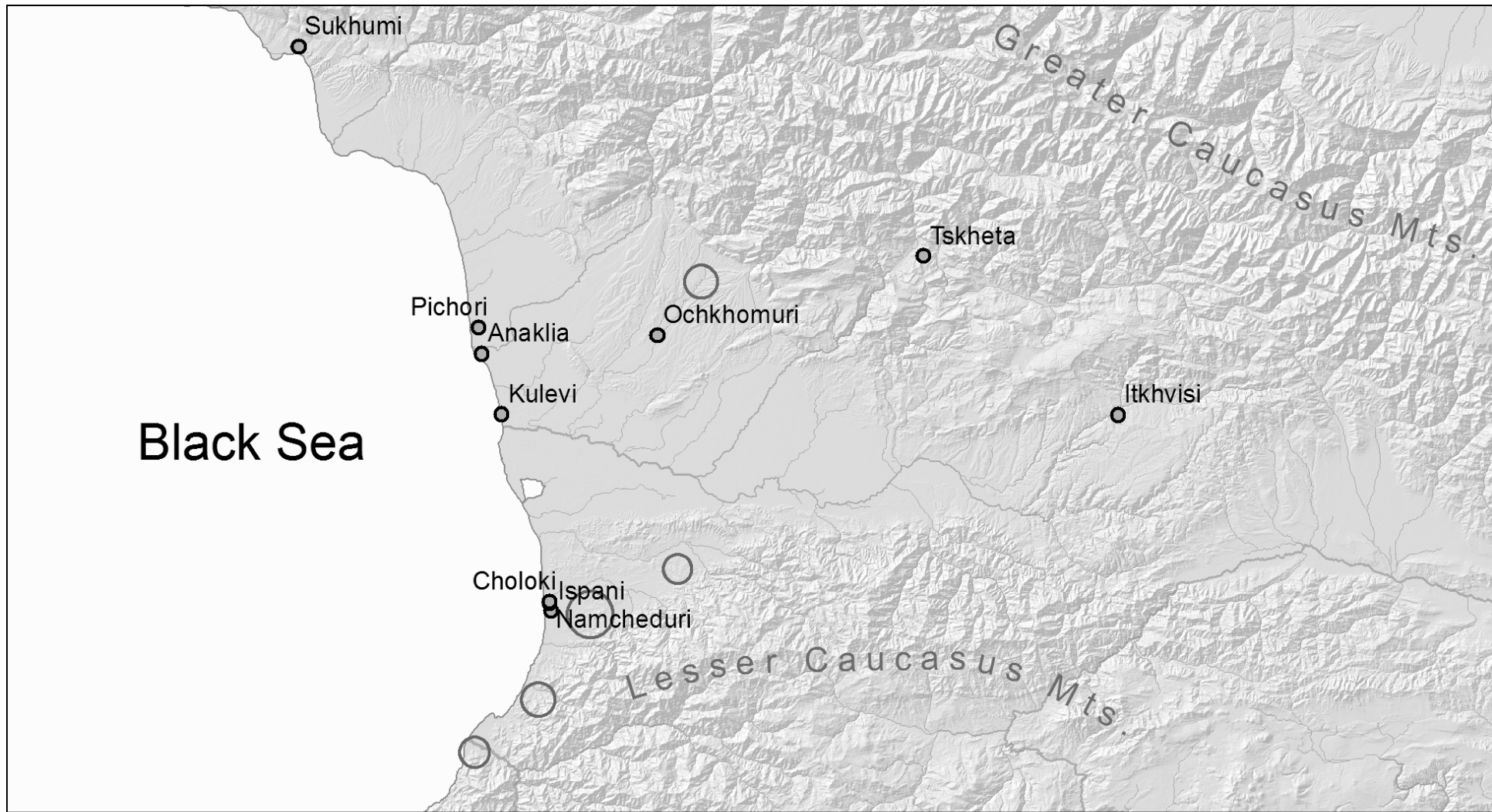
● Smelting Site (colored according to ore type used)



● Sites with evidence of secondary production

□ Primary Smelting Areas (Known)





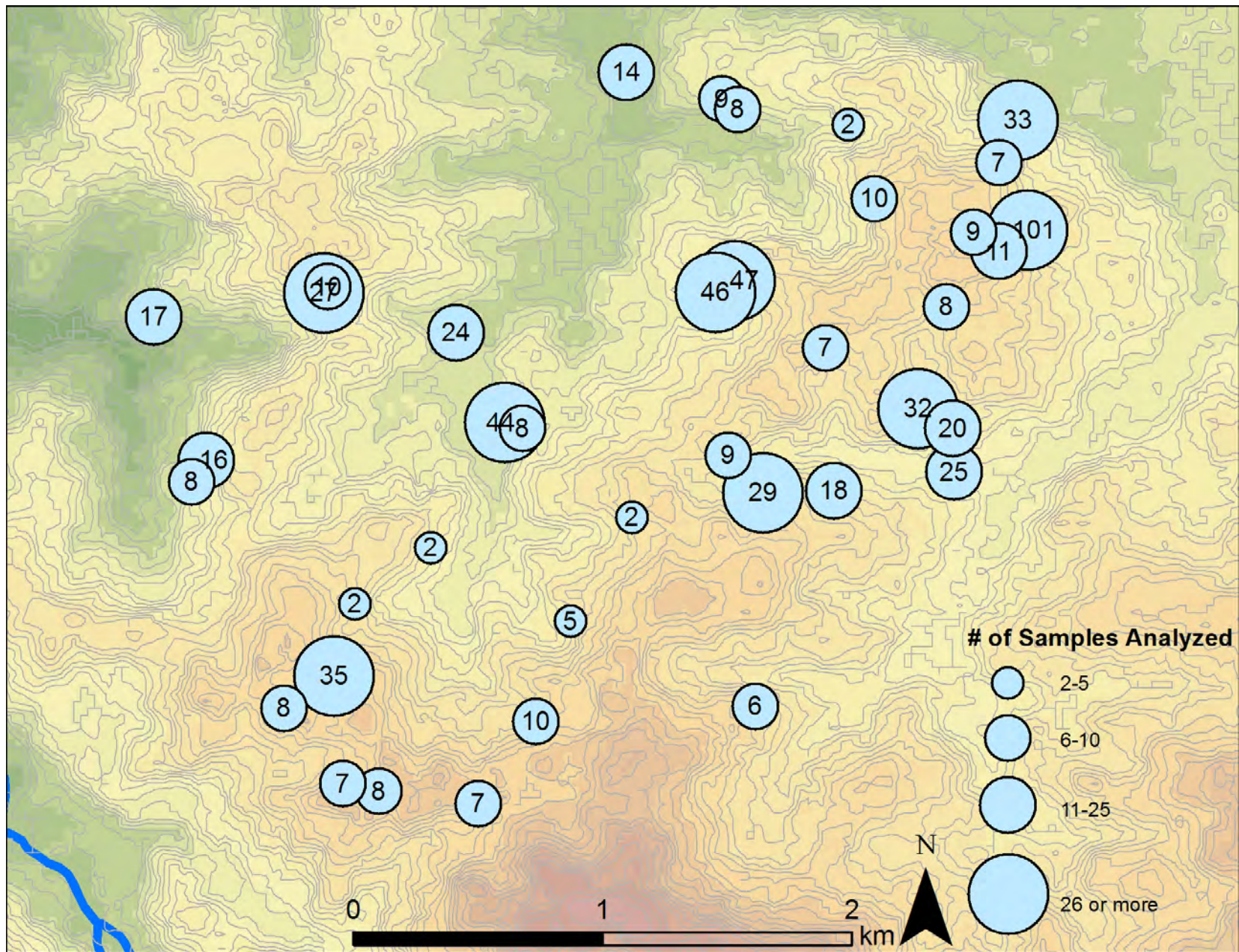
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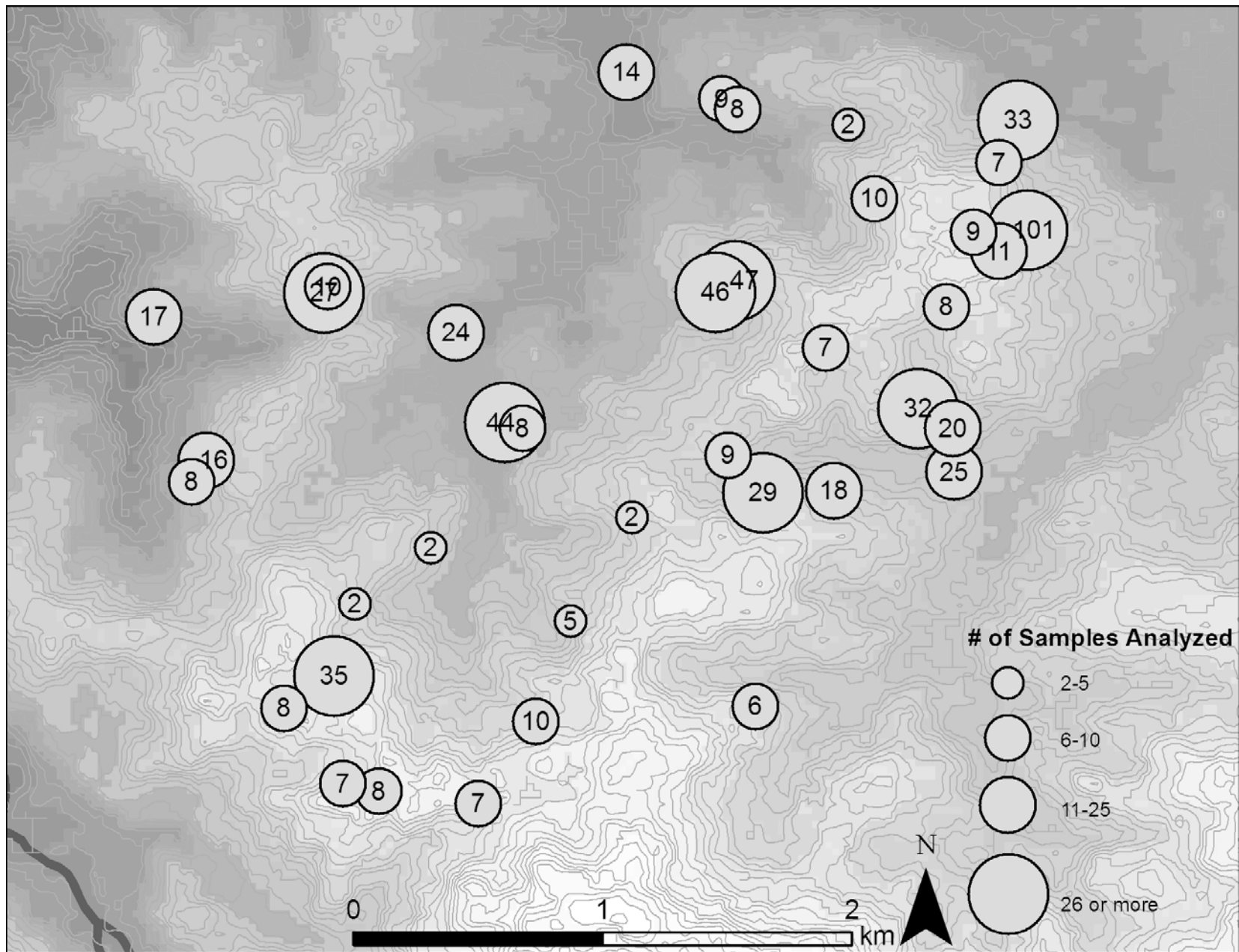
□ Primary Smelting Areas (Known)

0 40 80 120 km

N







Sample	Sample Type	Zn	Cu	Ni	Mo	Nb	Zr	Y
301	A	173	5937	64	59	6	97	23
302	A	995	5725	70	729	<5	35	30
303	D	204	2377	10	375	<5	77	18
304	D	1238	11843	121	1449	<5	20	23
305	D	1407	2507	40	1249	<5	1	33
306	A	1017	9511	106	873	<5	20	56
501	A	116	3294	9	184	<5	56	16
502	A	85	3337	<5	233	<5	58	19
504	A	55	4165	13	270	<0.5	53	14
506	D	51	3463	5	362	<0.5	68	19
508	D	49	4791	43	164	<0.5	71	12
511	A	29	3908	8	363	<0.5	69	19
512	D	65	9886	9	332	<5	45	11
515	D	45	5841	14	630	<0.5	28	9
802	TS	99006	6136	23	53	<5	64	14
803	D	135861	6375	35	71	<5	63	3
805	A	70647	12626	17	35	<5	53	9
806	D	23811	18334	14	23	<5	49	6
810	TS	124840	5427	26	41	<5	64	13
812	A	559	4465	12	243	<5	78	18
814	A	28499	6689	7	28	<5	71	13
3801	D	996	3437	92	1490	<0.5	32	25
3802	A	890	8572	105	823	<0.5	34	12
3805	A	542	7835	46	350	<5	56	28
3807	A	842	27504	108	405	<5	48	19
3808	A	939	6382	40	282	<0.5	34	14
4104	A	120	4512	14	147	7	96	13
4105	D	1097	5724	23	87	<5	70	23
4106	A	71	3354	14	135	<5	95	14
4303	D	135490	10895	33	29	<5	46	19
4310	A	208	13029	17	331	<5	47	15
4504	A	161	4902	9	169	<0.5	63	14
4602	A	66	6552	18	462	<0.5	27	6
4604	A	78	4355	7	449	<0.5	36	17
4607	D	38	16672	51	248	<0.5	55	16
4701	A	163	18466	46	74	<5	53	22
4705	A	2912	5700	128	2253	<5	-19	37

Sr	Rb	U	Th	Pb	Co	Mn	Cr	V
255	82	<5	<5	21	187	2629	89	509
240	48	46	9	337	343	2550	223	276
578	61	10	3	53	705	1865	87	175
205	44	57	19	1495	538	1647	194	290
260	49	78	9	314	351	1921	126	177
272	103	83	6	177	335	2740	107	227
197	74	5	5	14	922	1392	130	211
195	89	<5	5	17	666	1101	136	204
123	32	<1.6	5	9	1190	1064	108	167
273	68	8	5	7	1111	1547	144	172
292	53	4	2	12	2939	1463	80	121
219	186	10	4	8	232	966	129	148
143	49	<5	6	9	1480	1018	99	178
123	45	8	8	18	1645	818	67	148
323	24	<5	5	239	32	744	29	80
404	36	<5	5	805	46	871	28	59
274	17	<5	3	356	20	443	22	50
226	44	<5	7	108	109	1583	60	112
415	21	<5	7	632	43	604	35	110
279	65	<5	5	25	1214	1663	127	202
298	38	<5	6	478	35	1279	71	105
227	54	45	8	147	522	1990	210	242
100	25	5	15	1852	539	1102	184	315
203	44	14	8	95	192	1733	252	334
162	35	15	14	168	306	1676	302	348
159	33	10	5	126	253	1367	143	309
761	80	10	<5	38	746	1116	79	159
295	45	<5	5	39	543	1587	125	181
333	134	5	6	34	619	994	79	177
235	28	<5	5	1049	77	1768	20	52
249	120	18	5	13	454	1270	148	204
251	159	10	4	34	694	849	76	168
71	44	5	7	21	1301	811	124	188
169	51	6	4	11	717	1902	60	131
223	51	<1.6	4	23	2061	1397	66	145
136	33	<5	6	22	989	1053	37	68
248	43	116	13	603	580	1908	160	179

F	S	Cl	Sc	Ba	Sn
404	449	140	20	782	nm
852	808	150	21	2275	nm
531	1781	133	16	14930	nm
860	592	152	17	2356	nm
963	720	131	18	2528	nm
562	1977	155	17	1836	nm
1791	3172	154	24	799	nm
1484	3151	227	19	817	nm
nm	3955	nm	17	824	13
nm	6131	nm	17	2055	<2.3
nm	2247	nm	14	2165	3
nm	3349	nm	13	1907	<2.3
1957	6947	178	18	1112	nm
nm	5395	nm	13	984	16
591	2704	101	<5	15477	nm
481	1959	109	8	15224	nm
<50	5597	105	<5	14324	nm
1624	2561	141	7	2249	nm
516	4475	107	<5	22320	nm
1359	2036	204	20	1853	nm
308	3082	112	6	10083	nm
nm	3802	nm	10	1595	<2.3
nm	526	nm	12	1416	<2.3
901	545	129	30	1457	nm
237	1907	151	31	1371	nm
nm	691	nm	17	2003	<2.3
<50	1827	120	11	25676	nm
1368	1721	229	22	2548	nm
728	1030	139	14	4059	nm
1325	1601	126	6	6305	nm
600	3415	160	18	2929	nm
nm	3737	nm	11	2177	<2.3
nm	3340	nm	17	483	14
nm	3586	nm	12	731	6
nm	3204	nm	12	1167	12
2461	1636	186	7	445	nm
1647	3277	201	13	5886	nm

- A landscape of many small copper smelting sites was mapped in the South Caucasus.
- Though sites were highly dispersed, metal production was large-scale in aggregate.
- A pXRF survey of nearly 700 slag samples reveal spatial patterns in ore use.
- Spatial and archaeometric data suggest metalworkers lacked top-down coordination.
- This pattern of copper production contrasts with other parts of Western Asia.