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A sediment quality triad assessment of the impact of copper mine tailings disposal on the littoral sedimentary environment in the Atacama region of northern Chile

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Abstract

A sediment quality triad (SQT) assessment was made of the impact of copper mine tailings disposal on littoral meiofaunal assemblages in the Atacama region of northern Chile. This situation is unusual in that the disposal is direct into the high-energy coastal system and not via a river estuary or other low-energy environment. This situation also allows for the examination of the impact of copper mine tailings in the absence of confounding effects from other pollutants. The three components of the SQT were: 1. an analysis of the bioavailable metals in both the sedimentary porewater and the adjacent seawater, 2. a microcosm bioassay of both sediments and seawaters using meiofaunal assemblages, and 3. quantitative field samples of the meiofaunal assemblages. Twelve study sites with varying degrees of impact were used, including three reference sites. The study identified that both the meiofaunal assemblage densities and taxa diversities decrease with increasing levels of bioavailable copper, that the Foraminifera and Harpacticoida are sensitive to copper, and that otoplanid Turbellaria are often characteristic of impacted sites; tailings also have both chemical and physical impacts on the environment. In some cases the physical impact of tailings is more important in excluding some organisms e.g. the interstitial polychaete, *Saccocirrus sonomacus*, from a site than is their chemical impact.
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1. Introduction

The coastline of the Atacama region of northern Chile consists of rocky and sandy shores subject to a high degree of wave action with no protected bays or estuaries. For this reason pollutants are discharged directly into the high-energy coastal environment. In most parts of the world pollutants enter the coastal environment through low-energy environments such as estuaries, and it is in these environments that most marine pollution-impact studies have been conducted. The differences between high- and low-energy sedimentary environments have significant effects on the chemistry of pollutants. For example, high-energy sandy beaches are oxygen rich whereas the low-energy sedimentary environments are oxygen poor. In the case of metals, this strongly affects their partitioning and, therefore, their bioavailable concentrations (Luoma and Fisher, 1997). The dumping of copper mine tailings into the high-energy coastal environment of northern Chile represents an opportunity to study the impact metals have in this type of environment. Additionally, due to the nature of the Atacama region, the world's dryest desert, there is little other pollution-induced impact on the coastal environment. There is no agricultural run off, whilst freshwater input to the coastal environment and urban and industrial activity are minimal. Thus, this situation allows for the study of the impact of mine tailings without the confounding effects of other pollutants. The history of tailings dumping in the

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Chañaral area is discussed in detail elsewhere (Castilla and Correa, 1997).

The sediment quality triad (SQT) was first proposed by Long and Chapman (1985) as a means of examining the true impact of pollutants on the marine sedimentary environment. There was concern that simply measuring the levels of pollutants within a sediment was not a reliable predictor of pollution-induced degradation, which was defined as a biologically damaging excess of contamination (Chapman et al., 1987). Analysis of the sediment chemistry provides information on the pollutants present and their concentrations, but does not provide information on whether these pollutants are biologically damaging. Laboratory bioassays are thus used to determine whether the sediment is indeed biologically damaging. However, even the best bioassays do not accurately mimic the true natural conditions at the sites under examination, and therefore they constitute a best approximation. Knowledge of the sediment chemistry and its potential toxicity does not answer the 'so what' question (Long and Chapman, 1985; Chapman et al., 1996). Therefore, field data on the communities living in the sediments are required to establish whether there is observable pollution-induced degradation in the biota (Chapman et al., 1991). Field data alone, however, have to be treated with caution as differences between the biota at different sites could result from differences in any number of variables (e.g. salinity, depth, sediment characteristics, recruitment, etc.) and not necessarily the pollutant under examination.

The sediment quality triad therefore constitutes a weight-of-evidence approach (Chapman et al., 1996) to answer the 'so what' question and to establish if there is any pollution-induced degradation at the sites under study. Thus, the purpose of this paper was to conduct a meta-analysis of the previously published individual components of the SQT (Lee et al., 2002; Lee and Correa, 2004, 2005, in press), and to characterise the overall pollution-induced degradation at the study sites.

2. Methodology

Samples were collected from 12 sites covering the range of sediment and morphodynamic types occurring in the area (see Table 1 for site descriptions, and Fig. 1 for locations). These sites were subdivided a priori into three groups: the reference sites (Playa Zenteno, Torres del Inca and Las Piscinas) which were assumed to be sufficiently far south of the dumping point at Caleta Palito as to be unaffected by the tailings; the northern sites (Puerto Pan de Azucar, Frente Isla Pan de Azucar and Playa Blanca) which are located within the Parque Nacional Pan de Azucar and showed no evidence of tailings deposition based on visual inspection; the central sites (Caleta La Lancha, Caleta Agua Hedionda, Palito 1000m Norte, Playa Palito, Palito 2000m Sur and Playa Chañaral) located around the dumping point at Caleta Palito and experiencing varying degrees of tailings deposition. Physical sediment analyses

Table 1
Location of the beaches used in this study, the mean labile porewater copper concentration Cu_{pw} ($\mu g\ L^{-1}$), the sediment grain size (Md) in units of ϕ and the beach morphology (Type) after Short (1996)

Beach	Code	Cu_{pw}	Md (ϕ)	Type	Lat.
Puerto Pan de Azucar	Pue	14.5	−0.03	Reflective	26°08.3′S
Frente Isla Pan de Aazucar	Fre	11.5	1.54	Intermediate	26°08.4′S
Playa Blanca	Bla	59.0	2.43	Dissipative	26°11.1′S
Caleta La Lancha	Lan	287.5	1.96	Intermediate	26°13.4′S
Caleta Agua Hedionda	Hed	1149.6	1.94	Intermediate	26°15.3′S
Palito 100m Norte	Mil	101.1	−0.78	Reflective	26°16.1′S
Playa Palito	Pal	156.2	−0.78	Reflective	26°16.3′S
Palito 2000m Sur	Dos	97.0	−0.14	Reflective	26°17.0′S
Playa Chañaral	Cha	129.4	2.30	Dissipative	26°20.5′S
Las Piscinas	Pis	6.4	1.72	Dissipative	26°33.0′S
Torres del Inca	Tor	8.3	−0.10	Reflective	26°36.2′S
Playa Zenteno	Zen	10.6	1.67	Intermediate	26°51.1′S

were conducted for each of the sites and the graphic mean (Md) in units of ϕ are presented in Table 1. The sites were also classified by beach morphology (Table 1) using the scheme proposed by Short (1996).

The three components of the SQT were: 1. an analysis of the bioavailable (labile) metal concentrations in both seawater and porewater of the study sites (Lee et al., 2002), using the diffusion gradients in thin films methodology (DGT) (Davidson and Zhang, 1994). Mean labile porewater copper concentrations are listed in Table 1. 2. Multispecies microcosm bioassays of both sediment and seawater from six of the study sites (Puerto Pan de Azucar, Playa Blanca, Caleta La Lancha, Palito 1000m Norte, Playa Palito and Playa Chañaral) (Lee and Correa, in press). 3. A quantitative assessment of the littoral meiofaunal assemblages at each of the study sites over a period of four years (Lee and Correa, 2005), using five replicate 50 cm^3 core samples per site per sampling occasion.

Ratio-to-reference values (*RTR*) were calculated, for each of the measures or indicators found to be useful in assessing the impact status of the sites, by dividing the mean value for each measure at a site by the mean value for that measure from the reference sites (Chapman et al., 1987). *RTR* values provide a normalized measure of the degree to which a site differs from the reference sites and the other sites in the SQT. As bioassays were conducted for only six of the sites (Puerto Pan de Azucar, Playa Blanca, Caleta La Lancha, Palito 1000m Norte, Playa Palito and Playa Chañaral), only these sites were used for the SQT analysis presented here. The reference sites were Las Piscinas, Torres del Inca and Playa Zenteno. For the meiofaunal assemblage measures and the microcosm bioassay measures, the higher the value the less impacted the site. For metal concentrations, on the other hand, it was assumed that the higher the metal concentration the higher the impact. Therefore, in order to make the metals data comparable with the other two components,

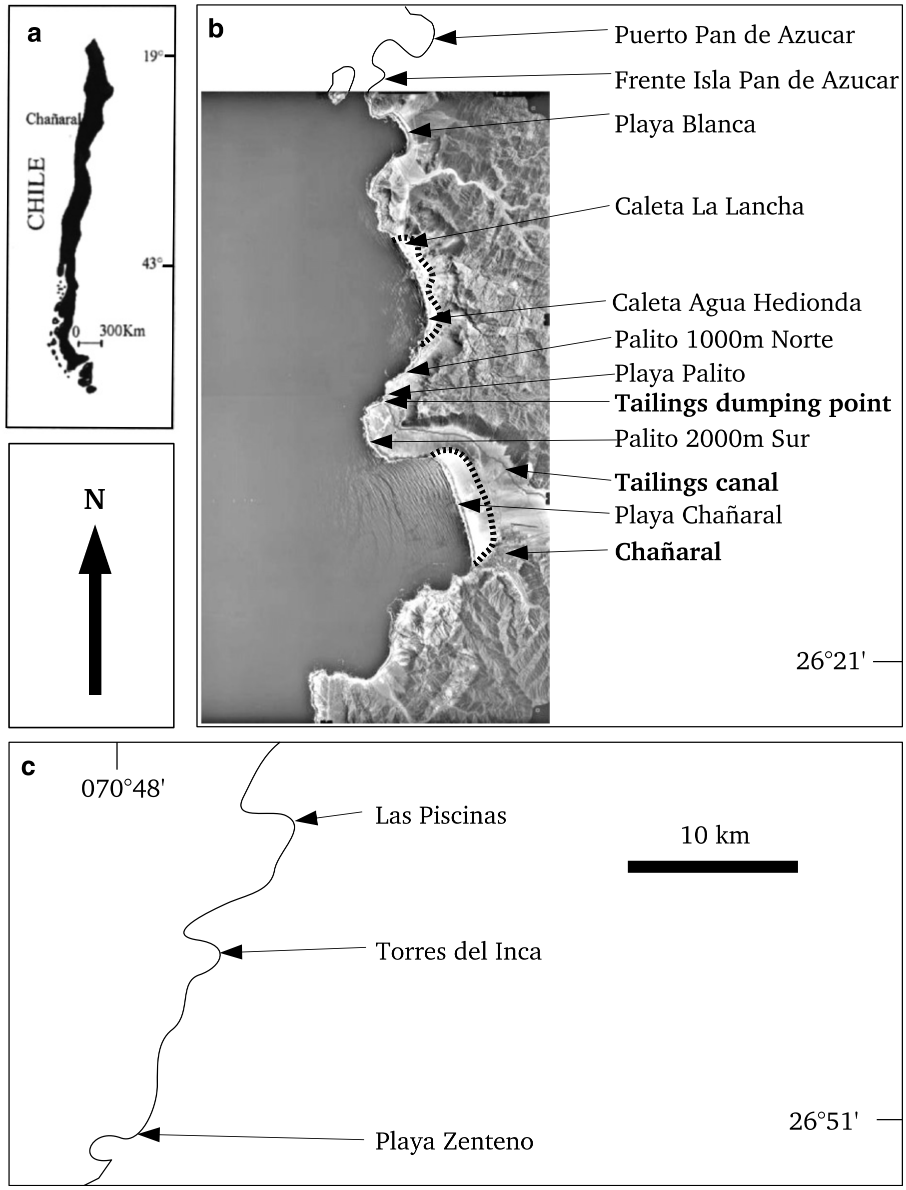

Fig. 1. A map of Chile indicating Chañaral (a) and showing the locations of the sampling sites: (b) the northern and central sites, and (c) the reference sites. The dashed line in (b) indicates the approximate position of the original coastline.

the resulting RTR value was transformed using Eq. (1), where RTR_f is the final transformed RTR value and RTR_i is the initial RTR value:

$$RTR_f = 1 - \frac{RTR_i}{100} \quad (1)$$

3. Results

The measures used for the SQT were as follows: for the metals data only the porewater bioavailable copper concentration was used (Lee et al., 2002). Porewater and seawater copper concentrations were highly correlated and therefore using both would add little discriminatory power to the analysis. None of the other metals measured showed any relation to the distribution of the tailings. None of the measured sediment parameters were used as they were unable to separate tailings from natural sediment. For example, Playa Blanca (natural sand) has an Md of 2.43ϕ compared with Playa Chañaral (100% tailings) which has an Md of 2.30ϕ. The only reliable way to distinguish the two is by colour, with Playa Blanca sediment being grey and Playa Chañaral sediment yellow (Lee, personal observation). This, however, is a subjective judgment and not useful in this analysis. The mean sediment grain size, often the most important variable in determining the meiofaunal assemblage structure, was not an important variable in describing the meiofaunal assemblages at the impacted sites in this study. This was determined using BIOENV tests (see Table 5 Lee and Correa, 2005, for details). From the microcosm sediment bioassays, measures of the meiofaunal assemblage, Foraminifera, and Harpacticoida densities were used (Lee and Correa, in press). The bioassay *RTR* values were calculated using the bioassay reference sites, Las Salinas and Playa Grande (see Lee and Correa, in press, for details). Finally, from field data, measures of meiofaunal assemblage, Foraminifera, and Harpacticoida densities along with meiofaunal assemblage taxa diversity were used (Lee and Correa, 2005). A mean *RTR* value was calculated for each of the components of the SQT. After plotting the data on a tri-axial plot (Fig. 2) the area of the triangles was calculated as an indicator of the pollution-induced degradation at each site, where the smaller the area of the triangle the higher the pollution-induced degradation. Each of the sites was ranked for each of the *RTR* values and the area of the triangle for the purposes of comparison.

The *RTR* values for each of the measures used in the SQT analysis are presented in Table 2. Using the area of the triangle on the triaxial plot (Fig. 2) as equivalent to the degree of pollution-induced degradation, the most impacted site was Playa Chañaral followed closely by Caleta La Lancha. The least impacted sites were clearly Puerto Pan de Azucar and Playa Blanca. The site with the lowest porewater copper concentration was Puerto Pan de Azucar whilst the highest concentration was recorded at Caleta La Lancha. The least impacted meiofaunal assemblage was at Playa Blanca and the most impacted at Palito 1000m Norte. Finally, for the microcosm sediments bioassays the least toxic sediment was from Playa Blanca and the most toxic from Playa Chañaral. Table 3 presents the ranks for each of the components of the SQT and the overall ranking of the sites (area). The component that best matches the area ranks is the microcosm bioassay, though

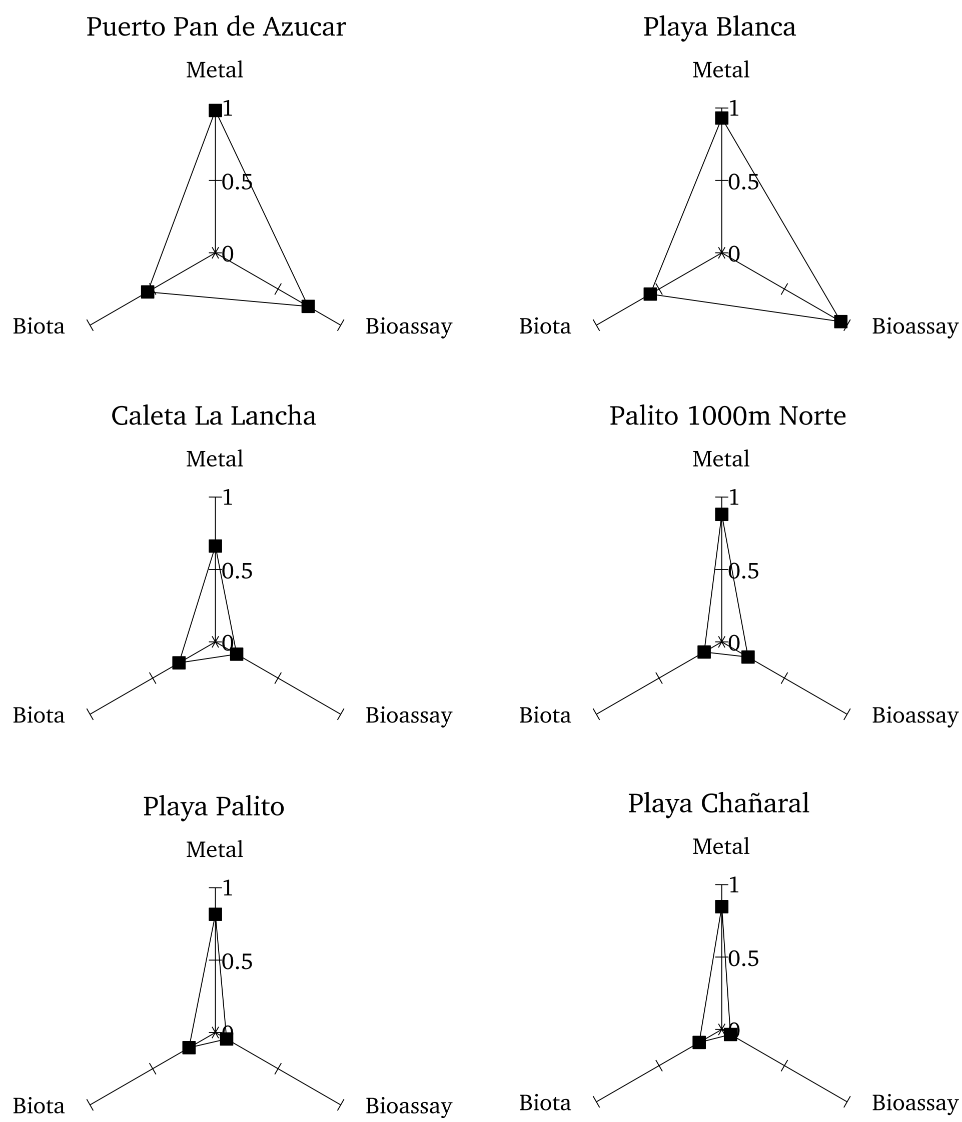

Fig. 2. A tri-axial plot of the mean *RTR* values for each of the components of the SQT. The smaller the area of the triangle the higher the pollution-induced degradation.

Table 2
Ratio-to-Reference (*RTR*) values for each of the selected measures from each of the components of the SQT

Site	Metal	Biota				Bioassay		
	Cu[a]	Den	Div	For	Har	Den	For	Har
Pue	0.98	0.29	1.09	0.32	0.44	0.63	0.26	1.33
Bla	0.93	0.33	0.90	0.93	0.13	1.00	0.72	1.13
Lan	0.66	0.14	0.43	0.01	0.00	0.17	0.20	0.14
Mil	0.88	0.08	0.48	0.00	0.01	0.28	0.24	0.10
Pal	0.82	0.11	0.71	0.02	0.01	0.13	0.11	0.04
Cha	0.85	0.15	0.54	0.01	0.01	0.07	0.08	0.07

Cu = Copper, Den = Density, Div = Diversity, For = Foraminifera, Har = Harpacticoida.
[a] The initial copper *RTR* values were transformed using Eq. (1).

Table 3
The rank order of the sites for each of the components of the SQT and the area of the triangles in Fig. 2 which is a measure of pollution induced degradation

Site	Metal[a]	Biota	Bioassay	Area
Pue	1	2	2	2
Bla	2	1	1	1
Lan	6	3	4	5
Mil	3	6	3	3
Pal	5	4	5	4
Cha	4	5	6	6

[a] The initial copper *RTR* values were transformed using Eq. (1).

the match is not perfect, as the positions of Caleta La Lancha and Playa Palito are reversed.

4. Discussion

Copper is clearly the most important metal at the sites studied in terms of impact on the biota. The labile copper concentration in seawater mirrors that in the interstitial porewater, strongly suggesting that one is the source of the other (Lee et al., 2002) and that the impact of the 'clear water' tailings now dumped at Caleta Palito is minimal. The highest concentrations of copper are associated with the beaches consisting entirely of tailings (Caleta La Lancha, Caleta Agua Hedionda and Playa Chañaral). The porewater labile copper concentration is broadly predictive of pollution-induced degradation. This is certainly because a close approximation to the bioavailable copper concentration, labile copper, was measured rather than the total sediment concentration, which is known not to be predictive of bioavailability (Chapman et al., 1998). The influence of the high-energy sandy beach environment over the partitioning of copper is significant. In this high-oxygen, low-organic carbon, high-energy environment there are much lower concentrations of ligands available to compete for the free copper ions than in the low-oxygen, high-organic carbon, low-energy environments more usually studied when considering the environmental impact of metals (Chapman et al., 1998). This suggests that much more of the total copper is bioavailable in high-energy sandy beach ecosystems when compared to their low energy counterparts.

In microcosm experiments where a non-contaminated tailings substitute (fine sand) was used to block the interstitial space of a natural coarse sediment (Lee and Correa, in press), the meiofaunal assemblage density increased. This increase was entirely due to an increase in the abundance of the surface utilizing Foraminifera. However, this increase was considered unlikely to occur in the field as a result of tailings disposal because the Foraminifera are sensitive to copper. In fact, Foraminifera density decreases with increasing concentrations of labile copper (Lee and Correa, 2005). In the microcosm experiments, meiofaunal assemblage diversity decreased when blocking of the interstitial space made the sediment unsuitable for true interstitial species. This was demonstrated experimentally for the interstitial polychaete *Saccocirrus sonomacus* (Lee and Correa, 2004). The experiments revealed that the concentrations of labile copper observed in the field did not exceed the LC_{50} value for *S. sonomacus* calculated from toxicity tests. Experiments also revealed that *S. sonomacus* always selects the coarser of the two sediments when offered a choice. The conclusion drawn from those experiments was that *S. sonomacus* may be eliminated from the impacted sites by the physical rather than the chemical impact of the tailings. These results could also be extrapolated to include other interstitial species (e.g. the hoplonemertine *Ototyphlonemertes americana*). It is likely, therefore, that the physical impact of the tailings is at least in part responsible for the observed pollution-induced degradation, particularly at those sites where tailings is mixed with natural coarse sediments (Palito 1000m Norte, Playa Palito and Palito 2000m Sur).

The microcosm bioassays indicated that sediments at the two northern sites, Puerto Pan de Azucar and Playa Blanca, were not toxic, unlike those from the central sites, Caleta La Lancha, Palito 1000m Norte, Playa Palito and Playa Chañaral. The microcosm bioassays were unable to distinguish between the 100% tailings sites and the sites consisting of a mixture of natural coarse sediment and tailings. As stated previously, bioassays do not accurately mimic the true natural conditions at the sites under examination. In this case the absence of wave action is the major concern. The degree of wave action is key to the dynamics of the physico-chemical conditions within sandy beaches, controlling dissolved oxygen concentrations, and both nutrient input and output, (for a detailed discussion of the interstitial environment see McLachlan and Turner (1994)). Over the six week period of the bioassays, the oxygen concentrations in the microcosms were probably lower than would be encountered in the field, but they were not considered to be limiting and anoxia was not observed.

Meiofaunal assemblage densities and taxa diversities both decrease with increasing concentrations of porewater labile copper (Lee and Correa, 2005). The meiofaunal assemblage diversity at the northern sites did not differ significantly from the reference sites suggesting that the pollution-induced degradation at these sites is in the form of chronic or sub-lethal effects, such as reduced fecundity in those species with direct benthic development. This is particularly important in the ecologically key group of the Harpacticoida, which are the primary consumers in the meiofaunal assemblage and particularly sensitive to copper (van Damme et al., 1984; Lee et al., 2001; Lee and Correa, 2005). Foraminifera and Harpacticoida densities decreased with increasing porewater labile copper concentrations. This sensitivity to copper in the Harpacticoida has already been forwarded as an indicator of pollution-induced degradation arising from metal contamination (Lee et al., 2001). Otoplanid turbellarians are common in the zone of retention of high-energy sandy beaches along the Chilean coast (Lee, personal observation). These flatworms are described as predators (Martens and Schockaert, 1986), but may also be able to survive on detritus (P. Boaden, personal communication) and do exhibit cannibalism (Lee, personal observation). Otoplanid turbellarians have a high tolerance for copper exhibiting zero mortality in toxicity tests with copper concentrations as high as 200 $\mu g\ L^{-1}$ (Lee, unpublished data). In the field they appear to increase, as a proportion of the meiofaunal assemblage, the higher the pollution-induced degradation; at Caleta La Lancha (100% tailings) they constitute 95% of the meiofaunal assemblage. These observations may well prove useful in providing another field-based indicator of metal-induced degradation.

Taking the area of the triangle on the triaxial plot as representative of the overall pollution-induced degradation at each site, the most impacted sites are, not surprisingly, the two 100% tailings sites at Caleta La Lancha and Playa Chañaral. None of the individual components of the SQT predicts this. Playa Chañaral has a lower porewater labile copper concentration than Caleta La Lancha and Playa Palito but appears more impacted than these two sites in both the sediment bioassays and the field samples of the meiofaunal assemblages. The reasons for this in the case of the bioassays is uncertain, but in the case of the field samples it is due to the presence of high densities of otoplanid turbellarians at Caleta La Lancha discussed above. The sites at Playa Palito and Palito 1000m Norte are also clearly impacted by the tailings dumping. The sediments from both were toxic in the microcosm bioassays, and the field samples also clearly showed signs of impact.

The source of the observed effects on the meiofaunal assemblage structure is clearly the tailings that are present at each of the sites, and the effects of the 'clear water' tailings currently being dumped at Caleta Palito appear to be either negligible or overwhelmed by the effects of the tailings already present. The principal source of copper in the seawater at each of the sites were the tailings already present at the sites (Lee et al., 2002). The two most impacted sites identified by the SQT analysis were Caleta La Lancha and Playa Chañaral where there are both high levels of bioavailable copper and severe physical impact by the tailings. Though Caleta Agua Hedionda was not bioassayed it is reasonable to predict that it would be grouped with these two sites since it had the highest concentrations of bioavailable copper and the most altered meiofaunal assemblage of any of the sites sampled. The second group of clearly impacted sites were Playa Palito, Palito 1000m Norte and Palito 2000m Sur where there were relatively high levels of bioavailable copper but a lower degree of physical impact by the tailings. In the SQT analysis the difference between the two groups of clearly impacted sites is obvious; using the individual components alone these differences are less clear.

The northern sites, Puerto Pan de Azucar, Frente Isla Pan de Azucar and Playa Blanca were not obviously impacted by the tailings dumped at Caleta Palito. Sediments from Playa Blanca and Puerto Pan de Azucar did not prove to be significantly toxic in the microcosm bioassays, and the levels of bioavailable copper were not high, though they were higher than at the reference sites. However, in the analysis of the biota, these sites consistently had lower meiofaunal densities, but not diversities, than the reference sites, suggesting that the dumping of the tailings may have resulted in some chronic sub-lethal effects on the meiofauna. Previous work on the rocky shore fauna at these sites, or ones adjacent, indicated that the coast in this area was unaffected by the dumping of tailings (Castilla, 1983, 1996; Castilla and Correa, 1997). However, the sublethal effects, such as reduced fecundity, would be more evident within the meiofauna than the rocky shore macrofauna due to differences in the predominant life-cycles of each group. For the meiofauna the majority of species exhibit direct benthic recruitment, and any reduction in reproductive output would be quickly reflected in the assemblage. On the other hand, a similar effect on the rocky shore macrofauna would probably be masked by recruitment from the plankton of larvae and juveniles from unaffected areas.

The information gathered for this research, and combined in the form of an SQT analysis, enabled the study sites to be divided into four groups, three of which were defined a priori. The first group comprised the reference sites at Las Piscinas, Torres del Inca and Playa Zenteno which were unimpacted by the tailings dumping. The second group were the northern sites at Puerto Pan de Azucar, Frente Isla Pan de Azucar and Playa Blanca, where there was some evidence of chronic or sub-lethal effects of the elevated bioavailable copper. The third group identified at the outset of the research were the impacted sites and it is this group that, on the basis of this research, can be further sub-divided into two additional groups. Firstly the impacted sites at Playa Palito, Palito 1000m Norte and Palito 2000m Sur, where there was clear impact by the tailings, with elevated concentrations of bioavailable copper and some degree of physical impact from the tailings. Secondly, the severely impacted sites at Caleta La Lancha, Caleta Agua Hedionda and Playa Chañaral, where the original habitat was completely smothered by tailings; in the case of Playa Chañaral there is little evidence of recovery 25 years after dumping ceased.

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