Elsevier Editorial System(tm) for Journal of Environmental Management

Manuscript Draft

Manuscript Number: JEMA-D-16-03925R1

Title: Airborne asbestos fibres monitoring in tunnel excavation

Article Type: Research Article

Keywords: Tunnelling; Naturally Occurring Asbestos (NOA); Airborne asbestos monitoring; Dust characterization; SEM-EDS; Occupational Health

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**Published in Journal of Environmental ManagementVolume 196, Pages 583 - 593 on 1 July 2017**
**DOI: 10.1016/j.jenvman.2017.03.055**

# Highlights

1. 1571 samples of dust analyzed by SEM-EDS for asbestos exposure in tunnelling.
2. In situ monitoring is effective in fast confirming the presence of asbestos.
3. SEM – EDS fibres counting has proven to be a reliable method for analyzing environment with high number of elongated minerals particles.
4. In dusty environment sampling, analysis and ventilation control the results.
5. Our results point out the critical issues of legislation on exposure to asbestos.

# Airborne asbestos fibres monitoring in tunnel excavation

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## Abstract

Tunnelling across ophiolitic formation with Naturally Occurring Asbestos (NOA) can release fibres into the environment, exposing workers, and the population, if fibres spread outside the tunnel, leading to increased risk of developing asbestos-related disease. Therefore, a careful plan of environmental monitoring is carried out during Terzo Valico tunnel excavation.

In the present study, data of 1571 samples of airborne dust, collected between 2014-2016 inside the tunnels, and analyzed by SEM-EDS for quantification of workers exposure, are discussed.

In particular, the engineering and monitoring management of 100 meters tunnelling excavation across a serpentinite lens (Cravasco adit), intercalated within calcschists, is reported. At this chrysotile occurrence, 84% of 128 analyzed samples (from the zone closer to the front rock) were above 2 ff/l. However, thanks to safety measures implemented and tunnel compartmentation in zones, the asbestos fibre concentration did not exceed the Italian standard of occupational exposure (100 ff/l) and 100% of samples collected in the outdoor square were below 1 ff/l.

During excavation under normal working conditions, asbestos concentrations were below 2 ff/l in 97.4% of the 668 analyzed samples.

Our results showed that air monitoring can objectively confirm the presence of asbestos minerals at a rock front in relative short time and provide information about the nature of the lithology at the front.

The present dataset, the engineering measures described and the operative conclusions are liable to support the improvement of legislation on workers exposure to asbestos referred to the tunnelling sector, lacking at present.


## *Keywords*

Tunnelling; Naturally Occurring Asbestos (NOA); Airborne asbestos monitoring; Dust characterization; SEM-EDS; Occupational Health


## 1. Introduction

Tunnelling across rocks characterized by naturally occurring asbestos (NOA) represents a serious concern for environmental and occupational health (Hashim, 2014). Because of its carcinogenic nature and pneumoconiosis-generating properties, asbestos dust is considered one of the most dangerous types of dust for workers' health (Szeszenia-Dąbrowska, 2016; Paustenbach, 2015).

More than 52 countries have banned or restricted the use of asbestos according to the World Health Organization (WHO) campaign to stop the use of all asbestos types, but controversies about health impact, identification criteria and normative limits are still on-going (Finkelstein, 2013; Bernstein, 2013; Jargin, 2015; Baur, 2016). Furthermore the decline in asbestos usage by more developed countries is being offset by less-developed countries that are continuing to use asbestos (Baur, 2015; Marsili, 2016) and many countries have to deal with management of existing asbestos removal and naturally occurring asbestos (EU Parliament, 2012; Hashim, 2014).

In this perspective, the tunnelling of a new high speed-high capacity railway line in Northern Italy, between Genoa and Milan (hereafter: Terzo Valico) is highly challenging for environmental issues and for occupational safety, because it involves excavation across a complex geology with ophiolitic formations, potentially containing NOA deposits and leading to possible dispersion of fibres into the environment (Wylie and Candela, 2015). NOA refers to asbestos that has not been

extracted and refined for commercial purposes, but rather has been exposed unintentionally by excavation activities (Harper, 2008; Lee, 2008; Wagner, 2015).

The Terzo Valico will improve connections among the harbour system in Liguria, the main railway lines of Northern Italy and the rest of Europe. The project is part of the Rhine-Alpine Corridor, within the trans-European transport network, connecting the most populated and industrialised European regions. The railway will be 53 km long, 37 km of which under tunnels, connected with the existing Genoa-Milan line through four, 14 km long, interconnections (Impregilo Salini, 2016). Starting at the Genoa hub, the new line will run along the Genoa-Milan route. The major infrastructure of the project is the 27.110 km Valico Tunnel, provided of four security adits (7.300 km long), from the south, Polcevera, Cravasco, Castagnola and Val Lemme, and minor tunnels that connect the southern and northern end of the Valico Tunnel with the existing railway lines: Campasso (0.716 km) and Serravalle (7.094 km), respectively (Linea III Valico Relazione Generale Illustrativa, 2005). Almost all the railway line is made of two one-track tunnels linked with cross passages each 500 m intervals for safety requirements (Fig. 1).

In the excavation of ophiolitic units, multiple dimensions have to be managed: the optimised excavation technique, the characterisation of rock waste and its fate after extraction, and finally the occupational and life exposure. Because of the geological conditions, the design and construction were carried out on the basis of the ADECO-RS approach (Lunardi, 2008). The northern portion of the Valico Tunnel, Serravalle Tunnel and Polcevera adit are carried out using the Tunnel Boring Machine (TBM). Conventional Tunnelling (basic mechanical excavators, eventually associated with drill-and-blasting) is used on the southern section of the Valico Tunnel, the interconnections and the rest of adits. Conventional Tunnelling is carried out in a cyclic process of repeated steps of excavation followed by the application of primary support that allows dealing with eventual problems during construction. All techniques encompass anyway the release of dust from the rock front to the atmosphere of the tunnel; at variable extent, all the excavation methods release mineral dust, in order of decreasing abundance: i) drill-and-blasting, ii) basic mechanical excavator and the iii) tunnel boring machine (Bradley, 1979).

Tunnelling activity can be assimilated to an indoor confined environment where the worker is potentially exposed to a continuously renewed source of dust, and eventually fibres. Therefore, while starting the activities, a careful monitoring plan (Asbestos Management Protocol) to verify the presence of asbestos both in bulk and air samples, inside and outside tunnels, during tunnelling, was written by the general contractor Consortium COCIV, with the regional authorities, and approved by the Ministry of the Environment and Protection of Land and Sea. Thus, the protocol prescriptions request monitoring of the tunnel environment inside and in its surroundings for: i)

mineral dust and eventually of airborne asbestos fibres, ii) concentration of hazardous minerals in the rock and in the waste.

International organizations of health and safety agree on the absence of a "safe" level of asbestos exposure for any type of asbestos fibre and exposure should therefore be kept as low as possible (IARC, 2012; WHO, 2014); neverthless reference values are necessary to provide health protection and surveillance.

An environmental background level of 2 fibres per liter (ff/l) is widely accepted and is enforced in many national and international regulations (e.g., Italian law on the remediation of indoor asbestos-contaminated environments, MD 06/09/1994). Regulatory authorities in charge of monitoring areas crossed by the railway plan, decided to consider a more precautionary limit value in life environment (1 ff/l), in accordance to WHO Air Quality Guidelines (WHO, 2000).

Chapter IX, Part III of Legislative Decree no. 81/2008 (art. 247-261) is about protection of workers from risks of exposure to asbestos during occupational activities; it describes the term "asbestos" as a collective name for a category of naturally occurring fibrous minerals from the groups of serpentine (chrysotile) or amphibole (i.e. amosite, crocidolite, tremolite, actinolite and anthophyllite). The LD 81/2008 classifies as respirable asbestos fibres that with length > 5 µm, diameter < 3 µm and length to diameter ratio > 3:1; methods described in the Ministerial Decrees 06/09/1994 and 14/05/1996 are indicated as guidelines to follow for detection and quantification of asbestos fibres. The LD 81/2008 sets an asbestos maximum working daily exposure of 100 ff/l, calculated as normalized average concentration over 8 hours work time. This value is in agreement with the occupational exposure limit for airborne asbestos in workplaces in EU countries, Directive 2003/18/EC and Directive/2009/148/EC (European Commission, 2003 and 2009).

This paper reports the results of the airborne fibres monitoring aimed to assess and to prevent professional exposure, during the first phase of Terzo Valico excavation, between September 2014 to July 2016 (about 7.5 km excavated). A total of 1571 samples, collected inside tunnels under construction, were analyzed. The concentration of asbestos fibres was determined by means of a Scanning Electron Microscope equipped with Energy Dispersive X-ray Spectroscopy device (SEM-EDS).

In particular, the engineering and monitoring management of 100 meters tunnelling excavation in the presence of a serpentinite lens, intercalated within calcschists, is reported. While constructing this conspicuous dataset, technical issues were dealt with in the lack of an analytical protocol and the significance of measure was correlated with problematic sampling in high humidity, high-dustiness environment. Thus, this dataset can be assumed as a world-class standard in management policy of hazardous minerals.

# 2. Materials and methods

## 2.1 Geological background

The Terzo Valico crosses an area of complex geology in north western Italy. The southern and central section of the line (Central Liguria) is situated at the southeastern termination of the Western Alps that represent the transition from the Alps to the Apennines (Capponi, 2008 and references within). The northern section of the line (Southeastern Piedmont) cuts across the sedimentary Tertiary Piedmont Basin, between the Ligurian Alps and Apennines to the south and the Po Plain to the north.

The Ligurian Alps-Apennines transition is formed by metamorphic ophiolite units derived from the Jurassic Ligurian–Piedmont ocean, by paleo-European continental margin units. The ophiolites were involved in the alpine orogenic events, recording a complex and multiphase metamorphic and structural evolution (Capponi, 2009 and references therein). Several generations of asbestos phases were formed since the origin of these lithotypes. Finally, during the Alps-Apennine built-up, the units were re-equilibrated under different pressure-temperature (P-T) conditions, from high to low P/T conditions: Voltri Unit (eclogite facies), Palmaro –Caffarella Unit and Cravasco-Voltaggio Unit (blueschist facies) and Figogna Unit (pumpellyite-actinolite facies). The metamorphic conditions account for the mineralogical diversity of asbestos herein developed.

The Tertiary (Eocene to Miocene) Piedmont Basin consists of a transgressed succession, composed of coarse-grained conglomerates involved in the late orogenic deformations (Capponi, 2009), grading upward to sandstone and marl members towards the Po Plain. The Molare Formation conglomerates represent the partial erosion of the alpine ophiolitic relief and of the continental metamorphic units of Central Liguria; the sandstones and Rigoroso Formation marls represent marine deposits.

## 2.2 Natural occurrences of asbestos

Due to the geologic complexity of the area, several lithotypes are liable to contain NOA deposits. Their occurrence depends on i) the metamorphic conditions ranging from anchi-metamorphic to blueschists facies (e.g. Giacomini, 2010), ii) the host-rock composition and iii) the structural framework. In particular, most asbestos concentrations are associated with development of vein-filling minerals, related with ductile to (more often) brittle structures like shear zones, fault planes and fractures (Gaggero et al., 2006 and 2013; Isola, 2010; Labagnara, 2013). A further

occurrence is as reaction zones between ultramafic and mafic rock bodies (Actinolite-tremolite schists). Finally, asbestos minerals spread within the rock-mass matrix in a network of cracks as effect of hydraulic fracturing (Ross, 1981; Ross & Nolan, 2003; Schreirer, 1989; Wruke, 1986).

In the Ligurian Alps, asbestos minerals are associated with the ophiolite complexes belonging to the Ligurian-Piedmont Domain, in particular Alpine serpentinites and serpentine-schists (Isola, 2010). Among ophiolites, serpentinites potentially may contain the highest concentrations of asbestos minerals, other rock-types potentially containing fibrous minerals are represented by chlorite-schists, metabasites and ophicarbonate rocks (Labagnara, 2013). Minor concentrations of asbestos minerals are also found in sedimentary rocks derived from the dismantling of asbestos-bearing lithologies. In the Western Alps, only chrysotile, tremolite and actinolite occur in significant amount. Chrysotile is the dominant fibrous phase of very low grade oceanic metamorphism, while tremolite-actinolite form during low grade orogenic metamorphism.

## 2.3 Analytical methods and statistical analysis

Air samples were collected onto 25 mm polycarbonate membranes with pore size of 0.8 µm at flow rate of 6-9 l/min. The 3000 litre volume of each monitoring was splitted on 4 or 6 filters depending on the quantity of the airborne dust. The sampling stations were placed at 20-35 m from the rock front, as close as possible to the source of asbestos dust.

The sampled filters were prepared and analyzed according to the method described in the Italian legislation MD 06/09/1994 (All. 2 - Quantitative determination of airborne asbestos fibre concentrations in indoor environments), which is very similar to the ISO Method 14996:2002 (ISO, 2002). Preparation and analyses were carried out at the Electron Microscopy Laboratory at the Earth Environment and Life Sciences Department (DISTAV), University of Genoa, appointed by the Ministry of Health for asbestos analyses.

A portion of each filter was attached onto an aluminium stub, then coated with a thin layer of gold to increase the conductivity (metallization) by a Quorum Q150T ES.

Randomly selected areas of each filter were analyzed using a Scanning Electron Microscope (TESCAN 3 XML) working at 2000x magnification, 20 kV of acceleration voltage. The SEM resolution with our working condition is 100 nm.

The elemental analysis of the fibres, that meets the geometric requisites criteria (length greater than 5 µm, diameter smaller than 3 µm, and length to diameter ratio equal to or greater than 3:1) was carried out by Energy Dispersive X-ray Spectroscopy (Oxford Instruments, AZtec 2.4).

Particles in accordance with dimensions and chemical composition were counted as asbestos fibres. Other elongated mineral phases composing the particulate were analyzed to assess their nature.

Their concentration (ff/l) was calculated using the following formula:

$$C\ (\mathrm{ff/l}) = N_f \cdot \frac{1}{a \cdot N_c} \cdot A_f \cdot \frac{1}{V}$$

Where $N_f$ is the total number of asbestos fibres counted, $a$ the field area at 2000X ($mm^2$), $N_c$ the total number of fields examined on the filter, $A_f$ effective collecting area of filter ($mm^2$), $V$ the volume of sampled air (l).

The analyses were performed within 12 hours from samples delivery to ensure immediate implementation of protection measures and eventual re-sampling should asbestos fibres occur.

The Detection Limit (DL), analytical sensitivity of the method, is the concentration equivalent to observation of one fibre ($N_f$ =1). It is function of the sampled air volume, effective collecting area of the filter and area of filter examined. Therefore, the DL had to be determined for every analyses at changing parameters (Musmeci, 2015). Theoretically, the DL could be reduced increasing the area of filter examined by SEM; in our case, it was necessary to find a compromise between acceptable DL and time/cost of the analysis. Therefore, the used DL was 0.3 ff/l, except at the Cravasco tunnel, cutting serpentinites (section 3.4), where the analytical sensitivity ranged from 0.1 ff/l to 0.96 ff/l, according to zones.

The ISO 16000-7 method requires that results < 3 fibres, to be reported as lower than the calculated DL based on the upper 95% confidence interval from a one sided Poisson distribution (Musmeci, 2015). However, while acknowledging and highlighting that low counts of fibres have a very poor precision, in order to obtain an accurate estimate of worker' exposure, we used the actual fibre counts for calculating the airborne fibre concentrations (Burdett, 2007).

During data elaboration, results below DL were replaced by a value equal to one-half the sensitivity limit. Descriptive statistics, such as measures of central tendency (arithmetic mean) and measures of dispersion (geometric standard deviation, SD) were calculated for asbestos concentration at each of the monitored tunnels.

Chi-squared test and *t*-test were used to determinate differences in relative frequencies percents and in the means of two group of data, respectively. Statistical significance was determined by a P value < 0.05.

### 2.4 Sampling frequency and safety measures

As tunnelling activity started, the monitoring of airborne fibres began to be carried out inside the tunnels in order to check workers exposure to asbestos.

Air sampling was performed in every tunnel one time per week for results below the DL, corresponding to a nul risk level (LR0). For fibres equal or higher than the DL until 1ff/l (LR1) the sampling was carried out on alternate days until no fibres were attained. In this case, workers were supplied with suitable personal protection equipment in order to reduce the asbestos risk exposure. For asbestos occurrence between 1 and 2 ff/l, sampling and analyses every day were assessed (LR2). If the result was equal or higher than 2 ff/l, excavation works were stopped and protective measures taken in order to reduce fibres dispersion in air and increase the safety of workers. In this case, all activities carried out by the general contractor were approved, checked and controlled in the field by the regulatory authorities.

## 3. Results and discussion

### 3.1 Analytical problems related to asbestos monitoring during tunnelling

The tunnelling activity produces a large amount of fine~~s~~ particles at the rocks mechanical breakdown; dust emission is the process where fine~~s~~ particles are detached from the rock surface to become suspended in the air (Petavratzi, 2005). The liability of suspended particles for dispersion is determined by the capacity of the dust particles to remain airborne, this may be influenced by both the weight of particles, the inter particle forces and the drag, lift and movement imparted by the flow of air on the particles. The amount, hence the airborne concentration, is likely to depend on the energy put into the process (World Health Organization, 1999). Factors affecting dust formation reside in the mechanical and physical properties of the rock (brittleness, hardness, porosity) and in the environmental conditions (ventilation, humidity, depth).

Generally, the extent of dust formation depends of the mechanical and physical properties of the rock and on the environmental conditions inside the tunnel. Conspicuous dust-formation is due to the high brittleness, hardness, low moisture content and porosity of the rocks (Panov, 1967). A minor amount of dust is given off from unaltered massive rocks, with low hardness, and relative plasticity. Low levels of dust in tunnels can be achieved with an efficient de-dusting system and watering the rock front. However, tunnels driven in the same rocks show different dust production for different alteration and fracturation degree of the rock, or for changed relative humidity from

dry to rainy season (only for tunnels close to the surface). Finally, different lithotypes produce different amounts of dust at the same mining conditions. (Güyagüler, 1993). Therefore, is very difficult to predict the dustiness of the environment.

The overload of filter with mineral dust was the most significant problem of the sampling activity during tunnelling excavation. High levels of airborne dust particles obscured fibres on the filter and lowered the count or made counting impossible. Furthermore, overloading of filters generated difficulties in X-ray spectrum interpretation; this added imprecision associated with the evaluation. Contamination from surface or exotic particles might give additional elements to the spectrum, precluding the identification of a fibre.

Little background literature on these aspects is available. During the monitoring, an internal classification of filters readability on the basis of their loading was established, as feedback to samplers. The best analysis conditions are represented in Fig. 2a and Fig. 2b, according to literature (Cattaneo, 2012; Musmeci, 2015). Filters as covered as in Fig. 2e were considered not readable. Even if only 4.3% of 668 filters (Fig. 5) were classified as unreadable, according to our scale reported in Fig. 2, the analyses were often difficult for filters as in Fig. 2c and 2d. Significant problems of dustiness were found at some interconnections tunnel junctions due the complicated position of de-dusting system. Difficult ventilation occurred at two fronts GN13 and GN16,-during the enlargement of the tunnel cross-section, creating low velocity zones with high dust concentrations. In GNSB tunnel, excavation by the drilling-and-blasting method produced peak of dust concentrations over relatively short periods that made the analysis very difficult.

The analyses were carried out using the BSE signal, instead of SE, in order to reduce the interference of combustion particles produced by vehicles equipments (Fig. 3). The number of backscattered electrons reaching a BSE detector is proportional to the mean atomic number (Z) of the sample. Thus, a brighter BSE intensity correlates with greater average Z in the sample, and dark areas have lower average Z (Reed, 2005). BSE images were very helpful at 2000x for quickly detecting composition differences; initial mineralogical composition could be inferred by increasing order of brightness: biogenic carbonaceous particles and sulphates, silicates, iron silicates and oxides (Noble, 2016). However, the SE detector was used at higher magnification for morphological analysis of fibres.

The splitting of sampled volume in many filters caused uneven portions, because combustion particles and mineral dusts were produced at variable intensity by different mining activities during the same sampling (sampling period between 6 to 8 hours, according to the flow rate). Thus, some filters were readable and others unreadable at the same sampling station.

The problem of readability is caused by underpowered ventilation system and, above all, by the lack of an appropriate standardized sampling method for these types of environment. The LD 81/2008, decree on workers protection, indicates to follow the analytical method described in MD 06/09/1994 and 14/05/1996. However these decrees are designed for sampling in closed clean environments, after remediation, and therefore require a sampling volume of 3000 l. When high dust conditions are present, lower sampled volume and flow rate would be recommended (Gualtieri, 2009), but these solutions affect negatively the fast restitution of data, because according to the formula, reported in section 2.2., it would be necessary increase the area examined to keep an acceptable DL.

In the present monitoring, a lot of elongated minerals particles (EMP) other than asbestos were found in airborne dust. For example calcium carbonate (Fig. S1b) and plagioclase (Fig. S1e) as well as gypsum (Fig. S1a) were found. They resemble amphibole asbestos morphologically, but were easily distinguished by their EDS spectra. Titanium dioxide (Fig. S1d) fractured to give needles, which met the regulatory fibre size criteria, sometimes with aspect ratios of 10:1. Chlorite (Fig. S1c) at 2000x magnification could resemble chrysotile fibres. Fragments of mica and sulphates often adhered to other minerals making difficult the interpretation of spectra.

Amphibole minerals not classified as asbestos were found and indicated in the report. The carcinogenicity of inhaled cleavage frament fibres of amphiboles, i.e. non-asbestiform amphiboles, is highly debated (Addison, 2008; Harper, 2008; Vignaroli, 2014; Whylie, 2015). Nevertheless, fibres that are not derived from specific asbestiform amphiboles or chrysotile are not currently included in the Italian occupational regulations.

## 3.2 Dataset

In about two years (September 2014-July 2016) 1571 samples were analysed: 668 samples during excavation in rocks not containing asbestos, 32 samples during other activities (installation of primary support elements, structural waterproofing and crown, bench and invert construction) and 871 over ten months of installation of dedusting system and excavation across a serpentinite lens intercalated within calcschists. The latter are specifically illustrated in the next section.

During this period, excavation activities were carried out in a total of 11 tunnels. Headings, and consequent number of measurements, increased with the development of the project; some tunnels as Campasso were finished.

In particular, during 2014 only four tunnels were excavated (Tab. S1), the overall sampling average was 16 samples/month. In 2015 the tunnels on activity were increased until eight with an overall sampling average of 21 samples/month (Tab. S2). At the end of 2015 and beginning of 2016, five artificial tunnels (GA) were driven with a sampling frequency of 9 samples/month. In the first half of 2016, ten tunnels were in excavation, achieving 51 samples/month (Tab. S3).

In Figure 4 are shown representative images of asbestos fibres detected. Chrysotile (Fig. 4c-h), the fibrous polymorph of serpentine; actinolite (Fig. 4a) and tremolite (Fig. 4b) belong to the amphibole group and show very similar structures, belonging to the same isomorph series (the tremolite–actinolite series). Actinolite differs from tremolite as part of Mg (located in the M sites) is replaced by Fe. Often the composition is intermediate between the two and the term tremolite-actinolite is used. In addition to the elemental composition, the morphology allows a good determination of the two asbestos groups.

Typically chrysotile occurs as fibrils (Fig. 4d), small bundles (Fig. 4c, g, h) or bundles with spraying ends (Fig. 4e-f). Amphibole asbestos can show cleavage directions and sharp ends (Fig. 4a-b), still in accordance to geometric requisites of LD 81/2008.

Results (Fig. 5 and Tab. 1) demonstrate that the fibres concentration was always under 1 ff/l in samples collected in interconnection~~s~~ tunnels, Polcevera, Campasso and Southern Valico. These tunnels cross the upper sedimentary members of the ophiolitic sequence: low metamorphic calcschists and blackish limestones. In particular, among the 209 samples analysed from these tunnels, fibres concentration (expressed as arithmetic mean of relative frequency) was under detection limit and between DL (0.3 ff/l) and 1 ff/l in 85.6% and 10.1% of total analysed samples, respectively. The other samples (3.6%) were unreadable due to dust particles overload. Therefore, in accordance with WHO limit for urban areas, these environments were considered as not contaminated by asbestos.

Analyses from metabasalts (Borzoli-Erzelli) showed that fibres concentration was under DL in 62%, between DL and 1 ff/ in 14.5%, between 1 ff/l and 2 ff/l in 14.5% of the 62 anlysed samples (Fig. 5). These data are in accordance with the mineralogy at the excavation front although the possibility of occurrence of asbestos (mostly tremolite-actinolite) had been initially envisaged.

Relative frequencies of values above 1 ff/l were 5.36% and 0.85% of the dataset collected in Val Lemme and Castagnola, respectively. Values between the DL and 1 ff/l were 10.7% in Val Lemme and 17% in Castagnola (Fig. 5). The low concentration of asbestos fibres (mostly actinolite-tremolite) could be related with NOA-bearing concrete aggregates used in the consolidation stage. M.D. 161/2012 allows extraction, treatment, further processing and re-use of natural mineral resources and preparations than contain asbestos with a mass content not exceeding 0.1%.

The 103 results of the Cravasco monitoring showed 77% of data below 1 ff/l; an occasional presence of chrysotile fibres occurred in June 2015 and increased in late July to > 2 ff/l. The concentration corresponded to a serpentinite lens intercalated within calcschists. Consequently to asbestos finding, frequency and points of monitoring were increased with 44 samples analyzed in July; therefore, 15.5% of total results were above 2 ff/l (Fig. 5), but these measures were related with this short period. Afterwards, the excavation work was stopped and preventive action were undertaken (section 3.4 – Cravasco data from August 2015 to May 2016).

Northern Valico was excavated in marls and monitoring demonstrated a very low but constant presence of fibres. In particular, among the 120 analyzed samples, 52.5% of results showed concentration between DL and 1 ff/l and 16.7% between 1 ff/l and 2 ff/l. Concentration exceeding 2 ff/l were determined in 5.7% of the monitoring dataset (Fig. 5).

## 3.3 Management policy

As a whole, the results showed that 86.7% of the total measurements were below 1 ff/l, of which 67.5% below the DL (no fibres found). Concentrations above 2 ff/l were found in 3.6% of analyzed samples during excavation at normal working conditions.

Air monitoring carried out at the rock front proved effective for the immediate detection of asbestos in the rocks. As a result of the data collected over two years, the contractor Cociv changed the monitoring frequencies into a Safety Operative Plan (SOP), in agreement with the regulatory bodies. Considering that the WHO recognizes 1 ff/l as the value of background in urban centres, the resampling was eliminated in cases of fibres found with concentration below 1 ff/l. Re-sampling and analysis were time and money consuming without important advantage on important information in relation with real exposure of workers. It was preferred to focus attention on values above 1 ff/l as early proxies of air pollution and NOA at the front.

## 3.4 Excavation across the serpentinite

At Cravasco, following the occurrence of asbestos fibres in driven crown sections a working group was assessed between the general contractor (COCIV), the Regional Agency for Environmental Protection (ARPAL) and Local Sanitary Authority (ASL) in order to implement and detail the asbestos management procedures.

Serpentinite rocks in contact with calcschists were crossed for the first time in the mid of July (2015), approximately starting at pk 0+700 and terminated at pk 0+800 (Fig. S2).

Air sampling confirmed the release of fibres into the ambient air at a concentration above 2 ff/l and monitoring was raised at H24 to analyze each working shift; 42 samples coming from different zones of the tunnel were analyzed in order to obtain information about the fibres dispersion from the rock front to the exit of the tunnel.

At the end of July the excavation activity was stopped due to the high concentration of asbestos fibres into the air, and engineering implementations were taken to i) minimize the generation of asbestos-bearing dust, ii) aspire the dust still released, iii) protect the workers from inhaling any remaining asbestos dust and iv) prevent the fibres dispersion outdoor. The engineering works were carried out until the end of the year together with many air monitoring stations in order to check different areas of the tunnel; a total of 199 samples were analysed in this period (Tab. S4).

The results of 111 measurements carried out during the safety implementation, in the zone closer to the front rock, demonstrated a residual concentration of fibres also at stopped excavation activity: 2.7% of data were above 2 ff/l. These values were definitely much lower ($P_{chi\ quadro} << 0.05$) than those of July (33.3% of data above 2 ff/l). In general, the fibres concentration was below 1 ff/l in 87% of samples, 67% of which below the DL (no fibres found).

At beginning of 2016, after 5 months of safety implementation and monitoring, the Cravasco adit was physically divided in three zones (A-B-C) by automatic sliding doors for entry and exit of large equipments, i.e. dumpers, wheeled loaders, drilling excavator, and workers. In this way, the dispersion of fibres from the excavation zone to other zones of the tunnel and the outside was significantly reduced.

In zone A (contaminated zone) the dust formation was decreased by using a fog cannon, spraying the rock and watering of the carriageway. The resulting waste-waters were collected and treated by ultrafiltration. Furthermore, a new system of exhaust ventilation and a dedusting equipment were installed to extract air as close as possible to the rock front and to purify it with an absolute filter system before its return into the outdoor environment. The excavated material, handled as hazardous waste, was loaded on dumpers under wet condition and covered during the transport. The driver's cabs of the large equipments were fitted with HEPA filtration system in order to keep the inside non-contaminated. This however required that the drivers got in and out the vehicles outside of zone A.

Beside the usual personal protective equipments normally used, fan-supported total masks were used in zone A (Class TMP3). In addition to this, hooded tyvek suits and rubber boots were worn.

Also the working shift was shorter with turnover between workers and activities in zone at different degree of asbestos exposure.

In zone B (decontamination zone) facilities for decontamination of vehicle equipments and workers were installed. One locker room (black unit) was used for vacuuming, taking off the first suit and other protective clothing and showering; the other one (white unit) was for putting on clean clothes. The supporting activities not related with excavation were carried out in zone C (decontaminated zone).

The area outside the tunnel was divided in three zone (D-E-F). The outside square (zone D) was dedicated to the loading of big bags on dumpers for final disposal in special landfill and management of raw materials. The excavated material was packed in big bags of 1 $m^3$ in a closed unit under vacuum and air filtration system (zone E). Inside this area one black and one white units were settled. The final treatment of wastewater was carried out in the filter press unit (zone F).

At the end of 2015 the modified SOP was approved by authorities and at the beginning of 2016 excavation activities restarted, following a detailed monitoring protocol identifying 13 air sampling stations. The high number of analyses (375 samples) carried out in January, February and March 2016 allowed detecting the 8 significant stations, frequencies and method of sampling. In particular:

- 3 sampling stations inside the tunnel (zone A, zone B, zone C);
- 3 sampling stations inside the driver' s cab of the large equipments (drilling excavator, wheel loader, dumper);
- 2 sampling stations inside the decontamination units (white and black) in zone B.

The samples were collected: in zone A (during both excavation and no excavation activities), in zone B and white unit every day; in black unit every 3 days; in zone C once a week; inside the driver' s cab of the large equipments once a week for each vehicle.

The asbestos exposure of workers was measured using static environmental sampler settled in the different zones, because this method was less invasive and more representative than personal sampler. A comparison between the two sampling methods was performed for 16 days. The results obtained by the personal sampler (mean= 15.57; SD=11.63) were significant lower ($P_{t\text{-test}}$ = 0.013) than that measured by static sampling in zone A during excavation (mean= 25.37; SD=13.69) (Tab. 1); these finding are in contrast with Dufresne et al. (2009) during two abatement projects. In the case of tunnelling, some critical situations remained totally undetected using personal sampler without knowing the residence time of workers in the different zones.

The DL used in the analyses of different zones (A, B, C, outdoor) was not the same (Tab. 1). The reason is the need to have a rapid result in zones which are the source of fibres or close to it (zone A and B), where fibres concentration is high; in these cases, a low DL was too costly in terms of time,

without significant addition in terms of reliability of the result. Conversely, it was necessary to keep a lower sensitivity when a low concentration of fibres is expected.

The data of the 301 samples collected in zone A, B, C and D from January to May 2016 during excavation are elaborated in Fig. 6 and Tab. 1. In particular, asbestos concentration was above 2 ff/l in 84% of samples analyzed from zone A, while the value was 24% and 4% in zone B and C, respectively. In zone B, the concentration was below 1 ff/l in 54% of the samples and this value increased in zone C (80%). These results demonstrated that the reduction of asbestos dust outside zone A was achieved due to abatement and mitigation measures. Analyses showed a significant decrease ($P_{chi\ quadro} << 0.05$) in the concentration of asbestos minerals and consequently in the level of risk, proceeding from the rock front (zone A) to the outside (zone C).

Even though most samples collected in zone A largely exceeded 2 ff/l, thanks to PPE and shorter work shift, the working daily exposure of 100 ff/l was never overtaken (Tab. 1). The workers were educated and informed about the risks relating to occupational exposure to asbestos fibres and the protocol to follow. Furthermore, monitoring of the outdoor square (zone D) indicated that no release of fibres occurred outside the tunnel (100% values under 1 ff/l). Therefore, the values did not exceed the limit of 1 ff/l.

The number of unreadable samples in zone A was very low, only 3 out of the 128 analyzed samples. All 152 samples collected in zone B and C were easily readable, similar to filters shown in Fig. 2a-b. These results were achieved due to the powerful extraction system and the decrease of sampled volume. The working group decided to change the sampling volume to 1500 l in zone A and B, 1800 l in zone C and large equipments, in order to get filters not excessively loaded and to avoid underestimate in fibres counting.

The 148 results of monitoring carried out in the 3 sampling stations inside the driver's cab of the large equipments (drilling excavator, wheel loader, dumper) and in 2 sampling stations inside the decontamination units (white and black) in zone B are gathered in Fig. 7 and Tab. 1. A dumper was used during waste rock removal and it was the only vehicle allowed out of the tunnel after decontamination. Two other equipments were used during excavation and always resided in zones A and B. Measurements of the concentration of asbestos fibres consequently recorded this different use. In particular, values below 1 ff/l were 83%, 24% and 5.8% in dumper, wheel loader and drilling excavator, respectively. The results from black and white decontamination units proved that the transport of fibres from zone A to B has been scarcely operator-dependent: values above 2 ff/l were 12% and 4.2%. These data demonstrated the effectiveness of abatement systems because workers were leaving zone A where 84.4% of monitoring of fibres concentration showed values above 2 ff/l. All ordered protective measures were maintained until the end of the excavation across

the serpentine vein at the end of May. The special protective measures were abandoned when two consecutive measures in the three zones (A-B-C) verified that the concentration of asbestos fibres in the air was less than 1 ff/l.

To sum up, the engineering and procedural management of Cravasco was difficult due to various reasons. Dust related issues are complex to approach, as influenced by many parameters (i.e., mechanical processes, rock properties, control techniques) and it is difficult to establish an efficient prevention and control protocol. In addition, a few previous experiences of excavation in NOA concerning both technical/engineering solutions and monitoring/analytical procedure were available as reference (Chromy, 2006).

As a general rule, I) the mineral dust concentration in tunnels is elevated and there is no specific regulation for air monitoring; the decree 06/09/1994 refers to closed environment after a remediation. This poses a problem for volume of sampled air.

II) The safety work limit of asbestos concentration is referred to handling of asbestos containing material (ACM) where the risk for workers may be previously determined with accuracy because the asbestos minerals contained in manufactures are generally homogeneous. However, naturally occurring asbestos (NOA) deposits contain intermixed phases of different mineral polymorphs, chemical compositions and fibre morphologies, which may lead to variable analytical results (Wagner, 2015). Tunnelling crosses natural rock bodies that often show, at least on a local scale, characteristics of dishomogeneity, therefore, in the case of underground infrastructures construction, the effect of random compositions can be much greater than in other industrial activities due to the nature of the input data (Labagnara, 2016).

III) EU directives and Italian legislation recommend the WHO method in Phase Contrast Microscopy (PCM) for measuring asbestos in workplaces (WHO, 1997). But this method is not able to detect extremely thin chrysotile, as found in our samples. Adopting PCM rather than SEM analysis would imply an underestimation of exposure (Cavallo, 2013).

IV) The task of identifying significant areas and monitoring frequency, during excavation across NOA, was quite long and heavy at management and analytical level; the results of this conspicuous number of measurements (630 samples) were daily made available for evaluation to all parties involved.

V) The delay between the occurrence of airborne asbestos fibres and its detection, is not overcome by any technology at the moment. A thorough investigation proved that no instruments suitable for such measurements are to date available on the market and those under development are incompatible with the temperature, humidity and pollution conditions typical of the tunnelling (Stopford, 2013; Labagnara, 2016).

However, in the Cravasco tunnel, the interdisciplinary approach among different disciplines (mining engineers, geologist, hygienist, etc.) allowed developing an efficient analytical protocol using the SEM-EDS method. The protocol developed at Cravasco under NAO tunneling will be replicated should similar situations occur in the Terzo Valico, providing a time and cost-effective management of the problem.

## 4. Conclusions

Dust containing asbestos minerals generated from tunnelling is a major issue with impacts upon the environment, human health, workers safety and productivity of underground construction. The excavation of rocks containing veins of asbestos induces the release of asbestos fibres in heterogeneous concentrations in space and time, thus it is difficult to predict the fibre-concentration in air. The issues associated with monitoring of asbestos dust from tunnelling operations proved therefore quite complex.

- The conspicuous numbers of data collected over two years of monitoring pointed out that the tunnelling environment is characterized by high dustiness and EMP occurence, therefore a compromise between sampling protocol, analytical method and improvement of measures on ventilation systems was necessary to obtain readable filters in order to assure time-effective monitoring and workers safety.
- Our analyses showed that SEM - EDS analysis can provide accurate results when high concentrations of small fibres are encountered and a significant amounts of non-asbestos fibre are suspected. Furthermore, BSE, or mixed BSE + SE signal demonstrated higher resolution than mere SE.
- During our monitoring activity, about 6200 m were excavated in eleven tunnels and only for 100 m in one tunnel NOA occured, causing the continuous exceeding of 2 ff /l in working environment. In this case, the physical division of the tunnel and a vacuum dedusting system were necessary to achieve an effective reduction of workers exposure.
- *In situ* static monitoring at the rock front proved to be an effective method to obtain undisturbed samples of air inside tunnels, which are fairly representative of the dust environment indoor and workers exposure consequently.

Finally, given the few documented experiences, this study offers an assessment on workers exposure to asbestos which could support the development and improvement of legislation referred to the tunnelling sector, lacking at present.

## *Acknowledgments*

The authors gratefully thank Laura Negretti for her valuable guidance on SEM imaging and EDS analysis interpretation.

The dataset was assembled in the monitoring activities of the Terzo Valico, funded by CIPE CUP F81H92000000008. The analyses were carried out on the Laboratorio di "Analisi delle proprietà microstrutturali, chimico-fisiche di materiali inorganici; determinazioni quantitative della composizione mineralogica di materiali naturali e delle proprietà tecniche dei materiali litici" appointed by the Italian Health Ministry to the analyses of asbestos with MOCF, XRPD and SEM-EDS.

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## *Figure Captions*

**Fig. 1.** Geological sketch map of the investigated area and railway line (modified from Terzo Valico Ferriovario dei Giovi, Protocollo Gestione Amianto, version 18. 03. 2014).

**Fig. 2.** SEM images (HV: 20 kV; MAG: 2000x; Det: BSE): ranking of readability. From a) to e) an increase of mineral dusts and combustion particles deposed on filter are associated with consequent decrease of filter readability.

**Fig. 3.** SE (a) and BSE (b) SEM images of an area of a field at working conditions (HV: 20 kV; MAG: 2000x).

**Fig. 4.** SEM images (HV: 20 kV; Det: BSE): examples of filters containing different types of asbestos fibres. a) actinolite; b) tremolite; c) to h) chrysotile.

**Fig. 5**. Asbestos sampling results of all the natural tunnels from September (2014) to July (2016) during excavation activity, represented as frequency distribution in five classes. < DL. (green square): concentration below the detection limit; DL - 1 (yellow square): concentration between the DL and 1 ff/l; 1-2 (orange square): concentration between 1 ff/l and 2 ff/l; >2 (red square): concentration of 2 ff/l or above; ND (gray square): unreadable samples.

**Fig. 6.** Asbestos sampling results of Cravasco adit from January 2016 to May 2016, during excavation in occurrence of asbestos and operating a three-zone isolation from the rock front (zone A) to portal (zone C). Data are represented as frequency distribution in five classes. < DL (green square): below the detection limit; DL - 1 (yellow square): between the DL. and 1 ff/l; 1-2 (orange square): between 1 ff/l and 2 ff/l; >2 (red square): 2 ff/l or more; ND (gray square): unreadable samples.

**Fig. 7.** Asbestos monitoring results of Cravasco adit from January 2016 to May 2016, during excavation in occurrence of asbestos. Data are represented as frequency distribution in five classes. < DL (green square): below the detection limit; DL –1 (yellow square): between the DL and 1 ff/l; 1-2 (orange square): between 1 ff/l and 2 ff/l; >2 (red square): 2 ff/l or more; ND (gray square): unreadable samples.

## *Table Captions*

**Tab. 1.** Asbestos fibres concentration (ff/l) detected in the different monitored tunnels during excavation activity (September 2014 - July 2016) and implemented monitoring during excavation across the serpentinite lens. Values represent sample size (N), mean, standard deviation (SD) and detection limit (DL).

## *Supplementary material*

**Tab. S1**. Number of monthly air samples of tunnels (Borzoli-Erzelli) and adits (Cravasco, Castagnola) analysed in 2014.

**Tab. S2**. Number of monthly air samples of tunnels (Borzoli-Erzelli, Campasso), adits (Castagnola, Cravasco, Polcevera, Val Lemme), Valico Tunnel (Southern and Northern) and artificial tunnels (CA14. 01, GA1L, GA1U) analysed in 2015.

**Tab. S3.** Number of monthly air samples of tunnels (Borzoli-Erzelli, Interconnections) adits (Castagnola, Cravasco, Polcevera, Val Lemme), Valico Tunnel (Southern and Northern) and artificial tunnels (CA14. 01, GA1U) analysed in 2016.

**Tab. S4.** Number of monthly Cravasco air samples analyzed while crossing the serpentine lens intercalated within calcschists.

**Fig. S1.** SEM images (HV: 20 kV; Det: BSE): examples of pseudo-fibres, i.e. other than asbestos phases. a) sulphate; b) calcite; c) chlorite; d) rutile; e) plagioclase.

**Fig. S2.** Rock front of Cravasco adit in Febbrary 2016, a serpentinite lens (green zone) with potentially – releasing asbestos shear zones (whitish zones) intercalated within calcschists (blackish zones).

**Fig. 1**

**Click here to download high resolution image**

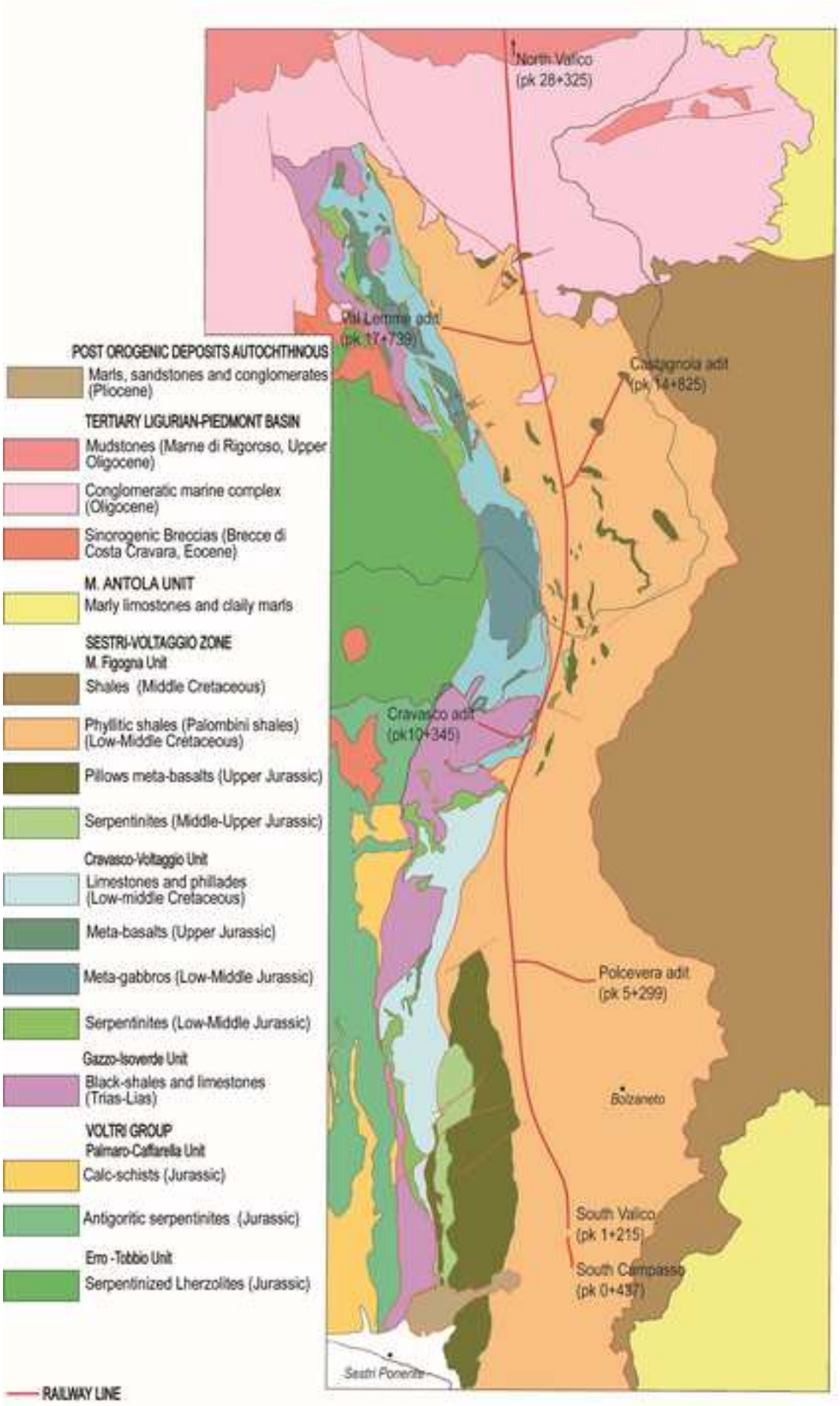

Fig. 2
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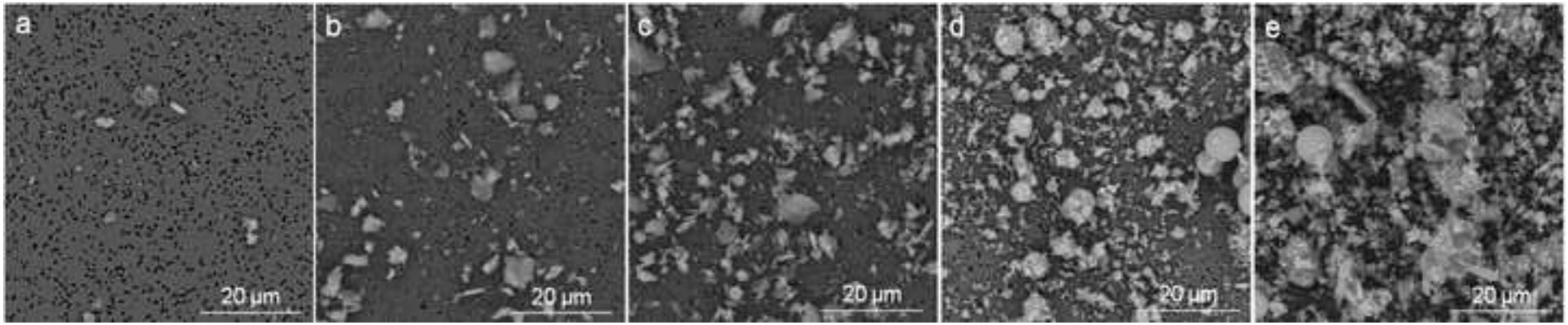

**Fig. 3**

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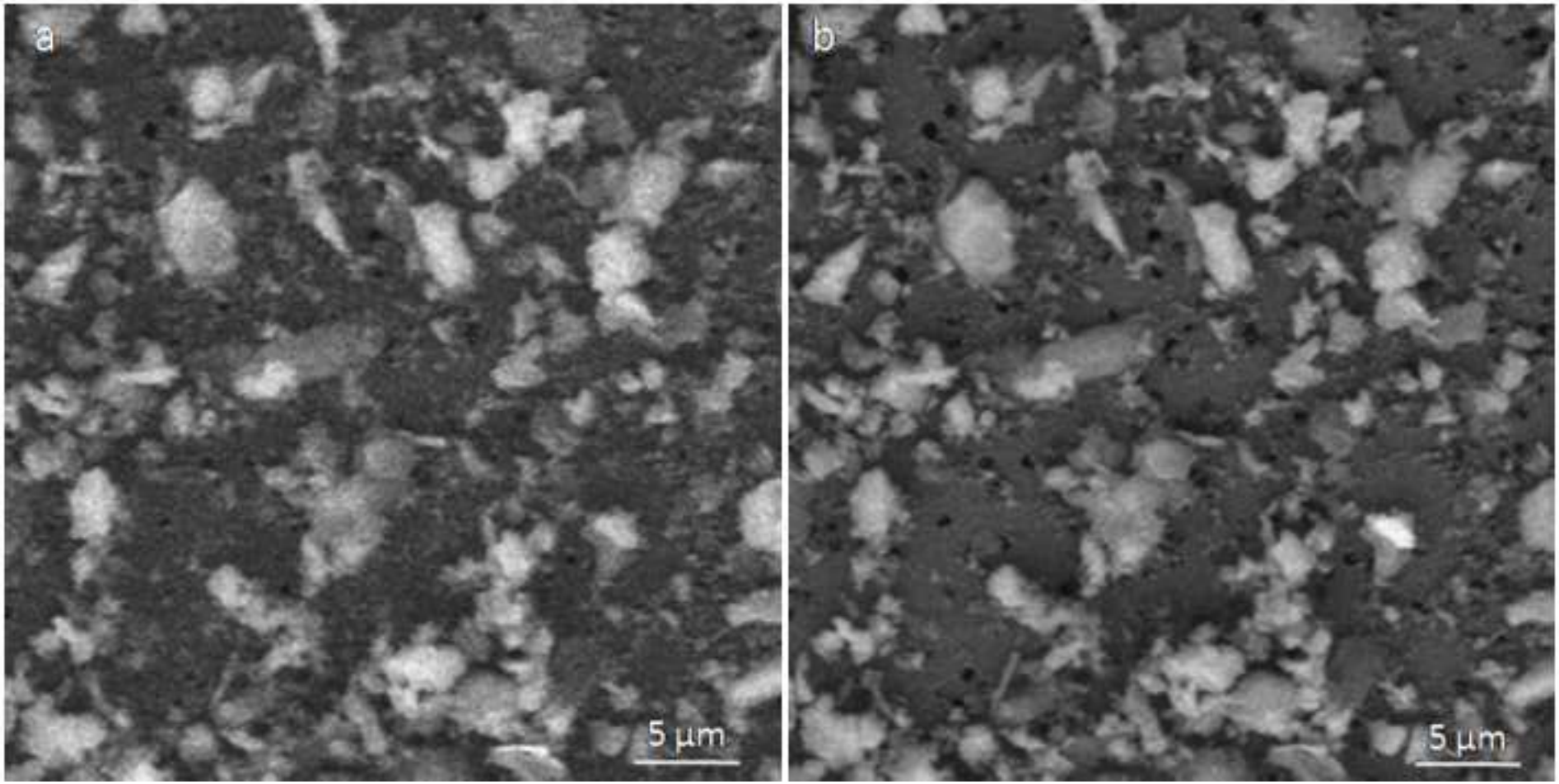

**Fig. 4**

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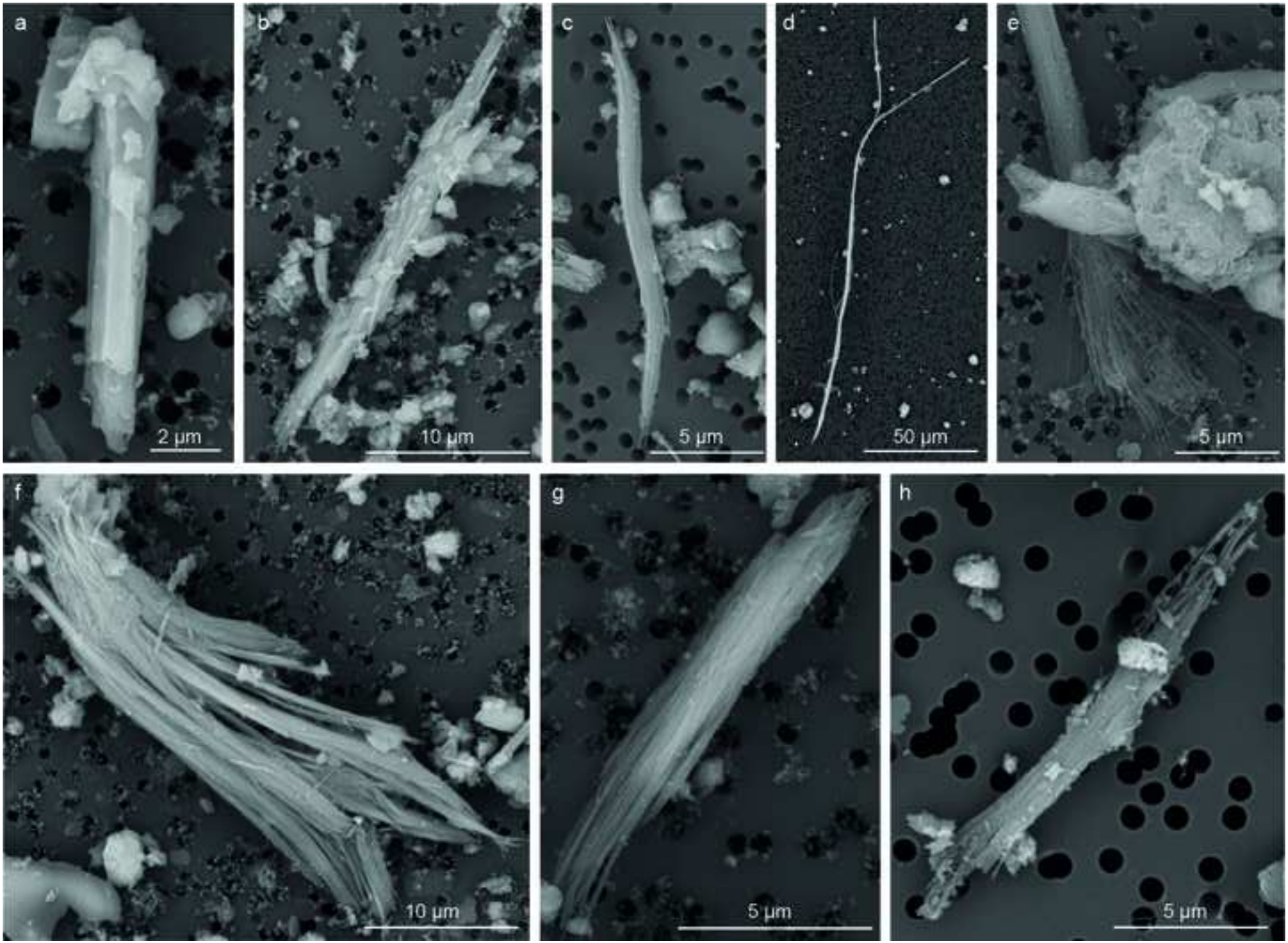

**Fig. 5**

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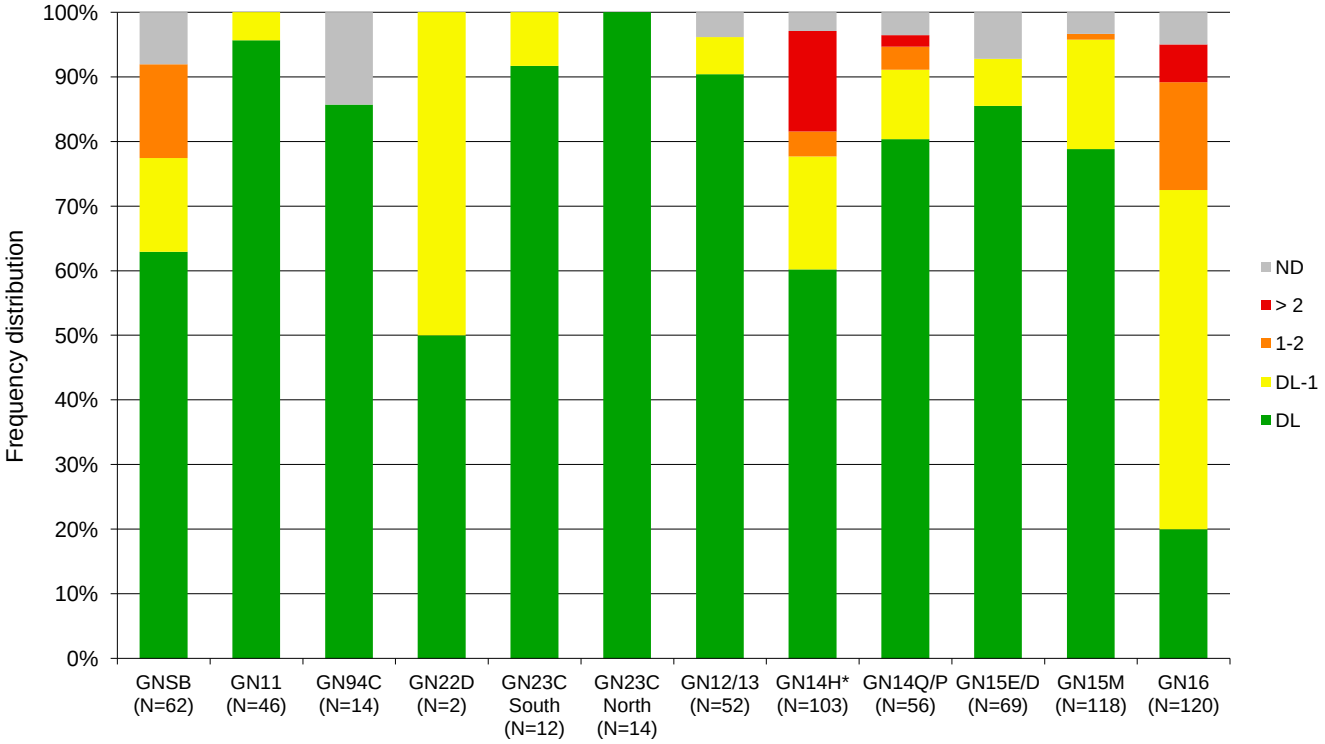


* Cravasco data from January 2016 to May 2016 are illustrated in Fig. 6-7

**Fig. 6**
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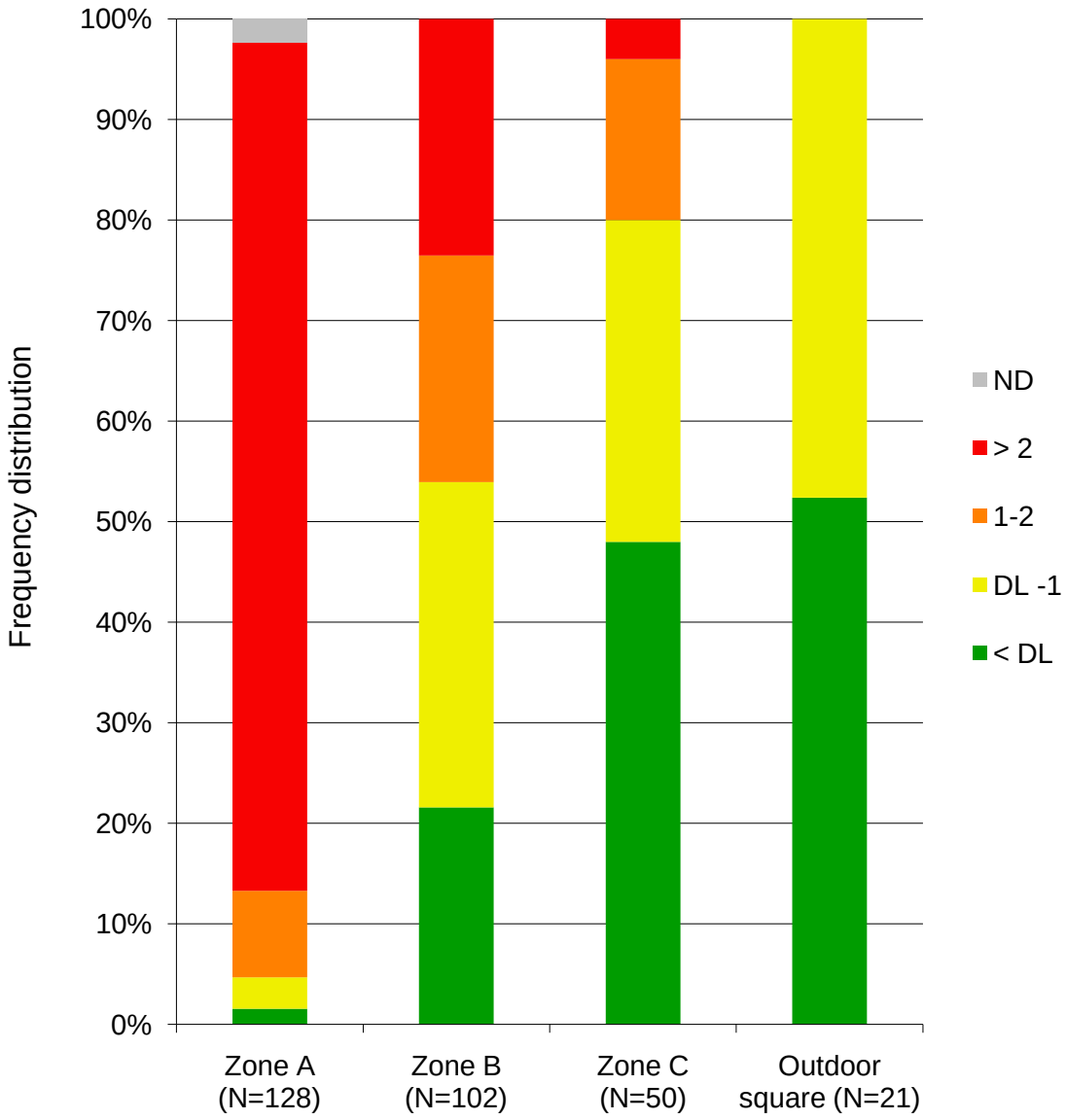

**Fig. 7**
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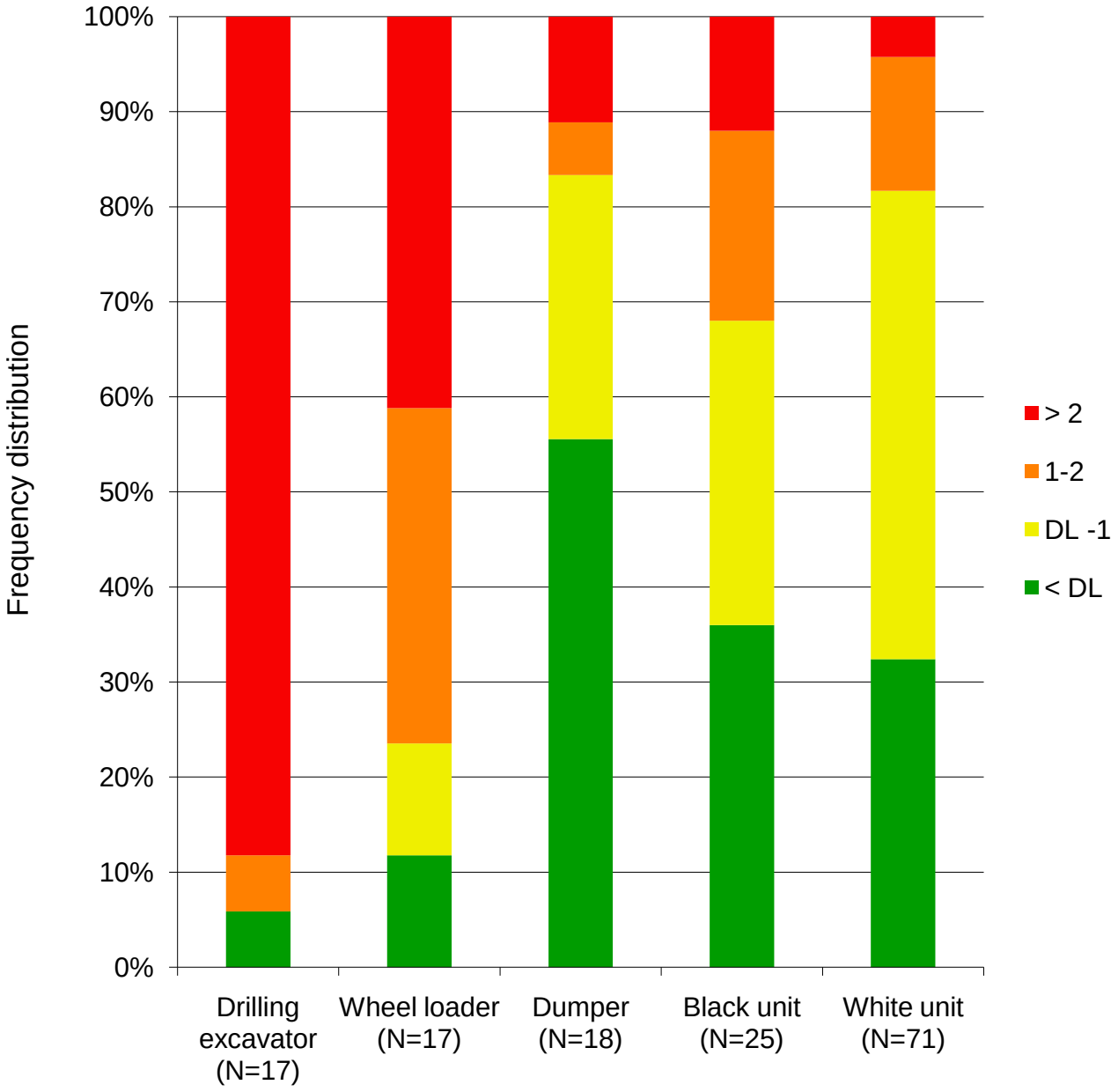

**Tab. 1**

Click here to download Table: Tab. 1.pdf

| Tunnel | N | Mean | SD | DL |
|---|---|---|---|---|
| GNSB | 62 | 0.34 | 0.40 | 0.3 |
| GN11 | 46 | 0.16 | 0.06 | 0.3 |
| GN94C[a] | 14 | 0.15 | 0.00 | 0.3 |
| GN22D[a] | 2 | 0.53 | 0.53 | 0.3 |
| GN23C Southern[a] | 12 | 0.16 | 0.05 | 0.3 |
| GN23C Northern[a] | 14 | 0.14 | 0.02 | 0.3 |
| GN12/13 Southern Valico | 52 | 0.16 | 0.04 | 0.3 |
| GN14H | 103 | 0.89 | 1.50 | 0.3 |
| GN14Q/P | 56 | 0.28 | 0.44 | 0.3 |
| GN15E/D | 69 | 0.16 | 0.09 | 0.3 |
| GN15M | 118 | 0.23 | 0.19 | 0.3 |
| GN16 Northern Valico | 120 | 0.76 | 0.69 | 0.3 |
| GN14H[b] | 111 | 0.54 | 0.86 | 0.3 |
| GN14H pers. sampler[c] | 16 | 15.57 | 11.63 | 0.85 |
| GN14H zona A[c] | 128 | 26.03 | 23.21 | 0.96 |
| GN14H zona B[c] | 102 | 1.94 | 2.17 | 0.96 |
| GN14H zona C[c] | 48 | 0.71 | 0.53 | 0.72 |
| GN14H outdoor square[c] | 21 | 0.09 | 0.07 | 0.1 |
| Drilling excavator[c] | 17 | 6.47 | 3.28 | 0.6 |
| Wheel loader[c] | 17 | 4.85 | 8.17 | 0.6 |
| Dumper[c] | 18 | 0.90 | 1.51 | 0.6 |
| Black unit[c] | 25 | 1.15 | 1.30 | 0.6 |
| White unit[c] | 71 | 0.62 | 0.68 | 0.42 |

[a] Interconnections tunnels

[b] Cravasco data from August to December 2015

[c] Cravasco data from January to May 2016

**Fig. S1**

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**Fig. S2**

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**Tab. S1**

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**Tab. S3**

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**Tab. S4**

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