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Established cases of the development of asbestos-related lung diseases in miners at the Salau tungsten mine in France due to exposure to asbestos actinolite and asbestos ferro-actinolite.

Maxime Misseri¹ and Marie Annick Billon-Galland²

ABSTRACT

Amphibole asbestos is present in the Salau massif. Its composition varies from ferro-actinolite to actinolite. Asbestos is found in post-Hercynian slip-dip faults and crack-seal veins, which are compatible in the Pyrenees with Mesozoic hydrothermal events. The amount of asbestos contained in the faults is sufficient to explain the levels of asbestos dust measured during the former mining activity.

According to different sources, the number of employees in the Salau mine varied from 150 to 600. Between 1982 and 1991, analyses were performed on sputum and/or bronchoalveolar washes on 28 patients. In 13 of these patients, the results showed significant retention of asbestos bodies, with concentrations equal to or higher than the values generally used as a reference in Europe. The occupational exposure limit of 8 hours (OEL_{8 hours}) could be estimated for each workstation. Estimates were based in part on PCM measurements. Simultaneous measurements by PCM and TEM allowed for a correction. The estimated OEL_{8 hours} have a unimodal distribution with an average of 0.05 actinolite fibers/cm³. The highest measurements (3.4%) were between 0.178 and 0.282 actinolite fibers/cm³. These occurred at the crusher and drilling

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sites of the work area. These results differ from those obtained in 2019 during the safety and sampling operations for asbestos detection prior to a drilling campaign, for which the company was supposed to take the asbestos hazard into account in its risk analysis. No asbestos fibers were observed, with TEM measurements, during the most emissive activities. Concentrations were less than 0.0048 f/cm³.

Keywords

Pneumoconioses, asbestos, actinolite, ferroactinolite, BAL, asbestos body, miners, slip fibers, cross fibers, TEM, PCM, PLM, IMA, OEL-8h

Introduction

The Salau mine is located in France, in the Pyrenees. The Salau tungsten mine was operated from 1971 to 1986 (mining company called C1). Given the significant need for tungsten in recent years, a mining exploration permit was obtained in March 2017 by a new mining company (called C2 in the article). This permit was cancelled for financial reasons in June 2019. The exploration permit was conditional, among other things, on controlling the asbestos risk in relation to the health of workers and local residents. Only the health of workers will be addressed in this article. Local authorities made use of external expertise to verify management of the asbestos risk during the new exploration phase. The fact that, before mining operations were closed, two cases of Asbestosis were recognized prompted the request for “external expertise”. They were two miners with no previous exposure to asbestos other than at the Salau mine, and who were suffering from occupational asbestos exposure with asbestosis characterized in 1983 for one worker and 1986 for the other.

During this study it was possible to:

- access the C1 company’s archives,
- obtain anonymized biometrology results for miners with pneumoconiosis,
- conduct interviews with former miners, doctors and a nurse who monitored the miners during the mining operation,
- conduct an interview with the head of asbestos metrology at the time of the mining operation.

The health history of employees exposed to dust at the time of the mining operation is based on documents from various sources. The information collected is fragmentary and not always fully correlated.

In a letter dated April 26, 2016, Dr Richard, who was-in charge of the healthcare of some of the mine workers on behalf of the SSM (Société de Secours Minier [Mine-workers' Welfare Society]) from 1980 onwards, wrote *“It was in this context that I was asked to diagnose cases of asbestosis, that is, lung diseases due to asbestos. It was very difficult to have the occupational disease recognized because exposure to asbestos in the mine had not been recognized. We were therefore dealing with patients with asbestos-related conditions but we did not know where they had come into contact with asbestos. It was in this context that miners brought me rocks and told me that they had come from the mine. These rocks, which I still possess, are at your disposal... “.*

The same doctor confirmed his testimony in an interview on June 13, 2018: *“I had detected on the chest X-ray of a miner an opacity similar to one which I had observed, in the pneumology department of the Timone Hospital in Marseilles, on X-rays of patients coming from Corsica said to be typical of asbestos exposure. So I sent the miners with such X-rays, first to the hospital in Ranguel and then to the pneumology department [...] in Toulouse, where screenings for*

asbestos bodies were carried out. When the diagnosis was made, the screening for asbestos exposure was initiated.”

Given the anonymization of certain documents, it was not possible to establish whether the first employee at the mine for whom the occupational disease was recognized by the SSM was a patient of Dr. Richard, but it was the case for the second.

For the first patient, the medical findings of pleuropulmonary pathology with characterized calcified pleural plaques and pneumoconiosis (asbestosis) are occupational diseases resulting from the inhalation of asbestos dust, which motivated the recognition of the occupational disease and Permanent Partial Disability by the SSM. The results of biometrological studies for asbestos bodies, markers of asbestos exposure, found in the sputum and bronchoalveolar lavage fluid of this patient show an abnormally high retention and also indicate a proven occupational exposure to asbestos. The personal and professional history of this patient shows that he could not have been exposed to asbestos outside of his professional activities as a laborer muleteer for the construction of the road leading to the mine from 1965 to 1970 and as an underground miner in various positions (maintenance, crushing supervision, ore washer supervision, discharge and filtration supervision) in the Salau mine from 1970 to 1984.

For the second patient, the medical conclusion of pulmonary asbestosis led to the recognition of occupational disease and Permanent Partial Disability. The quantity of asbestos bodies found in the sputum and alveolar lavage fluid during the biometrological examination is also characteristic of an occupational exposure to asbestos. This patient worked from 1952 to 1973 in an iron mine in Loraine and from 1973 to 1983 as a machine driver in the Salau mine. The

administrative investigation carried out at that time showed that asbestos exposure could only have occurred in the Salau mine.

A 1983 report from a state department reported 10 cases of asbestosis from employees of C1 company, including the two recognized cases and five cases under investigation by the Social Court. This data could not be correlated with the other information collected.

An August 1986 report on the follow-up of 106 employees at the Salau mine between December 1983 and June 1985 by the Toulouse hospital reported one case in addition to the two recognized cases of asbestosis. It is an asbestosis characterized by parenchymal fibrosis and thickening of the pleura.

After the closure of C1 company, only the surveys conducted by the associations make it possible to assess the health impact of the miners' exposures.

In a 1986 letter from Pezerat and Thebaud-Mony to the Institute of Occupational Medicine in Toulouse, 3 other cases of asbestosis, different from the two recognized cases, were reported without being able to establish whether one of the cases corresponds to that of the 1986 Toulouse hospital report. In this letter five cases of presumed asbestosis were also reported.

A survey carried out in 2016 by several associations including "Ban Asbestos France" and "the Henri Pézerat association" reported cancer of the pleura, 5 cases of asbestosis and 6 cases of suspected asbestosis. Twelve lung cancers, the cause of which was not mentioned, were also identified. This survey was conducted among 71 employees of the C1 company who had not left the region. Many miners with an immigrant background have since returned to their countries of origin and could not be contacted.

Due to the anonymization of the data in the documents available and the fact that the surveys were only carried out on part of the employees of the C1 company, it was not possible to conduct

all the necessary cross-checks to evaluate the pneumoconiosis that affected the employees. However, at a minimum, it has been established that two cases of asbestosis were recognized by the SSM, that three other cases of asbestosis, six cases of suspected asbestosis and cancer of the pleura were reported.

Some have questioned whether the asbestos-related pathologies, detected in Salau miners by physicians and pulmonologist, were due to occupational exposure. External expertise conducted an exhaustive inventory of biometrology tests to verify whether a significant number of miners had been exposed to asbestos dust in the Salau mine. Others argued that these pathologies were not due to "naturally occurring asbestos". The external expert checked the mineralogical characteristics of the fibrous rocks that outcrop in the mine from existing documents and additional analyses. One of the samples that had been preserved by Dr. Richard was analyzed as part of the study to make a comparison with the occurrences of fibrous asbestiform amphiboles from the mine. For yet others, the amount of fibrous rock is not sufficient to imprint the atmosphere based on the OEL-8h allowed at the time the mine was active. External expertise has reprocessed the dust measurements and calculations of the OEL-8h taking into account the current requirements in France to verify if this claim was still valid at our time. Others asked to ensure that the exploration work did not endanger the workers of the C2 company. The external expertise assessed the relevance of the geological model to understand how asbestos fibers were formed and thus be able to predict when asbestos-containing rocks are likely to be crossed during exploration work. The external expertise also verified the effectiveness of asbestos dust mitigation measures with TEM Airborne asbestos measurements.

All these checks and the methods used are described in this article.

Historical data collected from the C1 company's archives made it possible to evaluate

asbestos fiber dust levels at the time of the mining operation based on PCM (Phase Contrast Microscopy) measurements and TEM (Transmission Electron Microscopy) measurements. During the operation, this company had PCM analyses ((french regulatory method at the time of these monitoring) and some TEM analyses performed by the BRGM (*Bureau de Recherches Géologiques et Minières* [Geological and Mining Research Bureau]). 140 airborne dust measurements carried out with the PCM were found in the archives and used in this article. They cannot be directly compared to the measurements currently performed in France. PCM does not identify the nature of the fibers or observe thin fibers less than 0.2 μm wide. However, the BRGM at the time also carried out more extensive analyses using the TEM method making it possible to identify fibers according to their morphological, crystallographic and chemical aspects and to observe thin asbestos fibers. Actinolite amphibole fibers were identified in these studies and the BRGM estimated that half of the fibers counted by PCM were not asbestos.

Historical data have also enabled the reconstruction of an OEL, per workstation, which can be compared to the OEL currently in force in France: 0.01 fibers/cm³ (10 fibers/liter) over 8 hours measured by TEM following the recommendations of AFSSET (*Agence Française de Sécurité Sanitaire de l'Environnement et du Travail* [French Agency for Environmental and Occupational Health & Safety]) (now ANSES (*Agence Nationale de Sécurité Sanitaire de l'Alimentation, de l'Environnement et du Travail* [French Agency for Food, Environmental and Occupational Health & Safety]))¹.

The field data (rock analysis and atmospheric analysis) collected by the “external expertise” used to assess the suitability of the asbestos survey conducted by the C2 company, verify the presence of asbestos and verify the robustness of the risk analysis of the C2 mining exploration company, is the data reported in this article. C2’s data is not yet available. In order to verify the presence of

asbestos, C2, as part of its risk analysis, collected samples and atmospheric measurements according to its strategy within the perimeter of the exploration area it had defined. The “external expertise” collected samples in smaller numbers “to assay the specimen in duplicate” in the exploration area and collected samples according to its own strategy in and outside the exploration area.

The geology of the site was recently updated by Poitrenaud² who incorporated, among others, the work of Colchen et al.³, Ternet et al.⁴, Derré et al.⁵. The Salau mine deposit originates from a complex relationship between a pluton of intrusive igneous rocks and surrounding carbonate rocks. Physical and chemical transformations associated with this intrusion have transformed these rocks to form the Scheelite deposit, Passaqui⁶, Guiraudie⁷. The intrusion of igneous rocks (mainly Granodiorite and Diorite on the periphery of the intrusion) dates back to the Carboniferous Period during the Hercynian episode (312 Ma). The earlier carbonate rocks date back to the Upper Silurian Period for the Barregiennes, Caralp⁸ (Alternating limestones/pelites) and the Lower Devonian Period for the upper limestone formations, Moret⁹.

This high-temperature intrusion, due to reactions from contact metamorphism and metasomatism, transformed part of the Barregiennes into rocks called Corneans (Hornfels)

Derré (1980) and the upper limestones into marbles, which themselves were transformed, respectively, by contact with the surrounding rocks and the flow of fluids containing different elements, into Skarns.

In the first place, it was necessary to verify that the asbestos hazard (in accordance with standard *CSA Z1002*) at the mine site was established. In other words, that asbestos was indeed present in the geological formations. Except Soler¹⁰, who in his thesis of 1977 dealt in part with

the hydrothermal activity, the authors of scientific articles describing the geology of the site do not mention the presence of asbestos, certainly because it was not the subject of their study. Several documents concerning asbestos have been written with conflicting conclusions. Soler, was the first to describe asbestos in the Salau mine. Boulmier¹¹, in 1984, collected two samples from the mine in which he detected actinolite asbestos after analyzing them by TEM. Pezerat in two reports 1984¹² and 1986¹³ also concluded that asbestos was present based on mine samples and “Tailings” using XRD (X-Ray Diffraction) and TEM analysis. Marcoux¹⁴ analyzed the same type of rock by PLM (Polarized Light Microscopy) and SEM (Scanning Electron Microscope) in 2015. He also analyzed production residues (Tailings) from the former mine using XRD He concluded that there was no asbestos present in either type of sample. D’Arco¹⁵ using XRD analyses also did not detect asbestos in production residues (Tailings). Cesbron’s report¹⁶ in November 1983 described the presence of actinolite with prismatic and fibrous facies without having observed asbestiform facies in the cornean rocks (hornfels), skarns and limestones of the Salau mine. Poitrenaud described late N30°E and N160°E, multi-centimeter fibrous amphibole subvertical faults; the facies of these actinotes were not precisely described; these faults offset the mineralized body. In the C2 company’s model, asbestos is located in these late events. The results of the analyses carried out by the “external expertise” using PLM and TEM will help to specify the habit of the amphiboles concerned and confirm whether the fibrous amphiboles described in the late faults are asbestos.

Company C2's asbestos risk analysis during site securing and during sampling was verified. The C2 company initially defined an exploration area that was smaller than that of the original mine. It then conducted a detailed visual geological survey of the exploration area to verify that safety operations would not involve rocks that could potentially contain asbestos. It

secured the exploration area by sealing off, with structures, the galleries containing rocks or equipment, likely to contain asbestos, dating back to the time of the mining operation. The structures have been anchored on rocks known not to contain asbestos. The first geological survey also allowed the C2 company to classify the mapped rocks into three categories, according to the flowchart, outlining asbestos monitoring and metrology procedures during underground work proposed by ANSES 2015¹⁷:

- 1) rock known not to contain asbestos,
- 2) rock potentially containing serpentines or amphiboles,
- 3) rock containing asbestos.

The C2 company supplemented the visual asbestos inspection with a sampling campaign in order to remove any doubt about rocks likely to contain asbestos and to establish a predictive model of the presence of asbestos in the parts of the massif that were to be involved in prospecting and drilling operations. This step has not been completed.

The collection of samples is [directed](#) by asbestos regulations in France. The airborne asbestos during each work process must be evaluated and measured so that the respiratory protective equipment used can be adapted. A process is defined in current French regulations as follows: “techniques and operating methods used, taking into account the characteristics of the materials concerned and the means of collective protection implemented”. The C2 company had six processes planned in its sampling campaign. The C2 company performed airborne asbestos measurements for each of the processes. The “external expertise” verified the adequacy of the asbestos surveys and the efficiency of the company C2’s risk analysis during the sampling of its asbestos survey also by performing in smaller quantities, airborne asbestos measurements. Only measurements recorded by the external expertise during sampling of the most emissive material

are reported in this article.

Materials and Methods

SEARCH FOR ASBESTOS IN THE ROCKS

Sampling of fibrous amphibolite

The C2 company had located fibrous asbestiform amphiboles in cross-section 1 of Gallery 1230 of the exploration area. In this study, 8 samples were collected from this cross-section and analyzed. Fibrous amphiboles are carried by slip-dip faults combined with crack-seal veins. Geological model of the C2 company for the mineralization of asbestos fibers is that they grew mainly in these faults and veins at the end or after the intrusion of the granodiorite body. "External expertise" conducted its investigation outside the mining operation area in order to verify this geological model. Following the recognition of the first case of asbestos in 1983, geologists from the C1 company had conducted a survey of the fibrous rocks present in the mine. A location map and field reports were found in the C1 company's archives. Twenty-two indicators are described or located, only six have been found, most of the galleries having been filled by waste-rock. 5 samples were collected outside the exploration area as a result of these investigations. Ten samples of fibrous amphiboles were also collected by the C2 company as part of its asbestos survey prior to exploration drilling. Four of these samples were duplicated by the "external expertise" [Table 1].

Characterization of fibers in fibrous amphibolite

Since this is a rock that disintegrates easily and where the individual fibers detach under low mechanical stress, only crushed material were viewed by PLM prior to an analysis using TEM. The methodology and equipment were described in an earlier article¹⁸. Below is a description in some line of the method. The analyses were carried out by a mineralogist in a laboratory

specifically accredited to search for asbestos in the rocks. About 90% of the particles, after manual grinding, have a diameter of less than 50 μm . When a fiber was observed in the ground material of the rock under the stereomicroscope, it was mounted between a slide and a coverslip [in liquids with known refractive indices](#). Identification was based on the properties of the fiber in polarized light and dispersion staining. The subsample prepared for TEM analysis was suspended in 50 mL of deionized water. Dilution was adjusted according to the transparency in order to obtain less than 20% electron-dense material on the grids. The vial was submitted to ultrasound for 1 minute. The preparation of the TEM grid used the drop mount technique¹⁹. The TEM-EDS analyses were performed using a FEI CM200 equipped with a calibrated SAMx NumeriX EDS. Andrew Locock's software which followed the recommendations of IMA 12 (International Mineralogical Association), made it possible from the elemental analyses obtained with the Energy Dispersive Spectroscopy EDS, to calculate the structural formula, calculate the Fe^{3+} content and determine the mineral species. The structural formula was recalibrated by eliminating the "warnings" taking into account the measurement uncertainty for each element which was around 10%.

The asbestiform habit was determined with the following reference texts: ISO 22262-1²⁰EPA 1993²¹HSG 248²²MP 2015²³. In ISO 22262-1 it is the practical part of paragraph 7.2.3.7.1 which is used. The MP 2015 flowchart [Figure 1] used the criteria described in the literature. [It made it possible to determine particles coming from crystals which grew in the asbestiform habit](#) when few fibers were observed, which was necessary when the regulations did not set a threshold. The flowchart was tested with NIST standards and a sample of actinolite asbestos [Table 2]. It provided comparable results by TEM and PLM.

History of airborne asbestos measurements

The airborne fibers measurements performed during the C1 company's mining operations were retrieved from the C1 company's archives. It turns out that all the measurements performed by PCM were recorded in a register by this C1 company. This register was able to be found in the archives. The samples were collected by the BRGM from December 1983 to October 1984; then the samples were collected by the C1 company (same equipment, same procedure as the BRGM) until May 1986. 140 PCM dust level measurements were usable. There is generally no direct correlation between PCM measurements and actual asbestos content (AFSSET, Short Asbestos Fibers, 2009²⁴). However, the BRGM had carried out several TEM and PCM measurements in similar work situations, which may make it possible to estimate a conversion coefficient specific to the operation at the Salau mine. The fibers counted by TEM, in the BRGM report 9830, were in fact Elongated Mineral Particles of actinolite (EMPa) that had a length > 5 µm, a width < 3µm and a length to width ratio equal to 3, dimensions recommended by the WHO (World Health Organization). Jean Luc Boulmier made several observations. Under an electron microscope, he observed twice as many Elongated Mineral Particles (EMPs see ANSES 2015¹⁷ and Léocat²⁵) as in optical microscopy. On the other hand, he noted that about half of the EMPs were EMPa. He also found that non-asbestiform EPMa were much more abundant than asbestiform EPMa. In the end, the application of a correction coefficient of 0.5 on EMP concentration measurements performed by PCM to estimate the concentrations of asbestiform EMPa by TEM, was an acceptable approximation in the context of the Salau mine. It is a high estimate. In the rest of the text, we will name the PCM data reprocessed from the information contained in the BRGM report and in the C1 company's register "Asbestos, exposure to fibers, time and content" "Concentration Estimation of Airborne Actinolite Asbestos (CE3A_{0.5})".

Estimated Historical Occupational Exposure Limit Value

The Occupational Exposure Limit Value over eight hours in France (F.OEL_{8-hour}) is the calculation of exposure that takes into account the concentration (C) of the dust level in the process, the values of the Assigned Protection Factor (APF) and the duration (T) of the operational phases with direct or indirect exposure²⁶. It must currently be less than 10 asbestos fibers per liter of air (0.010f/cm³) according to French regulations.

The F.OEL_{8-hour} of SALAU mine employees cannot be directly calculated because the concentration measures were made by PCM and the processes were not defined exactly as they are now. However, they can be reconstructed with the available information.

$$\text{F.OEL}_{8\text{-hour}} \text{ calculation} = [((C)_1 \times T_1)/\text{APF}) + \dots + ((M_n \times T_n)/\text{APF})]/8$$

This type of calculation can only give an order of magnitude because several calculation methods may be chosen and certain parameters are estimated. One hundred thirteen F.OEL_{8-hour} were reconstructed from the data contained in the C1 company's register "Asbestos fibers exposure, splitting of the work, and concentrations", four reconstructed from the dust measurements of the C1 company's register "Asbestos, exposure to fibers, duration and concentration". The protective factor of the masks used at the time, estimated at 2, was applied based on the information gathered during the investigation [Table 3].

In 1980, it was not possible, during the sampling, to continuously monitor the nature of the rock impacted by the mining works. The results of the PCM measurements do not completely exclude that there were acute peaks of point exposure on some emissive processes such as digging (underground miner).

"WORKPLACE EXPOSURE MEASUREMENTS

Airborne asbestos measurements during sampling by "external expertise"

The following measurements meet a current regulatory obligation. The processes of the sampling

work, and those of mining in the 1980s are different. Also, the comparison of the results of the measurements carried out during these processes cannot be directly compared.

At the time of verification by the external expertise, of the asbestos occurrence model in the mine, proposed by the C2 company, two airborne asbestos measurements were performed by TEM on operators who sampled highly emissive fibrous amphibolite. This was an analysis carried out using TEM according to the indirect method (NF X43-050 standard) with sampling performed on operators at 3 liters per minute according to the NF X 43-269 standard. The work process was “sampling of a rock with visible amphibole fibers, using tweezers, and with continuous water misting”. Because the sampling times were short, the operators were equipped with two samplers (37 mm conductive Sampling Filter Cassette) to achieve an analytical sensitivity between 1 and 3 fibers per liter. Two measurements of the same type were made during circulation in the mine galleries. Two static measurements were carried out, with a flow of 7 liters/min, downstream of the work area in relation to the direction of the airflow in the galleries during sampling operations. The analyses were performed using the indirect method by TEM according to the NF X 43-050 standard. Airborne asbestos measurements were performed by an ISO 17025 accredited laboratory.

Airborne asbestos measurements during sampling operations by the C2 company

The C2 company has identified rocks that may contain asbestos and rocks that may not contain asbestos [Table 4]. The C2 company did its risk analysis for each sampling process of these rocks during the asbestos survey. The C2 company checked with operator measurements and static measurements the dust levels during each process. Most of the measurements were duplicated by the external expertise [Table 5]. [Only measurements recorded during the fibrous amphibole sampling process, with tweezers and continuous misting, to verify the effectiveness of](#)

the mitigation measures, are reported in this article. A measurement on an operator close to the source, a measurement in the work area and a measurement near the “Mobile Decontamination Unit” were performed. Airborne asbestos measurements were carried out using the same methods and equipment as the previous paragraph.

ASBESTOS BODIES COUNTING

With regard to studies on counting for asbestos bodies, respiratory physicians, pathologists and epidemiologists frequently make use of the possibilities offered by “biometrology” to characterize individual exposures to asbestos fibers. In general, this term refers to all methods used to study human exposures to pollutants by measuring the pollutants (or their metabolites) in human biological samples called “indicator samples”.

As part of the screening of a subject who has had asbestos exposure or a patient with suspected asbestos pathology, biometrology aims to determine the concentration of fibers retained in the lungs at the time the sample is collected. The measured level of retention incorporates both the phenomena of deposition and clearance of fibers in the respiratory tract. These analyses, which make use of mineralogy, have provided important information for understanding pathologies related to inhaled fibers. They have the advantage of providing an individual estimate of cumulative exposure and are particularly useful when data on occupational history is absent, unreliable or vague.

Mineralogical analyses carried out in the context of asbestos concerns mainly use samples of lung tissue and bronchoalveolar lavage fluid (BAL), and possibly less invasive sputum samples. Biometrological studies concerning asbestos refer to both individual cases and to groups of subjects of particular interest in terms of their pathological manifestations or their circumstances of exposure. They can be classified on the basis of the pathology explored, the occupation, the

type of exposure, the geographical origin of the subjects, the type of sample, the analytical technique (optical microscopy, electron microscopy), the type of marker sought (asbestos body (AB) or fibers and the type of fiber concerned. (See AFSSET report²⁴). Asbestos bodies (AB) form on inhaled asbestos fibers, deposited for at least four to six months in the lower airways. Only a minority of inhaled fibers will become coated and give rise to AB. This coating allows for optical microscopy (OM) detection. The appearance of AB in the lungs is closely associated with the concentration of long amphibole fibers; it is rare for fibers less than 10 microns to be coated. However, high concentrations of AB formed on chrysotile fibers can be observed in the lungs of workers with high exposure to chrysotile.

Thus, the data in the literature shows the particular propensity of amphibole asbestos to form asbestos bodies and in the case of exposure to chrysotile, the fibers disappear^{27,28} from biological environments, meaning that the absence of asbestos bodies cannot be considered as evidence of non-exposure.

The practical aspects of quantifying asbestos fibers and asbestos bodies in biological samples and interpretation of the results obtained were reviewed by several teams and found consensus among the European laboratories specialized in such analyses. In terms of interpreting the results of AB counts, several laboratories in Europe and North America consider that there is significant exposure to asbestos when the measured concentrations are higher than the following values: 1 AB in sputum, 1 AB/mL in BAL, 1000 AB/g of dry lung tissue. Exceeding these threshold values indicate a level of retention corresponding to an exposure considered unusual for the general population^{29,30,31,32,33}.

Results and Discussion

Presence of asbestos in fibrous amphibolite

Analyses performed by TEM and PLM on crushed material show that all sampled fibrous amphibolite contains fibers from asbestiform minerals. In the vast majority of samples, the asbestiform habit is recognized regardless of the reference used: ISO 22262-1, EPA 1993, HSG 248, MP 2015 [Tables 6 and 1].

It was possible to verify that geological objects containing asbestos are slip-dip faults and crack-seal veins with late or post-Hercynian activity. That is, after the intrusion of granodiorite, after the formation of skarns and after the formation of massive sulfides. The dominant faults are NW-SE-oriented slip-dip faults combined with NS-oriented crack-seal veins [Figure 2].

Asbestos is either under the form of “slip fiber” or “cross fiber” [Figure 3]. Cross fibers are fibers that usually develop perpendicular to the walls during the opening of crack-seal veins. The length of cross fibers is limited to the size of the fault opening. In the massif, these cracks have a width of no more than a few centimeters. Slip fibers are formed during intense deformations. They line the slip-dip faults. “Slip fibers” develop during movement. The fibers can reach 20 cm long. They are sub-parallel to the fault plan and the direction of movement. The fibers in the massif are generally oriented in the largest slope of the fault plane. The shear direction could not be determined with certainty.

Two types of fibrous amphibolite [Figure 4], are present in the mine’s slip-dip faults and crack-seal veins.

A facies with dark green, acicular amphiboles multi-centimeter, with a composition ranging from ferro-actinolite to iron-rich actinolite. By scraping with a scalpel on the sides of these minerals, asbestiform fibers can come off. The ferro-actinolite in this facies can be associated with up to 50% calcite. With TEM observation, the detached fibers have morphological criteria that allow them to be classified as originating from asbestiform minerals according to ISO 22262-1 and

MB2015.

The second most common facies is composed almost exclusively of acicular to asbestiform amphibole whose mineral composition varies from a very iron-rich ferro-actinolite to magnesium-actinolite. It is a greenish-grey rock that disintegrates easily under low mechanical stress. These amphibolites can contain up to 99% asbestiform fibers.

Asbestiform ferro-actinolite is present in the Salau mine to a lesser extent than asbestiform actinolite. Some samples contain equivalent proportions of actinolite and ferro-actinolite [Table 1] without being able to differentiate them morphologically, only the optical properties and chemical data change.

In [Figure 5], points representative of asbestiform amphibole fibers, coming from all the fibrous rocks collected in Slip-dip faults and crack-seal veins outside the exploration area and within the exploration area, are distributed over a large area of the diagram “Si apfu versus Mg/Mg+Fe²⁺”, ranging from ferro-actinolite compositions to magnesium-actinolite compositions.

Doctor Richard’s fibrous amphibolite samples have all the characteristics of fibers derived from asbestiform minerals [Figure 6]. On the diagram “Si apfu versus Mg/Mg+Fe²⁺” [Figure 7], they have the same compositional signature as the fibers from two samples collected from the fibrous amphiboles at the C1-1 and C1-6.2 mine.

Discussion regarding the presence of asbestos in fibrous amphibolite

The field observations made on fibrous amphiboles and the analytical results are consistent with the conclusions of Boulmier, Pezerat and consistent with the descriptions of Soler. In 1977, in his doctoral thesis, he wrote “*in calcium rocks there is the presence of fibrous amphiboles with an asbestos structure in veins measuring centimeters to decimeters in length. It is often associated with calcite.*” Marcoux¹⁴ in his 2015 report, based solely on the dimensions of the thickest fibers,

came to a different conclusion. However, in the two SEM images of his report, when the thinnest fibers are taken into account, we can observe:

1. Parallel fibers with a length-to-width ratio greater than 20 and a width of about 0.2 μm ;
2. Bundles of fibers with splayed ends;
3. Fibers that divide;
4. Masses of fibers tangled with individual fibers
5. That more than fifty percent of fibers greater than five microns have a length-to-width ratio greater than five.

According to EPA1993, HSG248, NF ISO 22262-1 standard, fibers with these characteristics are considered to be derived from asbestiform minerals.

Ferro-actinolite is a mineral that can be asbestiform³⁴. This is the case in the Salau mine. These minerals, except for one point, [Figure 5] remain restricted to the field of “undifferentiated-actinolite-amphibole” see previous work¹⁸. Actinolite asbestos is regulated. Regarding ferro-actinolite it is not so clear. French regulations are currently based on standard NF X 43 050. The theoretical structural formula given for actinolite in the standard is $\text{Ca}_2 (\text{Mg}, \text{Fe}^{2+})_5 (\text{Si}_8\text{O}_{22}) (\text{OH}, \text{F})_2$. The strict application of this structural formula allows to integrate only, a tiny part of ferro-actinolites (the most siliceous) in the field of actinolite. The wide application of the structural formula with the possible substitution of Ca by K, Na and Si by Al, Cr, Fe^{3+} , Ti makes it possible to integrate all the ferro-actinolites but also all the other calcic amphiboles. Mineralogically (IMA 12), the distinction between actinolite and ferro-actinolite was not determined by the effect of these minerals on health, but on the variation in their iron content. It is appropriate to question their toxicity. Rats were exposed to ferro-actinolite fibers by intratracheal instillation or intrapleural injection in two studies^{35,36} which show the strong

carcinogenic potential of these fibers. Therefore, it is possible that exposure to asbestiform ferro-actinolite contributed in part to the development of pneumoconioses in the C1 company employees without being able to quantify it.

Slip-dip faults and crack-seal veins were post or late Hercynian. Verifying the shear directions of Slip-dip faults would have required getting very close to the outcrop or sampling larger boulders. In both cases the risk of increasing the exposure of geologists of the “external expertise” was greater. This risk was not taken. It was therefore not possible to determine whether these were normal or reverse faults. However, the gap in these slip-dip faults and crack-seal veins was accompanied by hydrothermal circulation, which is expressed by the presence of actinolite and ferro-actinolite fibers. This is compatible in the Pyrenees chain with Mesozoic or Cenozoic hydrothermal events (rifting associated with the opening of the Thetis and the Atlantic accompanied by a warming of the Hercynian intrusive massifs³⁷).

The actinolite fibers in the fibrous amphibolite of the Salau mine are generally unrelated. The faults containing amphibole asbestos were identified by the C1 company’s geologists in 1983 allowed the C1 company to estimate the amount of asbestos relative to the rock mass mined. The estimate was about 100m² of panel containing asbestos over several thousand square meters. A 100 m² fracture area containing asbestos can release about 200 billion asbestos fibers. After reading the documents consulted in the C1 company’s archives, it appears that no measure was taken to neutralize the asbestos-containing fractures. The fibrous contents of the fractures were crushed and finely ground like ore and in part, captured in the mine air vent. The power to release and disseminate fibers was underestimated, especially since the regulatory limit at the time of 2 fibers/cm³ was never exceeded in PCM dust measurements at workstations.

The C2 company’s proposal to consider the slip-dip faults and crack-seal veins that contain

actinolite and ferro-actinolite asbestos fibers as the main sources of dust in asbestos fibers and in elongated mineral particles originating from cleavage fragments of these same minerals is a model that makes sense.

In the Cesbron Report¹⁶, rocks containing in varying proportion prismatic to fibrous actinote amphiboles that, without being asbestiform, could, after significant mechanical stress, produce mineral particles or fibers having the characteristics of regulatory asbestos (non-asbestos EMPa with a length to width ratio > 3 , width $< 3 \mu\text{m}$ and length $>5 \mu\text{m}$). The genesis of these amphiboles corresponds to phenomena of alterations of pyroxenes prior³⁸to the appearance of slip-dip faults and crack-seal veins. For Boulmier and Pezerat, these rocks can also contribute to dust generation. Asbestos detection prior to exploration activities by the C2 company included an analysis of these rocks. The results are not currently available and are not included in this article.

Collecting samples from production residues (tailings) with an analysis exclusively by XRD (Marcoux¹⁴ et d'Arco¹⁵) to demonstrate the absence of asbestos in the mine is not the best approach. During fine grinding, the majority of asbestos fibers were suspended in the air, captured by the ventilation system and then released and diluted into the atmosphere (if no sufficiently effective filtration device was put in place to retain them). The asbestos is hydrophilic. It is quite possible that fibers remaining in the crushed ore were suspended in the washing water and then settled in the retention basin or, if the length of time was not sufficient, entered the Cougnets Creek. Any fibers that may have remained in the pulp exiting the washing area, were certainly suspended in the air, retained in the dryer filter or entered the stream. In the end, the chances of finding asbestos fibers in production residues (tailings) are minimal. Failure to find asbestos fibers in the tailings does not prove that there is no asbestos in the mine. The choice of XRD analysis is not suitable. It was found that this technique does not allow to

determine the mineral's habit. It has a very low detection limit. It was not adopted by the regulations neither in 2003³⁹ nor in 2019⁴⁰. In terms of the standardization, in ISO22262-3⁴¹, it is clearly specified that XRD analysis, can be used for the quantification of asbestos but only after identification by PLM, TEM or SEM microscopy according to standard NF ISO 22262-1.

HISTORICAL EXPOSURE TO ASBESTOS AT THE WORKPLACE

Reprocessing of PCM dust measurements for the C1 company (historical)

Workplace airborne fibers measurements carried out by PCM at the time of mining operations were reprocessed to estimate the concentration of actinolite asbestos (CE3A). Distribution [Figure 8] of these recalculated values shows:

- That only 5% of estimated concentrations are less than 0.010 actinolite fibers/cm³,
- That 93.6% of estimated measurements are below 0.400 actinolite fibers/cm³,
- That the remaining 6.7% measurements relate to 9 measurements with an estimated concentration between 0.400 actinolite fibers/cm³ and 0.850 actinolite fibers/cm³, including 7 performed at the crushing station which includes the primary crusher, the console control station, the upper level screening and the gyratory crusher and 2 at the jumbo drill.
- A peak in estimated concentrations between 0.050 and 0.100 actinolite fibers/cm³.

Reconstruction of Occupational Exposure Limits (historical)

The eight hours occupational exposure limit for asbestos in France (F.OEL_{8 hours}) is based on TEM measurements for each work process. Data from the C1 company's register "Asbestos fibers exposure, splitting of the work, and concentrations" and the estimation of dust levels at the workstation (CE3A) described in the previous paragraph made it possible to reconstruct (F.OEL₈

hours) values that can be compared to current regulatory French requirements. Distribution of these F.OEL_{8 hours} values. The distribution of the 117 reconstituted F.OEL_{8 hours} [Figure 9] values shows:

- That 95.7% of F.OEL_{8 hours} values are higher than 0.010 actinolite fibers/cm³,
- That 96.6% of F.OEL_{8 hours} values are lower than 0.178 actinolite fibers/cm³,
- That 3.4% of F.OEL_{8 hours} values remaining, are between 0.178 actinolite fibers/cm³ and 0.282 actinolite fibers/cm³, and concern the crushing station at the console control station, the upper level screening, the gyratory crusher as well as a jumbo drill;
- That F.OEL_{8 hours} values peak with values between 0.040 and 0.060 actinolite fibers/cm³.

Screening for asbestos bodies (historical)

As part of the studies of employees who worked at the Salau mine, biometrological analyses screening for asbestos bodies were carried out by the LEPI (Laboratory for the Study of Inhaled Particles of the Department of Paris; the current name is LAFP) reference laboratory, accredited by Cofrac (French Accreditation Committee) to search for asbestos fibers in materials, air and biological indicator samples in relation to the respiratory system. These analyses were carried out on sputum and/or bronchoalveolar washes (BAL) from 1982 to 1991, on 28 patients followed mainly at the Purpan University Hospital in Toulouse. The results showed a significant presence of asbestos bodies in 13 of these patients [Table 7], with concentrations equal to or higher than the values generally used as a reference in Europe of 1 AB in sputum and 1 AB/mL in BAL. Of the 13 positive cases, 9 were underground miners, 3 worked in washing and/or crushing, and 1 in drying, stripping and bagging.

Discussion of exposure of employees of the C1 company during the operation of the mine (historical)

Almost all of the miners were exposed to a F.OEL_{8 hours} value estimated as higher than the Occupational Exposure Limit currently in force in the regulations in France which is 0.010 asbestos fibers/cm³ (10f/L). The first average occupational exposure value over 8 hours adopted in 1977 was 2f/cm³ (2f/mL) measured by PCM. It was lowered in 1992 to 0.600f/cm³ when chrysotile was the only mineral type of asbestos present and to 0.30 f/cm³ for all other mineral types of asbestos, either isolated or mixed, including a mixture containing chrysotile. [In 1996, the value for a one-hour work period was set at 0.10 f/cm³](#). In 2012, the method of measuring asbestos dust levels and monitoring compliance with OEL by PCM was replaced by TEM analyses to take into account the nature of fibers and thin asbestos fibers. The OEL_{8 hours} value not to exceed, was first set at 0.100 asbestos fiber/cm³ then to 0.010 asbestos fiber/cm³ in 2015.

A significant presence of asbestos bodies was detected in 13 people with pneumoconiosis working in the mine at the time of its operation. The analytical method of optical microscopy does not identify the constituent AB fiber, however, the context in which the research is conducted as well as data concerning the occupation and the type of exposure are important indicators for determining the nature of the fiber. As stated above, ABs are preferentially formed on amphibole fibers and the BRGM studies carried out in 1983 and 1984 (see details in the historical review of measurements) on rock samples with fibrous facies show actinolite referred to as asbestos and for fibers detaching from the rock, as fine asbestiform particles. The electron microscopy (TEM) analyses also refer to actinolite asbestos fibers with or without asbestiform facies. On the other hand, out of the ten TEM measurements where actinolite asbestos was quantified, Boulmier also detected some rare chrysotile fibers on a single filter [Table 8]. The

brake pads on mining equipment is the likely source of this chrysotile.

The indisputable presence of asbestiform actinolite in fibrous amphibolite, the non-neutralization of fibrous amphibolite during mining, the results of TEM airborne asbestos measurements during mining operations, the results of the screening for asbestos bodies and the recognition of two people who had worked at the mine without previous exposure to asbestos other than at the Salau mine who were suffering from occupational asbestos exposure with characterized asbestosis, are all elements which show that asbestiform actinolite and ferro-actinolite are, or in part, the mineral agents that can have contributed to the pneumoconioses in the C1 company's staff. If asbestiform actinolites are the sole culprits of these diseases, this would show that F.OEL_{8-hour} values less than 0.015 asbestiform actinolite fibers/cm³ can cause pneumoconiosis. The F.OEL_{8-hour} of 0.015 asbestiform actinolite fibers/cm³ corresponds to the average F.OEL_{8-hour} estimated for the washing process. The result of the AB screening from a BAL sample of a patient who worked 14 years in the washing station is 3.7 AB/mL. However, we must remain cautious because the monitoring did not aim to measure the highest levels.

MEASUREMENTS AT THE WORKPLACE DURING ASBESTOS SURVEY

Airborne asbestos measurements during verification of C2's model

Measurements were carried out during the "the external expertise," of the asbestos occurrence model in the mine, proposed by the C2 company. The process that was used was "the sampling of fibrous amphibolite using tweezers with moistening of the material before the operation and continuous misting throughout. The airborne asbestos measurements were carried out by TEM:

- on two operators during amphibolite sampling;
- on two operators during movement through the galleries.
- Static measurements during two working sessions downstream from the work area.

No regulatory actinolite asbestos fibers were detected. Ferro-actinolite asbestos is not precisely defined by regulation and by the current French NFX 43 050 standard. A ferro-actinolite asbestos fiber was detected and however, has been taken into account. The results [Table 9] are expressed when less than 4 fibers are counted, according to the NF X43-050 standard, as lower than the upper limit of the measurement uncertainty. Either for the detected ferro-actinolite asbestiform fiber, the result is given as less than 0.009 fibers ferro-actinolite asbestiform cm³, (less than 9.9 fibers / L). The detected fiber was emitted during sample collection C1-6.1 or C1-6.2.

Over 8 hours, the operators completed two sessions, one of 83 minutes and one of 53 minutes, while wearing a face mask with assisted ventilation equipped with a P3 filter cartridge with an assigned protective factor of 60. The F.OEL_{8-hour} value was less than 0.0037 asbestos fibers/cm³.

Airborne asbestos measurements during asbestos survey by the C2 company

During its asbestos survey, the C2 company used the same process to sample fibrous amphiboles as that of the third-party expertise. A measurement on an observer in the work area, a fixed measurement in the work area and a fixed measurement in the vicinity of the “Mobile Decontamination Unit” were made during the C2 company’s sampling by external expertise in addition to the measurements taken by the C2 company.

No asbestos fiber was detected in the airborne asbestos measurements. The results [Table 9] are given as “less than the upper limit of measurement uncertainty.”

Discussion of Airborne asbestos measurements

Sampling operations involved the mine’s most emissive material. They were carried out in accordance with the provisions currently in force in France. Sampling with tweezers, in the rocks

in which the fibers were visible with misting, was an effective technique in view of airborne asbestos measurements. Sampling did not cause any pollution. The risk analysis for asbestos detection was adapted.

Conclusion

The presence of actinolite and ferro-actinolite asbestos in the Salau mine is confirmed. These minerals are observed in post or late Hercynian slip-dip faults and crack-seal veins. They are the main minerals involved in the pneumoconioses that affected employees during mining operations between 1971 and 1986. The crushing of fibrous amphibolite also produces elongated mineral particles of actinolite and ferro-actinolite (EMPa).

Hercynian alteration of pyroxene into amphibole may be an additional potential source of EMPa. The results of the asbestos survey conducted by the C2 company as it was planning to conduct an exploration drilling campaign are not available. These results would make it possible to answer this question and in the event of a positive response, to assess the involvement of the rocks concerned in the production of EMPa. The asbestos risk analysis of the mining exploration company was done in the best possible way at least in the phases of the project that were carried out.

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TABLE 1 : Fibrous amphibolite sampling

N°	Gallery altitude	Lithology	TEM on ground material asbestos EMPa	TEM on ground material non asbestos EMPa
C1-1	1430	Dip slip fault containing fibrous amphiboles which mark the lineation with a pitch close to 90 °	95% Actinolite	4% Actinolite, ferro-actinolite
C1-6.1	1475	Dip slip fault containing fibrous amphiboles which mark the lineation with a pitch close to 90 °	20% Actinolite, ferro-actinolite	2% Actinolite, ferro-actinolite
C1-6.2	1476	Dip slip fault containing fibrous amphiboles which mark the lineation with a pitch close to 90 °	95% Ferro-actinolite	4% Actinolite, ferro-actinolite
C1-14	1506	Extension fractures with cross fibers of dark green fibrous amphiboles	<1% Actinolite	<1% Actinolite
C1-22	1532	Dip slip fault containing fibrous amphiboles which mark the lineation with a pitch close to 90 °	95%Ferro-actinolite	4% Actinolite, ferro-actinolite
C2-nord 1	1230	Dip slip fault containing fibrous amphiboles which mark the lineation with a pitch close to 90 °	50% Actinolite	5% Actinolite
C2-sud 2	1230	Extension fractures with cross fibers of fibrous amphiboles	70% Actinolite	5% Actinolite
C2-sud 3	1230	Dip slip fault containing fibrous amphiboles which mark the lineation with a pitch close to 90 °	85% Actinolite	5% Actinolite

C2-T86	1230	Extension fractures with cross fibers of fibrous amphiboles	99% Actinolite	0,5% Actinolite
C2-T5*	1230	Dip slip fault containing fibrous millimeter amphiboles which mark the lineation with a pitch close to 90 °	0,5% Actinolite	ND
C2-T6*	1230	Dip slip fault containing fibrous millimeter amphiboles which mark the lineation with a pitch close to 90 °	7% Actinolite	1% Actinolite
C2-T11*	1230	Dip slip fault containing fibrous white amphiboles which mark the lineation with a pitch close to 90 °	12% Actinolite	1% Actinolite
C2-T13*	1230	Extension fractures with cross fibers of white fibrous amphiboles and calcite	90% Actinolite	1% actinolite

The samples, the number of which begins with C1, correspond to indices spotted by the C1 company outside the exploration zone. Samples whose number begins with C2 come from the exploration area. The samples with a star were taken simultaneously by the external expert and by the company C2.

TABLE 2 : MB 2015 test

Analytical method	Reference	Amosite NIST SRM 1866a	Tremolite NIST SRM 1867	Actinolite NIST SRM 1867	Actinolite, dolerite from Vendée (France)
TEM	MB 2015	100%	66%	70%	98%
	ISO 2262-01	99%	62%	67%	98%
	Van Orden	99%	21%	3%	43%
PLM	MB 2015	91%	66%	67%	100%
	EPA 1993	87%	47%	51%	98%

The table shows from NIST standard samples and a natural sample the difference between the methods for identifying amphibole particles coming from asbestiform minerals. The results obtain with TEM and PLM are comparable with the use of MB 2015.

The test was performed on 100 particles for each sample and each reference method.

TABLE 3: Estimation of the protection factor (mask) and elementary operations

Elementary operation = partial times	Protection factor
Crushing station	
5h = Crushing operation	2
2h = Cleaning-maintenance-various stops	1
1h = travel - start and end	1
Drying ovens	
3 h = Oven operation	2
3h = Other work inside the room	1
2h = Other work outside the room	1
Sample preparation station	
3h = Operation of crushing and division of samples	2
3h = Various work in the room	1
2h = Start-up and end - various work outside the room	1
Digging of waste rock tunnels	
Drillers	
4h = Pure drilling time	2
2h = Other front work: watering-purging-equipment and take off equipment-mining-blasting	2
1h = Other work outside the front	1
1h = start and end - travel	1
Chargers	
4h = Loading-transport-unloading time	2
2h = Travel in various galleries	1
1h = Daily maintenance of machinery-workshop-breakdowns	1
1h = travel-Start and end	1
Ore tracing-unstacking	
Drillers: same as tunneling	
Chargers: same as tunneling	
Digging of backfill rooms	
Drillers: same as tunneling	
Chargers: same as tunneling	
Tipping into hopper at 1320	
4h = Work on hopper: Breaking blocks-Flow of products	2
3h = Other work: Supply of materials-ore waiting.	1
1h = travel - Start and end	1
Ore washer	
8h = Ore washing work	2
Filtration and discharge of waste rock from the ore washer	
6h = Work inside the room	2
2h = Work outside the room: Cleaning of conveyors - moving conveyors.	1

Allocation of the protection factor (mask) according to the elementary operations described in the document “Asbestos fibers exposure, splitting of the work, and concentrations” (company C1 archive).

TABLE 4 : Classification of rocks according to their possible asbestos content in the exploration area by the company C2

May not contain asbestos	Suspected of containing asbestos	Fibrous amphibolite
Unaltered granodiorite	Skarns near quartz faults	Fibrous amphibole veins
Limestones and Marbles	Altered granodiorite (epidotized)	
Schists of Mont Rouch	Epidote veins	
Massive sulphides alone	Hydrothermalized breccia	
Quartz faults	Skarns cross cut by massive sulphides	
Quartz and calcite faults	Hornblende diorites	
Quartz, calcite and chlorite faults		
Quartz, calcite and sulphide faults		
Quartz and sulphide fault		
Aplite veins		
Unaltered skarns		

TABLE 5 : Description of the C2 Company processes used during sampling.

Processes	Material	Technique	Collective protection
1	Rocks likely to be low emissive	Massette or hammer and chisel	Misting
2	Rocks likely to be emissive	Massette or hammer and chisel	Misting
3	Rocks likely to be low emissivity	Electric hammer chipping with variable frequency	Misting Aspiration at the source
4	Rocks likely to be emissive	Electric hammer chipping with variable frequency	Misting Aspiration at the source
5	Very emissive, visible asbestos	Tweezers	Misting
6	Dust	Spoon	Misting

TABLE 6 : Asbestiform habit of amphiboles in fibrous amphibolites

Analytical methods Reference	TEM		SEM			PLM on ground material			
	MB 2015	ISO 22262- 1	ISO 22262- 1	EPA 1993	HSG 248	MB 2015	EPA 1993	HSG 248	ISO 22262- 1
<i>From bibliography</i>									
(photos) prof. E. Marcoux	Na	Na	✓	✓	✓	Na	Na	Na	Na
(photos) J. L. Boulmier Dr	✓	✓	Na	Na	Na	Na	Na	Na	Na
Doctor F. Richard	✓	✓	Na	Na	Na	✓	✓	✓	✓
<i>Verification of C2's model</i>									
C1-1	✓	✓	Na	Na	Na	✓	✓	✓	✓
C1-6.1	✓	✓	Na	Na	Na	✓	✓	✓	✓
C1-6.2	✓	✓	Na	Na	Na	✓	✓	✓	✓
C1-14	✓	X	Na	Na	Na	X	X	X	X
C1-22	✓	✓	Na	Na	Na	✓	✓	✓	✓
C2-nord 1	✓	✓	Na	Na	Na	✓	✓	✓	✓
C2-sud 2	✓	✓	Na	Na	Na	✓	✓	✓	✓
C2-sud 3	✓	✓	Na	Na	Na	✓	✓	✓	✓
C2-T86	✓	✓	Na	Na	Na	✓	✓	✓	✓
<i>Duplicate sampling during the C2 company asbestos survey</i>									
C2-T5	✓	✓	Na	Na	Na	✓	X	✓	✓
C2-T6	✓	✓	Na	Na	Na	✓	✓	✓	✓
C2-T11	✓	✓	Na	Na	Na	✓	✓	✓	✓
C2-T13	✓	✓	Na	Na	Na	✓	✓	✓	✓

✓ asbestiform, X non asbestiform, Na non applicable

TABLE 7 : Asbestos bodies counting

Age (at first Analysis)	Number of years at the SALAU mine (at the date of the analysis)	Expo. in Salau (at the date of the analysis)	Results: AB / sputum	Results: BAL AB/ml	Analysis date
55	10	Engine driver - underground miner	7 AB		1982
			1 AB		1984
	5	Laborer muleteer			
	2	Maintenance worker			
	1	Crushing monitoring			
	6	Ore washing	ND	3 AB/ml	1983
37	4	Discharge filtration monitoring	4 AB	5,3 AB/ml	1984
	2	Underground miner	1 AB		1983
	8			ND	1984
				2 AB dans 36ml	1986
30	7	Underground miner	1 AB	0,05 AB/ml	1984
51	1	Drying ovens - stripping	ND	0,45 AB/ml 0,95* AB/ml	1984
	8	Bagging		ND	1986
64	12	Underground miner		10 AB/ml	1984
43	13	Underground miner	ND		1985
			1 AB	0,45 AB/ml	1984
60	18	Underground miner		0,5 AB/ml	1984
			55AB/ 56 AB		1989
?	4	Underground miner	1CA / 3 AB		?
52	12	Supervisor (ore washing and crushing)	16 AB	38,5 AB/ml	1985
53	14	Ore washing	ND	3,7 AB/ml	1986
40	10	Underground miner	1 AB	0,45 AB/ml	1986
68	14	Underground	1 AB/2AB		1987

		miner		
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AB: asbestotic body observed in optical microscopy; 1 AB or more / sputum or 1 AB / ml of bronchoalveolar lavage (BAL) or more: abnormally high pulmonary retention in AB significant of occupational exposure to asbestos - * borderline result (uncertainties to be taken into account).

TABLE 8: TEM airborne asbestos measurements carried by Jean Luc Boulmier

Report No., J.L. Boulmier	Sampling date	Workplace	TEM in fibers / cm ³	nature of fibers	method
M 9830	14/12/1983	Crushing control station	0,2	Actinolite	indirect
M 9830	14/12/1983	Crushing control station	0,2	Actinolite	direct
M 9830	14/12/1983	screening	0,3	Actinolite	indirect
M 9830	14/12/1983	screening	0,2	Actinolite	direct
M 9830	14/12/1983	1230, during drilling	0,1	Actinolite	indirect
M 9830	15/12/1983	DV390, during drilling	0,1	Actinolite	indirect
M 9830	15/12/1983	DV422 loading / unloading	0,1	Actinolite	direct
M 9072	14/05/1985	Filtration of discharge « plat des Pommiers »	0,05	Actinolite	indirect
M 9072	14/05/1985	Ore washing	<0,009	Actinolite	indirect
M 9072	14/05/1985	Circulation in mine galleries	0,015	Actinolite and rare chrysotile	indirect

TABLE 9: TEM Airborne asbestos measurements carried out by external expertise

No.	Type of measurement	sampling date	Location and activity	SA in fibers / cm3	Calculated concentration Result in fibers / cm3	TEM concentration Result in fibers / cm3	Fiber/ type
<i>Verification of C2's model</i>							
P-122	Environmental	24-avr-19	Level 1430	0.00148	0	<0.0048	NAD*
P-123	Personal sampling	24-avr-19	Ope. 1, levels 1430-1475-1483, very emissive materials, sampling with tweezers, misting	0.00188	0.0019	<0.0099	1 Ferro actinolite
P-124	Personal sampling	24-avr-19	Ope.2, levels 1430-1475-1483, walking and traveling by electric vehicle	0.00191	0	<0.0062	NAD*
P-125	Personal sampling	25-avr-19	Ope. 2, levels 1506-1532 (quarry)very emissive materials, sampling with tweezers, misting	0.00296	0	<0.0097	NAD*
P-126	Personal sampling	25-avr-19	Ope. 1, levels 1230,1320, 1430, 1475, 1506, 1532, walking and traveling by electric vehicle	0.00128	0	<0.0042	NAD*
P-127	Environmental	25-avr-19	Level 1430	0.00148	0	<0.0048	NAD*
<i>Duplicate air monitoring during the C2's asbestos survey</i>							
P-158	Personal sampling	30-mai-19	Level 1230, tweezers sampling, highly emissive materials, Ope. 1 observer	0.00098	0	<0.0032	NAD*
P-157	Environmental	30-mai-19	Cross-section R1 of gallery 1230, work area	0.00147	0	<0.0048	NAD*
P-146	Environmental	30-mai-19	Mobile decontamination unit area	0.0014	0	<0.0046	NAD*

NAD* No Asbestos Detected

FIG. 1 Determination of the asbestiform habit

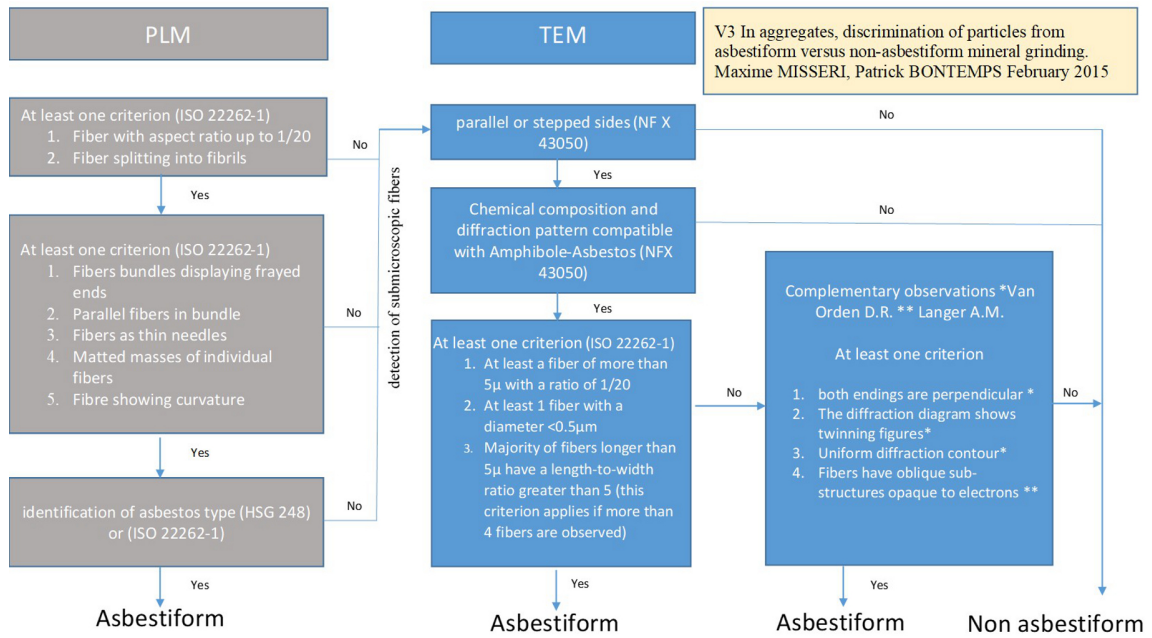


FIG. 2A: fault containing asbestiform amphiboles V3

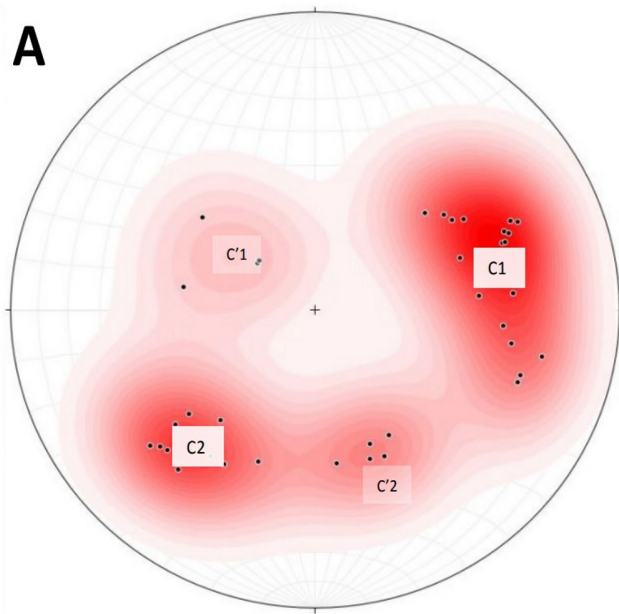


FIG. 2B: fault containing asbestiform amphiboles V3

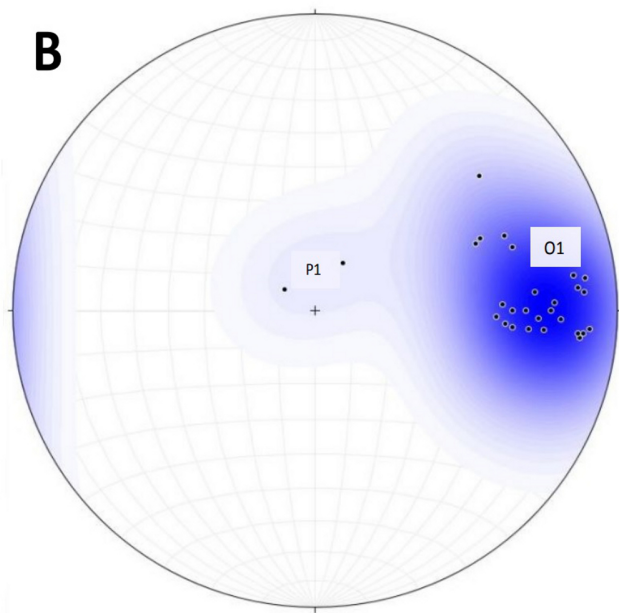


FIG. 3A: Slip fiber



FIG. 3B: Cross fiber



FIG. 4A: ferro iron rich actinolite

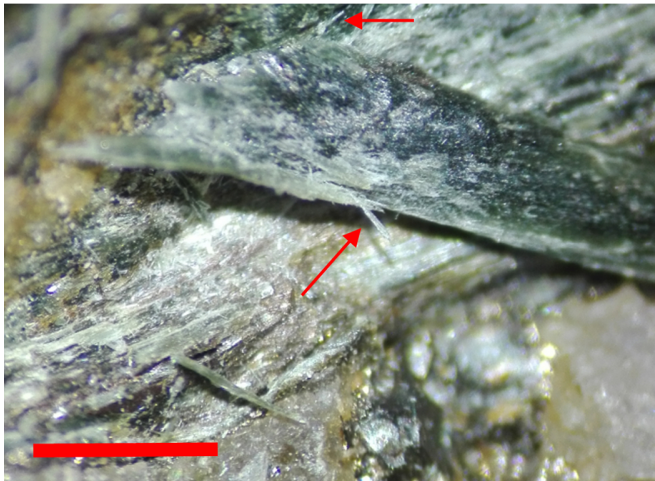


FIG. 4B: ferro to magnesium rich actinolite



FIG. 5: Elemental analyses obtained on asbestiform amphiboles

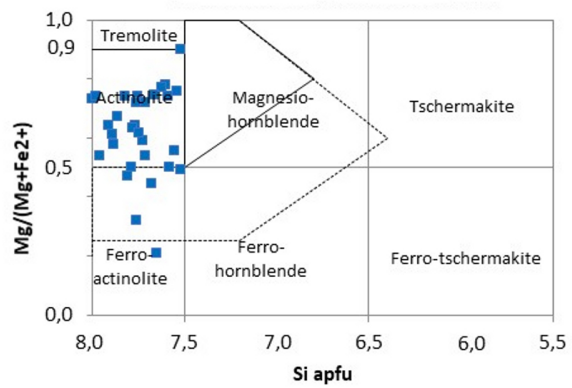


FIG. 6A: Sample of Doctor Richard macro



FIG. 6B: Sample of Doctor Richard TEM

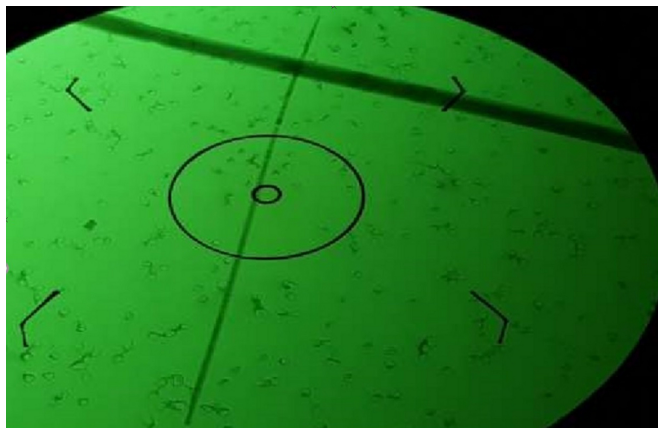


FIG. 6C: Sample of Doctor Richard PLM



FIG. 6D: Sample of Doctor Richard McCrone

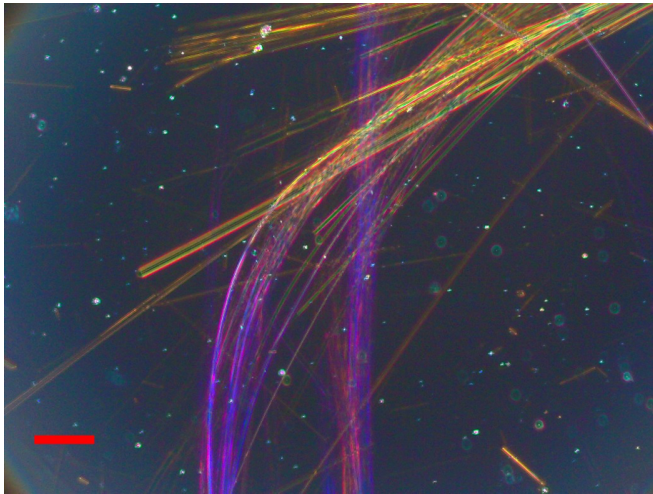


FIG. 7: Comparison of Asbestiform Amphiboles

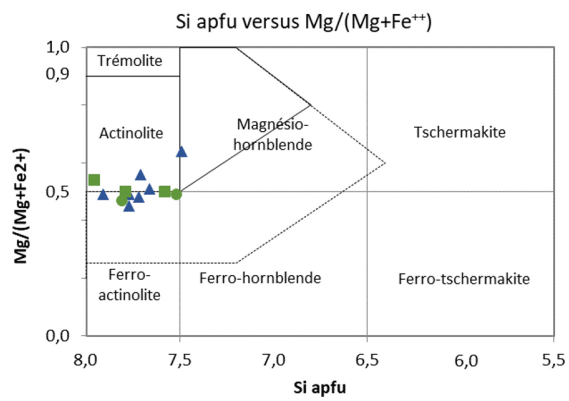


FIG. 8: Distribution of CE3A0,5

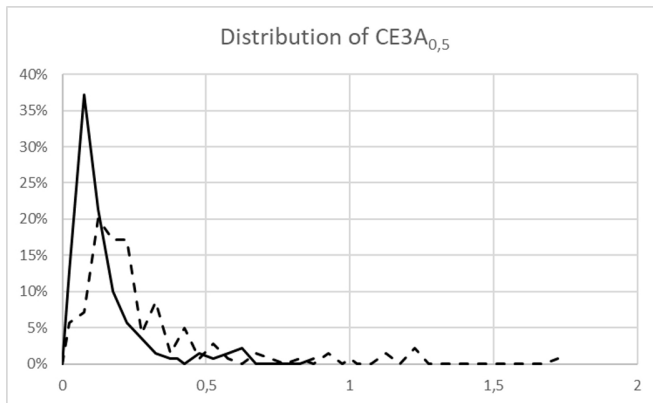
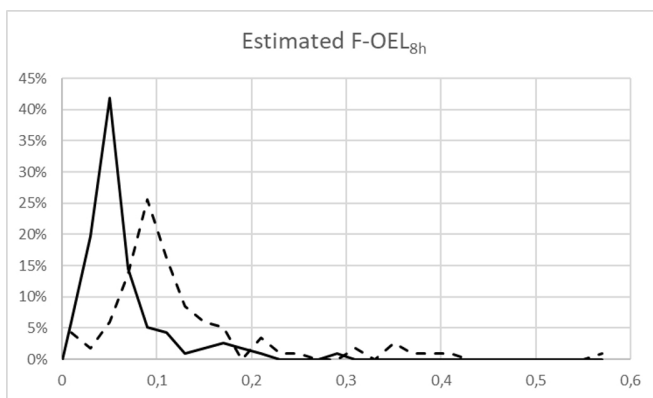


FIG. 9: Estimated F OEL8 hours



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