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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

Citation

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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

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in Europe. The occupational exposure limit of 8 hours (OEL_{8hours}) could be estimated for each workstation. Estimates were based in part on phase contrast microscopy (PCM) measurements. Simultaneous measurements by PCM and transmission electron microscopy (TEM) allowed for a correction. The estimated OEL_{8hours} have a unimodal distribution with an average of 0.05 actinolite fibers/cm^3. The highest measurements (3.4%) were between 0.178 and 0.282 actinolite fibers/cm^3. These occurred at the crusher and drilling sites of the work area. These results differ from those obtained in 2019 during the safety and sampling operations for asbestos detection before 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 fibers/cm^3.

Keywords

pneumoconioses, asbestos, actinolite, ferroactinolite, bronchoalveolar lavage fluid (BAL), asbestos body, miners, slip fibers, cross fibers, transmission electron microscopy (TEM), phase contrast microscopy (PCM), polarized light microscopy (PLM), International Mineralogical Association (IMA), OEL_{8hours}

Introduction

The Salau mine is located in France, in the Pyrenees. The Salau tungsten mine was operated from 1971 to 1986 by a mining company (called C1 in this article). 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 this 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 is addressed in this article. Local authorities made use of external expertise to verify management of the asbestos risk during the new exploration phase. Before mining operations were closed, two cases of asbestosis were recognized, which prompted the request for "external expertise." Two miners, who had no previous exposure to asbestos other than at the Salau mine, were suffering from occupational asbestos exposure with asbestosis characterized in 1983 for one worker and 1986 for the other.

During this study, the following were possible:

- access company C1'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; and
- 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 health care 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 Rangueil 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 (AB), 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 AB 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 company C1, 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 company C1, 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, three 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, five cases of asbestosis, and six 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 company C1 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.

Because of the anonymization of the data in the documents available and the fact that the surveys were carried out only on part of the employees of company C1, it was not possible to conduct all the necessary cross-checks to evaluate the pneumoconiosis that affected the employees. At a minimum, however, it has been established that two cases of asbestos were recognized by the SSM, and that three other cases of asbestosis as well as six cases of suspected asbestos 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 occupational exposure limit of 8 hours (OEL_{8hours}) allowed at the time the mine was active. External expertise has reprocessed the dust measurements and calculations of the OEL_{8hours} 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 were 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 transmission electron microscopy (TEM) airborne asbestos measurements.

These checks and the methods used are described in this paper.

Historical data collected from company C1's archives made it possible to evaluate asbestos fiber dust levels at the time of the mining operation based on phase contrast microscopy (PCM) measurements and TEM measurements. During the operation, this company had PCM analyses (the 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]). This paper used 140 airborne dust measurements that were carried out with the PCM and that were found in the archives. 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. The BRGM at the time, however, 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 also have enabled the reconstruction of an OEL, per workstation, which can be compared with the OEL currently in force in France: 0.01 fibers/cm^3 (10 fibers/liter) over 8 h 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 and 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 (e.g., rock analysis and atmospheric analysis) reported in this paper were collected by the "external experts" and were 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. The data for C2 are not yet available. 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 experts" 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 Poitrenaud[2] who incorporated, among others, the work of Colchen et al.;[3] Ternet et al.;[4] Derré, Fonteilles, and Nansot.[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.[6,7] 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, alternating limestones and pelites,[8] and date back to the Lower Devonian Period for the upper limestone formations.[9]

This high-temperature intrusion, because of reactions from contact metamorphism and metasomatism, transformed part of the Barregiennes into rocks called corneans (hornfels) and the upper limestones into marbles, which themselves were transformed, respectively, as a result of contact with the surrounding rocks and the flow of fluids containing different elements, into the Skarns.

In the first place, it was necessary to verify that the asbestos hazard (in accordance with standard *CSA Z1002*) at the mine site had been established. In other words, that asbestos was indeed present in the geological formations. Except for Soler,[10] who in his 1977 thesis 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. Boulmier,[11] in 1984, collected two samples from the mine in which he detected actinolite asbestos after analyzing them by TEM. Pezerat in two reports 1984[12] and 1986[13] also concluded that asbestos was present based on mine samples and tailings using X-ray diffraction (XRD) and TEM analysis. Marcoux[14] analyzed the same type of rock by polarized light microscopy (PLM) and scanning electron microscope (SEM) 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'Arco,[15] using XRD analyses, also failed to detect asbestos in production residues (tailings). Cesbron's report[16] 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, multicentimeter 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 experts" using PLM and TEM help to specify the habit of the amphiboles concerned and can 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. Company C2 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 potentially could contain asbestos. It secured the exploration area by sealing off, with structures, the galleries containing rocks or equipment, which were likely to contain asbestos, dating back to the time of the mining operation. The structures have been anchored on rocks known not to have contained asbestos. The first geological survey also allowed company C2 to classify the mapped rocks into three categories, according to the flowchart, outlining asbestos monitoring and metrology procedures during underground work proposed by ANSES 2015[17]:

- rock known not to contain asbestos,
- rock potentially containing serpentines or amphiboles, and
- rock containing asbestos.

Company C2 supplemented the visual asbestos inspection with a sampling campaign 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."[18] Company C2 had six processes planned in its sampling campaign. Company C2 performed airborne asbestos measurements for each of the processes. The "external experts" verified the adequacy of the asbestos surveys and the efficiency of company C2's risk analysis during the sampling of its asbestos survey also by performing airborne asbestos measurements in smaller quantities. Only those measurements recorded by the external experts 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

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

TABLE 1 Fibrous amphibolite sampling

No.	Gallery Altitude	Lithology	TEM on Ground Material, Asbestos EMPa	TEM on Ground Material, Nonasbestos EMPa
C1-1	1430	Dip-slip fault containing fibrous amphiboles that 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 that 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 that 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 that 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 that 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 that 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 that mark the lineation with a pitch close to 90°	0.5% Actinolite	ND
C2-T6*	1230	Dip-slip fault containing fibrous millimeter amphiboles that mark the lineation with a pitch close to 90°	7% Actinolite	1% Actinolite
C2-T11*	1230	Dip-slip fault containing fibrous white amphiboles that 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

Note: The samples, the number of which begins with C1, correspond to indices spotted by company C1 outside the exploration zone. Samples whose number begins with C2 come from the exploration area. The samples with an asterisk (*) were taken simultaneously by the external expert and company C2.

CHARACTERIZATION OF FIBERS IN FIBROUS AMPHIBOLITE

Because this rock disintegrates easily and the individual fibers detach under low mechanical stress, only crushed material were viewed by PLM before the analysis using TEM. The methodology and equipment were described in an earlier article.[19] A short description of the method is given next. 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, had 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 to obtain less than 20% electron-dense material on the grids. The vial was submitted to ultrasound for 1 min. The preparation of the TEM grid used the drop-mount technique.[20] The TEM-EDS analyses were performed using an FEI CM200 equipped with a calibrated SAMx NumeriX EDS. Andrew Locock's software, which followed the recommendations of the International Mineralogical Association (IMA 12), made it possible (thanks to 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" and taking into account the measurement uncertainty for each element, which was around 10%.

The asbestiform habit was determined with the following reference texts: ISO 22262-1,[21] EPA 1993,[22] HSG248,[23] and MP 2015.[24] In ISO 22262-1 it is the practical part of paragraph 7.2.3.7.1, which is used. The MP 2015 flowchart (fig. 1) used the criteria described in the literature. It made it possible to determine particles coming from crystals that 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 company C1's mining operations were retrieved from company C1's archives. It turns out that all the measurements performed by PCM were recorded in a register by company C1. 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 company C1 (same equipment, same procedure as the BRGM) until May 1986. Of the total, 140 PCM dust-level measurements were usable. Generally, there were no direct correlation between PCM measurements and actual asbestos content (AFSSET, Short Asbestos Fibers, 2009[25]). The BRGM had carried out several TEM and PCM measurements, however, in similar work situations, which may make it possible to estimate a conversion coefficient specific to the operation at the Salau mine. The fibers

FIG. 1 Determination of the asbestiform habit.

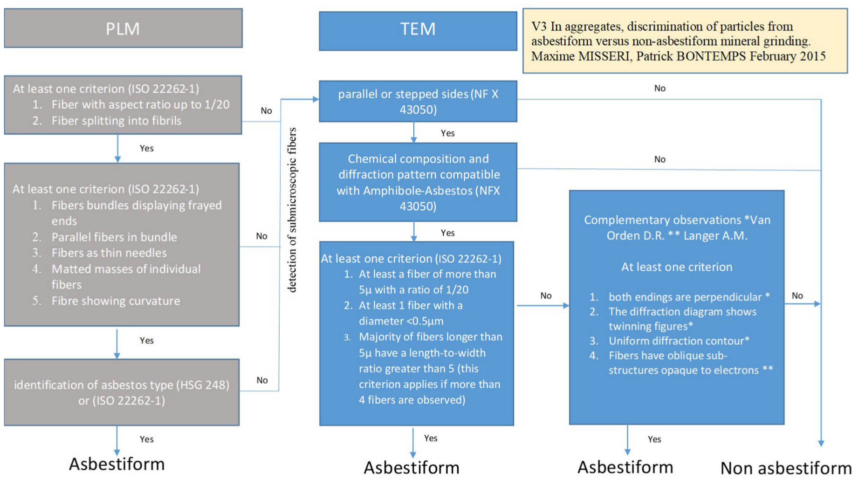


TABLE 2 MB 2015 test

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%

Note: The table shows the difference between the methods for identifying amphibole particles coming from asbestiform minerals. The results obtained with TEM and PLM are comparable with the use of MB 2015. Analyzes were performed on three NIST standards and on one natural sample. The test was performed on 100 particles for each sample and each reference method.

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 <3 µm and a length to width ratio equal to 3, dimensions recommended by the World Health Organization. Jean Luc Boulmier made several observations. Under an electron microscope, he observed twice as many Elongated Mineral Particles (EMPs see ANSES 2015[17] and Léocat[26]) as in optical microscopy. In contrast, he noted that about half of the EMPs were EMPa. He also found that nonasbestiform EPMa were much more abundant than asbestiform EPMa. In the end, the application of a correction coefficient of 0.5 on EMPs 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 company C1's register "Asbestos, exposure to fibers, time and content" and "Concentration Estimation of Airborne Actinolite Asbestos ($CE3A_{0.5}$)."

ESTIMATED HISTORICAL OCCUPATIONAL EXPOSURE LIMIT VALUE

The occupational exposure limit value over 8 h in France ($F.OEL_{8hour)}$ 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 exposure.[27] It must currently be less than 10 asbestos fibers per liter of air ($0.010 f/cm^3$), according to French regulations.

The $F.OEL_{8hour}$ 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. They can be reconstructed, however, with the available information:

$$F.OEL_{8hour}\ \text{calculation} = [((C_1 \times T_1)/APF) + \ldots + ((C_n \times T_n)/APF)]/8. \qquad (1)$$

This type of calculation can give only an order of magnitude because several calculation methods may be chosen and certain parameters are estimated. One hundred thirteen $F.OEL_{8hour}$ were reconstructed from the data contained in company C1's register "Asbestos fibers exposure, splitting of the work, and concentrations," and four were reconstructed from the dust measurements of company C1's register "Asbestos, exposure to fibers, duration and concentration." The protective factor of the masks used at the time, estimated at two, 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 affected by the mining works. The results of the PCM measurements do not completely exclude the fact that there were acute peaks of point exposure on some emissive processes, such as digging (underground miner).

Workplace Exposure Measurments

AIRBORNE ASBESTOS MEASUREMENTS DURING SAMPLING BY "EXTERNAL EXPERTS"

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 company C2, two airborne asbestos measurements were performed by TEM on operators who sampled highly emissive fibrous amphibolite. This analysis was carried out using TEM according to the indirect

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

Elementary Operation = Partial Times	Protection Factor
Crushing station	
5 h = Crushing operation	2
2 h = Cleaning-maintenance-various stops	1
1 h = travel - start and end	1
Drying ovens	
3 h = Oven operation	2
3 h = Other work inside the room	1
2 h = Other work outside the room	1
Sample preparation station	
3 h = Operation of crushing and division of samples	2
3 h = Various work in the room	1
2 h = Start-up and end - various work outside the room	1
Digging of waste rock tunnels	
Drillers	
4 h = Pure drilling time	2
2 h = Other front work: watering-purging-equipment and take-off equipment-mining-blasting	2
1 h = Other work outside the front	1
1 h = start and end - travel	1
Chargers	
4 h = Loading-transport-unloading time	2
2 h = Travel in various galleries	1
1 h = Daily maintenance of machinery-workshop-breakdowns	1
1 h = 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	
4 h = Work on hopper: breaking blocks - flow of products	2
3 h = Other work: supply of materials-ore waiting	1
1 h = Travel - start and end	1
Ore washer	
8 h = Ore washing work	2
Filtration and discharge of waste rock from the ore washer	
6 h = Work inside the room	2
2 h = Work outside the room: cleaning of conveyors - moving conveyors.	1

Note: 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).

method (NF X43-050 standard) with sampling performed on operators at 3 L/min according to the NF X 43-269 standard. The work process included 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 L/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 COMPANY C2

Company C2 identified rocks that may contain asbestos and rocks that may not contain asbestos (table 4). Company C2 did its risk analysis for each sampling process of these rocks during the asbestos survey. Company C2 checked the operator measurements and static measurements of the dust levels during each process. Most of the measurements were duplicated by the external experts (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 paper. Measurements on an operator close to the source, in the work area, and near the "Mobile Decontamination Unit" were performed. Airborne asbestos measurements were carried out using the same methods and equipment as noted in the previous paragraph.

TABLE 4 Classification of rocks according to their possible asbestos content in the exploration area by 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 sulfides alone	Hydrothermalized breccia	
Quartz faults	Skarns cross cut by massive sulfides	
Quartz and calcite faults	Hornblende diorites	
Quartz, calcite and chlorite faults		
Quartz, calcite and sulfide faults		
Quartz and sulfide fault		
Aplite veins		
Unaltered skarns		

TABLE 5 Description of company C2's 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

Asbestos Bodies Counting

With regard to studies on counting for AB, 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 (e.g., optical microscopy, electron microscopy), the type of marker sought (e.g., AB or fibers), and the type of fiber concerned (see the AFSSET report[25]). 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 µ to be coated. High concentrations of AB formed on chrysotile fibers, however, can be observed in the lungs of workers with high exposure to chrysotile.

Thus, the data in the literature show the particular propensity of amphibole asbestos to form AB; in the case of exposure to chrysotile, the fibers disappear from biological environments,[28,29] meaning that the absence of asbestos bodies cannot be considered as evidence of nonexposure.

The practical aspects of quantifying asbestos fibers and AB in biological samples and interpretation of the results obtained were reviewed by several teams and consensus was reached 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, and 1,000 AB/g of dry lung tissue. Exceeding these threshold values indicates a level of retention corresponding to an exposure considered unusual for the general population.[30–34]

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, HSG248, and MP 2015 (**table 6**; see also **table 1**).

TABLE 6 Asbestiform habit of amphiboles in fibrous amphibolites

Analytical Methods	TEM		SEM			PLM on Ground Material			
Reference	MB 2015	ISO 22262-1	ISO 22262-1	EPA 1993	HSG 248	MB 2015	EPA 1993	HSG 248	ISO 22262-1
From bibliography									
(photos) Prof. E. Marcoux	Na	Na	✓	✓	✓	Na	Na	Na	Na
(photos) Dr. J. L. Boulmier	✓	✓	Na	Na	Na	Na	Na	Na	Na
Dr. F. Richard	✓	✓	Na	Na	Na	✓	✓	✓	✓
Verification of C2's model									
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	✓	✓	✓	✓
Duplicate sampling during company C2's asbestos survey									
C2-T5	✓	✓	Na	Na	Na	✓	X	✓	✓
C2-T6	✓	✓	Na	Na	Na	✓	✓	✓	✓
C2-T11	✓	✓	Na	Na	Na	✓	✓	✓	✓
C2-T13	✓	✓	Na	Na	Na	✓	✓	✓	✓

Note: ✓ = asbestiform; X = nonasbestiform; Na = not applicable.

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 (fig. 2).

Asbestos is either under the form of "slip fiber" or "cross fiber" (fig. 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 subparallel to the fault plan and the direction of movement. The fibers in the massif generally are oriented toward the largest slope of the fault plane. The shear direction cannot be determined with certainty.

Two types of fibrous amphibolite (fig. 4), are present in the mine's slip-dip faults and crack-seal veins.

The first facies is composed of dark green, multicentimeter acicular amphiboles, with a composition ranging from ferro-actinolite to iron-rich actinolite. By using a scalpel to scrape 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.

FIG. 2 (*A*) Fault containing asbestiform amphiboles, poles of dip-slip faults containing "slip fibers" of asbestos amphiboles, C1 and C2 major conjugate faults, C′1 and C′2 minor conjugate faults. (*B*) Fault containing asbestiform amphiboles, poles of crack seal vein containing amphibole asbestos "cross fibers", O1 major family, P1 minor family. Stereograms made from measurements by company C2 and the external expertise, in and outside the exploration area.

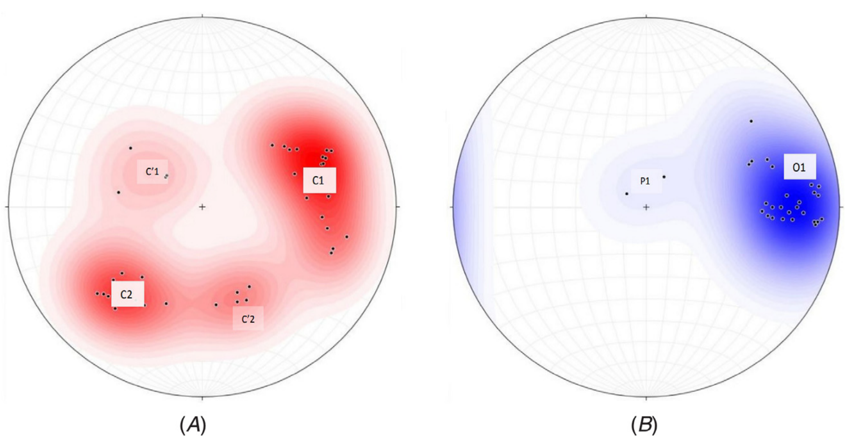


FIG. 3 (*A*) Dip-slip fault containing ferro-actinote "slip fibers" at level 1532, outside the exploration zone, the bar equals 15 cm, index 22 of company C1. (*B*) Crack-seal veins containing asbestiform actinolite cross fibers in the R1 drift of level 1230 of the exploration area.

(*A*) (*B*)

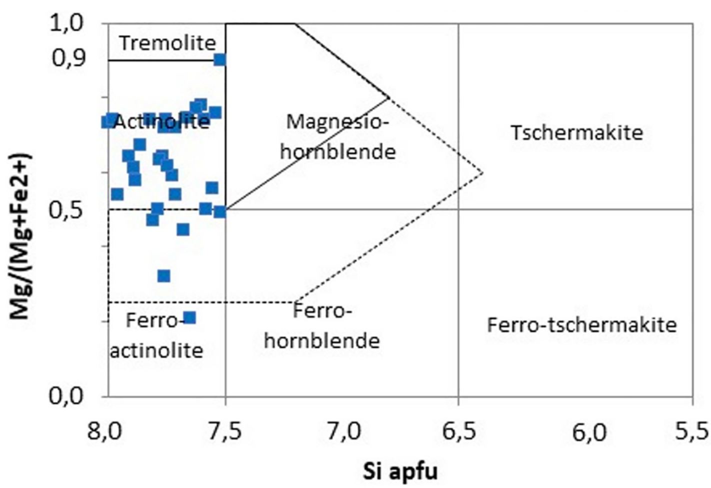
FIG. 4 (*A*) Two varieties of asbestiform amphibole, the first facies of amphibole varies in composition from ferro-actinolite to iron-rich actinolite. By scraping with a scalpel on the sides of these minerals, asbestiform fibers can come off (arrows); Bar = 0.5 mm. (*B*) Two varieties of asbestiform amphibole, the second amphibole facies is composed almost exclusively of acicular to asbestiform amphibole, the mineralogical composition of which varies from ferro-actinolite to magnesian actinolite.

(*A*) (*B*)

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-gray 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

FIG. 5 Elemental analyses obtained on asbestiform amphiboles; this Si apfu versus Mg/Mg + Fe^{2+} diagram is established from the point chemical compositions measured with an EDS. The structural formula was recalibrated by eliminating the "warnings" taking into account the measurement uncertainty for each element which was around 10%. The squares correspond to measurements made on asbestiform amphibole fibers from all fibrous rocks taken from slip-dip faults and crack-seal veins outside the exploration sector and in the exploration sector. The "undifferentiated-actinolitic-amphibole" compositional field corresponds to the field delimited by dotted lines. The calculated uncertainty is ± 2.4% on Si apfu and on Mg/Mg + Fe^{2+}.



and ferro-actinolite (table 1) without being able to differentiate them morphologically, only the optical properties and chemical data change.

As shown in figure 5, points representative of asbestiform amphibole fibers, coming from all of 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+Fe^{2+}." These fibers range from ferro-actinolite compositions to magnesium-actinolite compositions.

Dr. Richard's fibrous amphibolite samples have all the characteristics of fibers derived from asbestiform minerals (fig. 6). On the diagram "Si apfu versus Mg/Mg+Fe^{2+}" (fig. 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 and Pezerat and with the descriptions

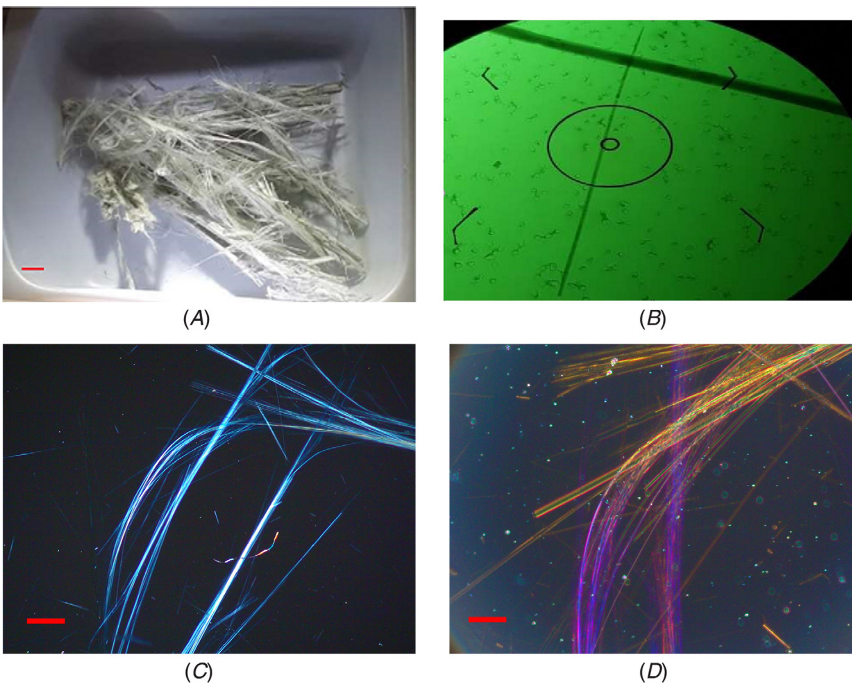
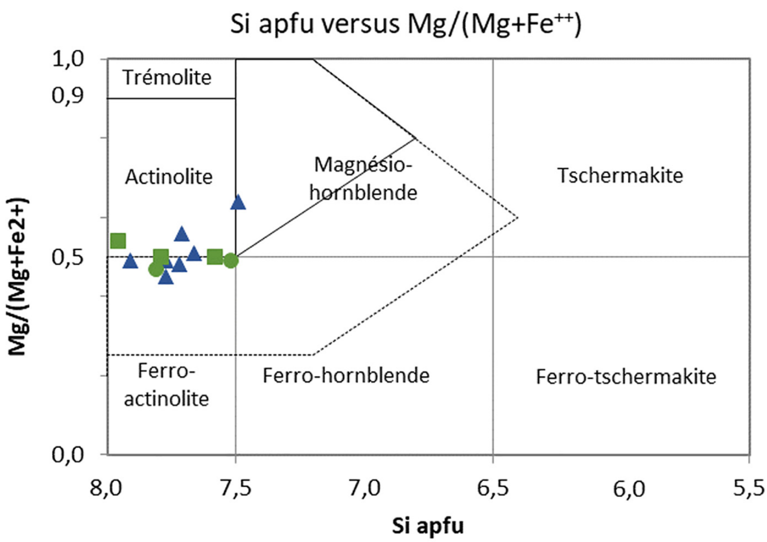


FIG. 6 (*A*) Macroscopic sample from Dr. Richard; barre = 1 cm. (*B*) Sample from Dr. Richard, TEM image, actinolite asbestos fibers, the small circle has a diameter of 0.45 μm. (*C*) Sample from Dr. Richard; PLM image in polarized and analyzed light, bar = 100 μm. (*D*) Sample from Dr. Richard; PLM image, dispersion staining color obtained with a McCrone objective and a liquid with a refractive index (RI) of 1.64; bar = 100 μm.

of Soler. In 1977, in his doctoral thesis, Soler 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."[10] Based solely on the dimensions of the thickest fibers, in his 2015 report, Marcoux came to a different conclusion.[14] In the two SEM images of his report, however, when the thinnest fibers are taken into account, we can observe the following:

- Parallel fibers with a length-to-width ratio greater than 20 and a width of about 0.2 μm;
- Bundles of fibers with splayed ends;
- Fibers that divide;
- Masses of fibers tangled with individual fibers; and
- That more than 50% of fibers greater than five microns have a length-to-width ratio greater than five.

FIG. 7 Comparison of asbestiform amphiboles from Dr. Richard's sample with those sampled in fibrous amphibolites from the mine. This Si apfu versus $Mg/Mg + Fe^{2+}$ diagram is established from the point chemical compositions measured with an EDS. The structural formula was recalibrated by eliminating the "warnings" taking into account the measurement uncertainty for each element, which was around 10%. C1-6.2, circle and C1-1, square, are samples from outcrops in the mine of fibrous amphibolites identified by C1; triangle, sample from Dr. Richard. The calculated uncertainty is ± 2.4% on Si apfu and on $Mg/Mg + Fe^{2+}$.



According to EPA1993, HSG248, and 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 asbestiform,[35] as found in the Salau mine. These minerals, except for at one point (fig. 5) remain restricted to the field of "undifferentiated-actinolite-amphibole" (see previous work[18]). Actinolite asbestos is regulated, but regulations regarding ferro-actinolite are 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 Ca_2 $(Mg, Fe^{2+})_5$ $(Si_8O_{22})(OH, F)_2$. The strict application of this structural formula allows us 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 calcium by potassium, sodium, and silicon by aluminum, chromium, iron(3+), titanium makes it possible to integrate all of the ferro-actinolites as well as all of 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 rather 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,[36,37] which identified 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 company C1 employees without being able to quantify in that proportion.

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 the geologists with external expertise was significant and this risk was not taken. Therefore, it was not possible to determine whether these were normal or reverse faults. The movements of these slip-dip faults and crack-seal veins, however, 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 massifs[38]).

The actinolite fibers in the fibrous amphibolite of the Salau mine are generally unrelated. The faults containing amphibole asbestos were identified by company C1's geologists in 1983 and allowed company C1 to estimate the amount of asbestos relative to the rock mass mined. The estimate was about 100 m^2 of panel containing asbestos over several thousand square meters. A 100 m^2 fracture area containing asbestos can release about 200 billion asbestos fibers. After reading the documents consulted in company C1'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, were captured in the mine air vent. The power to release and disseminate fibers was underestimated, especially because the regulatory limit at the time of 2 fibers/cm^3 was never exceeded in PCM dust measurements at workstations.

Company C2'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.

According to the Cesbron Report,[16] rocks containing varying proportions of prismatic to fibrous actinote amphiboles, without being asbestiform, could, after significant mechanical stress, produce mineral particles or fibers having the characteristics of regulatory asbestos (nonasbestos EMPa with a length-to-width ratio >3, width <3 μm, and length >5 μm). The genesis of these amphiboles corresponds to phenomena of alterations of pyroxenes[39] before the appearance of slip-dip faults and crack-seal veins. For Boulmier and Pezerat, these rocks also contribute to dust generation. Asbestos detection before exploration activities by company C2 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 (Marcoux[14] and D'Arco[15]) 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 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 could not be used to determine the mineral's habit. It has a very low detection limit and was not adopted by the regulations in 2003[40] or in 2019.[41] In terms of the standardization, ISO 22262-3[42] clearly specifies 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 COMPANY C1 (HISTORICAL)

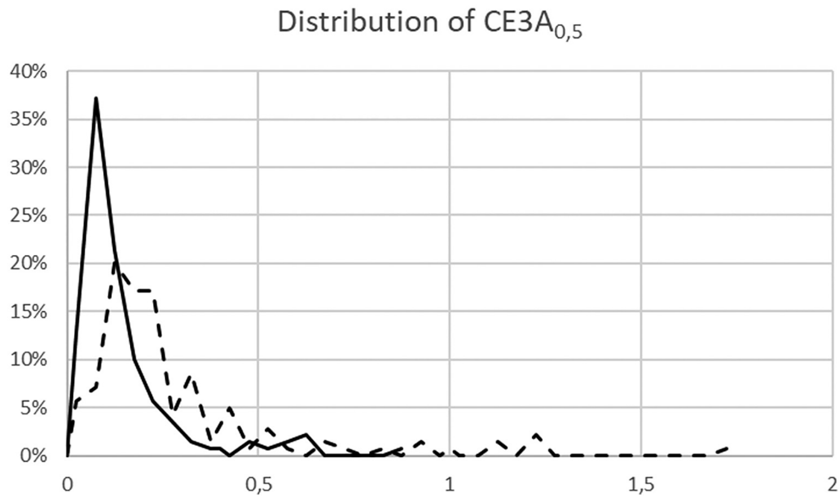
Workplace airborne fibers measurements carried out by PCM at the time of mining operations were reprocessed to estimate the concentration of actinolite asbestos (CE3A). Distribution (**fig. 8**) of these recalculated values shows the following:

- Only 5% of estimated concentrations are less than 0.010 actinolite fibers/cm^3;
- 93.6% of estimated measurements are below 0.400 actinolite fibers/cm^3;
- The remaining 6.7% measurements relate to nine measurements with an estimated concentration between 0.400 actinolite fibers/cm^3 and 0.850 actinolite fibers/cm^3, including seven performed at the crushing station, which includes the primary crusher, the console control station, the upper-level screening, and the gyratory crusher, and two at the jumbo drill; and
- A peak in estimated concentrations between 0.050 and 0.100 actinolite fibers/cm^3.

RECONSTRUCTION OF OCCUPATIONAL EXPOSURE LIMITS (HISTORICAL)

The 8-h occupational exposure limit for asbestos in France ($F.OEL_{8hours}$) is based on TEM measurements for each work process. Data from company C1'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 ($F.OEL_{8hours}$) values that could be compared with current regulatory French requirements. Distribution of these $F.OEL_{8hours}$

FIG. 8 Distribution of CE3A0.5; distribution of 140 measurements of fiber concentration measured in PCM (dotted curve) reprocessed to establish the distribution of the estimated concentration of asbestos actinolite suspended in the air (CE3A, full curve); on the *y*-axis, the percent of measurements; and on the *x*-axis, the fiber concentration per cm^3.



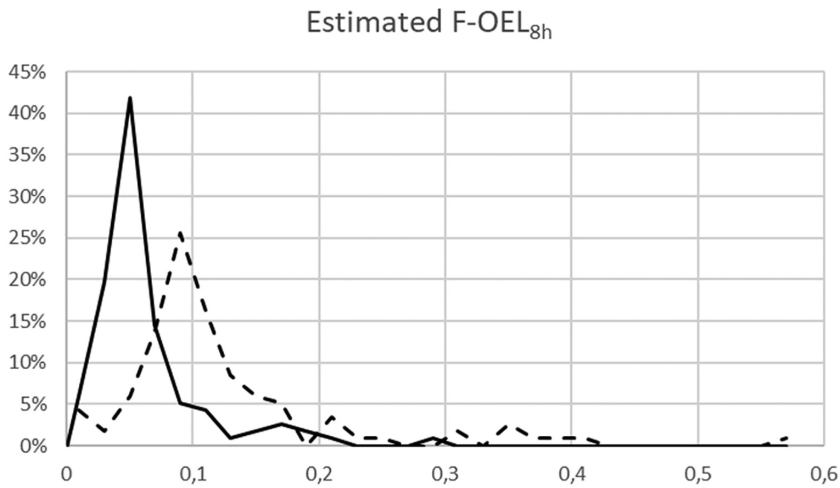
values, including the distribution of the 117 reconstituted $F.OEL_{8hours}$ (fig. 9) values, shows the following:

- 95.7% of $F.OEL_{8hours}$ values are higher than 0.010 actinolite fibers/cm^3;
- 96.6% of $F.OEL_{8hours}$ values are lower than 0.178 actinolite fibers/cm^3;
- 3.4% of $F.OEL_{8hours}$ values remaining are between 0.178 actinolite fibers/cm^3 and 0.282 actinolite fibers/cm^3 and concern the crushing station at the console control station, the upper level screening, the gyratory crusher, and a jumbo drill; and
- $F.OEL_{8hours}$ values peak with values between 0.040 and 0.060 actinolite fibers/cm^3.

SCREENING FOR ASBESTOS BODIES (HISTORICAL)

As part of the studies of employees who worked at the Salau mine, the LEPI (Laboratory for the Study of Inhaled Particles of the Department of Paris; the current name is LAFP) reference laboratory, carried out biometrological analyses screening for asbestos bodies. This laboratory is 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 or bronchoalveolar washes (BAL) from 28 patients followed mainly at the Purpan University Hospital in Toulouse between 1982 and 1991. The results

FIG. 9 Estimated $F.OEL_{8hours}$; distribution of 117, $F.OEL_{8hours}$, in actinolite asbestos fibers per cm^3 (reconstituted) full curve and in fibers (not characterized) per cm^3, dotted curve; on the *y*-axis, the percent of measurements and on the *x*-axis, the $F.OEL_{8hours}$ in f/cm^3.



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, nine were underground miners; three worked in washing or crushing; and one worked in drying, stripping, and bagging.

DISCUSSION OF EXPOSURE OF EMPLOYEES OF COMPANY C1 DURING THE OPERATION OF THE MINE (HISTORICAL)

Almost all of the miners were exposed to an $F.OEL_{8hours}$ value estimated as higher than the OEL currently in force in the regulations in France, which is 0.010 asbestos fibers/cm^3 (10 f/L). The first average occupational exposure value over 8 h adopted in 1977 was 2 f/cm^3 (2 f/mL) measured by PCM. It was lowered in 1992 to 0.600 f/cm^3 when chrysotile was the only mineral type of asbestos present and to 0.30 f/cm^3 for all other mineral types of asbestos, either isolated or mixed, including a mixture containing chrysotile. In 1996, the value for a 1-h work period was set at 0.100 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_{8hours} value not to exceed was first set at 0.100 asbestos fiber/cm^3 and then to 0.010 asbestos fiber/cm^3 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

TABLE 7 Asbestos bodies counting

Age (at First Analysis)	Number of Years at the Salau Mine (at the Date of the Analysis)	Exposure 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
56	5	Laborer muleteer			
	2	Maintenance worker			
	1	Crushing monitoring			
	6	Ore washing	ND	**3 AB/mL**	1983
	4	Discharge filtration monitoring	**4 AB**	**5.3 AB/mL**	1984
37	2	Underground miner	**1 AB**		1983
	8			ND	1984
				2 AB dans 36 mL	1986
30	7	Underground miner	**1 AB**	0.05 AB/mL	1984
51	1	Drying ovens - stripping	ND	0.45 AB/mL	1984
				0.95* AB/mL	
	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
			55 AB/56 AB		1989
?	4	Underground miner	**1 CA/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 miner	**1 AB/2AB**		1987

Note: AB = asbestosic 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).

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, AB 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 referred to actinolite as asbestos and to fibers detaching from the rock as fine asbestiform particles. The TEM analyses also referred to actinolite asbestos fibers with or without asbestiform facies. In contrast, out of the 10 TEM measurements for which actinolite asbestos was quantified, Boulmier also detected some rare chrysotile fibers on a single filter (table 8). The brake pads on mining equipment was 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 that show that asbestiform actinolite and ferro-actinolite are, or in part, the mineral agents that may have contributed to the pneumoconioses in company C1's staff. If asbestiform actinolites are the sole culprits of these diseases, this would show that $F.OEL_{8hour}$ values less than 0.015 asbestiform actinolite fibers/cm^3 can cause pneumoconiosis. The $F.OEL_{8hour}$ of 0.015 asbestiform actinolite fibers/cm^3 corresponds to the average $F.OEL_{8hour}$ estimated for the washing process. The result of the AB screening from a BAL sample of a patient who worked for 14 years in the washing station was 3.7 AB/mL. We must remain cautious of these results, however, because the monitoring did not aim to measure the highest levels.

Measurments at the Workplace During Asbestos Survey

AIRBORNE ASBESTOS MEASUREMENTS DURING VERIFICATION OF COMPANY C2'S MODEL

Measurements were carried out by the "the external expert" to assess the asbestos occurrence model in the mine, as proposed by company C2. The process that was used was the sampling of fibrous amphibolite using tweezers with moistening of the

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 and 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

material before the operation and continuous misting throughout. The airborne asbestos measurements were carried out as follows:

- by TEM on two operators during amphibolite sampling;
- by TEM on two operators during movement through the galleries; and
- with static measurements taken 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, however, and has been taken into account. The results shown in 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. For the detected ferro-actinolite asbestiform fiber, the result is given as less than 0.009 fibers ferro-actinolite asbestiform per cm^3 (<9.9 fibers/L). The detected fiber was emitted during sample collection C1-6.1 or C1-6.2.

Over 8 h, the operators completed two sessions, one of 83 min 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 $F.OEL_{8hour}$ value was less than 0.0037 asbestos fibers/cm^3.

AIRBORNE ASBESTOS MEASUREMENTS DURING ASBESTOS SURVEY BY COMPANY C2

During its asbestos survey, company C2 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 company C2's sampling by the external expert in addition to the measurements taken by company C2. No asbestos fiber was detected in the airborne asbestos measurements. The results in 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 has been confirmed. These minerals were observed in post- or late-Hercynian slip-dip faults and crack-seal veins. They minerals 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).

TABLE 9 TEM Airborne asbestos measurements carried out by external expert

No.	Type of Measurement	Sampling Date	Location and Activity	SA in Fibers/cm^3	Calculated Concentration Result in Fibers/cm^3	TEM Concentration Result in Fibers/cm^3	Fiber Type
Verification of C2's model							
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*
Duplicate air monitoring during C2's asbestos survey							
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*

Note: NAD = no asbestos detected.

Hercynian alteration of pyroxene into amphibole may be an additional potential source of EMPa. The results of the asbestos survey conducted by company C2 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 conducted in the best possible way in the phases of the project that were carried out.

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