Current Cancer Research

Joseph R. Testa *Editor*

Asbestos and Mesothelioma

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Current Cancer Research

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Springer

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ISSN 2199-2584 ISSN 2199-2592 (electronic)
Current Cancer Research
ISBN 978-3-319-53558-6 ISBN 978-3-319-53560-9 (eBook)
DOI 10.1007/978-3-319-53560-9

Library of Congress Control Number: 2017935488

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This monograph is inspired by and dedicated to patients afflicted with asbestos-related diseases, their families, medical caregivers, patient advocates, and researchers worldwide who are committed to advancing the understanding of the biological underpinnings of mesothelioma and its prevention, as well as the development of more effective therapies.
This volume is also dedicated to my wife, Priscilla, *for her unwavering support and my daughter,* Courtney, *for her indefatigable spirit and optimism about the future.*

Contents

Chapter 1
Malignant Mesothelioma: An Asbestos Legacy

Joseph R. Testa

Abstract With the advent of the industrial age, asbestos' unique properties, including its resistance to fire, tensile strength, softness and flexibility, resulted in its widespread commercial use. Decades later, its usage was shown to have tragic medical consequences, as these fibrous minerals became causally linked to malignant mesothelioma and other debilitating diseases. Malignant mesotheliomas are aggressive tumors that arise from serous membranes, such as the pleura and the peritoneum. Mesothelioma has a dismal prognosis due to its inherent chemo- and radio-resistance as well as to the general ineffectiveness of surgical intervention. Mesotheliomas account for approximately 3200 deaths per year in the USA, with more than 450,000 deaths predicted over the next 40 years in the USA, Europe, Australia, and Japan. Legal compensation alone is projected to amount to hundreds of billions of dollars worldwide over this time span, and this already enormous figure does not include health care costs. Currently, about 125 million people worldwide are exposed to asbestos in the workplace. Given such continued exposure to asbestos fibers, there is thus great public, medical, and legal interest in this malignancy. This introduction provides a general overview of the mesothelioma burden and a brief outline about the contents of this monograph, which includes a multidisciplinary assessment of the characteristics of asbestos along with the epidemiology, cell biology, pathology, and treatment of mesothelioma. Psychological aspects and legal challenges facing mesothelioma patients and their families are also presented.

Keywords History of asbestos usage • Health effects of asbestos • Malignant mesothelioma • Mesothelioma epidemiology • Pathology and treatment • Mesothelioma cell biology and genetics • Germline and somatic mutations • Rodent models of mesothelioma • Psychological and legal issues

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J.R. Testa (ed.), *Asbestos and Mesothelioma*, Current Cancer Research,
DOI 10.1007/978-3-319-53560-9_1

1.1 Asbestos Usage Over the Years

Asbestos refers to a family of six silicate minerals that contain silicon and oxygen embodied as fibrous aggregates of long, thin crystals that can readily separate. Among its remarkably useful attributes are its resistance to fire, tensile strength, flexibility, softness, and affordability, with early usage of asbestos dating back at least two millennia. In their fascinating historical account of the ups-and-downs of asbestos' past, Alleman and Mossman alluded to the irony of the asbestos tragedy, i.e., that the medical catastrophe would never have become so severe had the industrial world not previously found the substance to be so valuable commercially (Alleman and Mossman 1997).

Over the years, asbestos has been used to weave cloaks, tablecloths, theater curtains, and flameproof suits for shielding against fires. Other everyday uses have included automobile brake shoes, air filters for military gas masks, hospital ventilators, and even cigarette filters. Mixed with rubber, asbestos permitted the development of durable steam engine components, such as steam gaskets. When melded into tar, burlap, and paper, asbestos fibers provided fire-resistant roofing material, thereby opening up a vast industry of asbestos-based construction products. Mixtures of asbestos and cement were heavily used for paneling in buildings and ships, as well as for pipes and synthetic slate roof shingles. When mixed with plastic, asbestos was used in everything from electrical boards to telephones, and vinyl-asbestos tiles became paramount in the flooring industry, including in schools. In skyscrapers, spray-on asbestos coating was used to protect steel structures against fire-induced buckling (Alleman and Mossman 1997).

1.2 Malignant Mesothelioma and Other Health Effects of Asbestos

In a seminal report published in 1960, Wagner and colleagues provided conclusive epidemiological evidence linking asbestos to malignant mesothelioma in individuals living and/or working in a crocidolite asbestos mining area of South Africa (Wagner et al. 1960). Malignant mesotheliomas are tumors derived from mesothelial cells that form the serosal membranes lining the chest and abdomen. Most mesotheliomas are highly aggressive neoplasms that have a median survival of about 9 months from the time of diagnosis. The incidence of malignant mesothelioma is several-fold higher in men than in women and is often diagnosed during the seventh and eighth decades of life, typically 20–50 years after initial exposure to asbestos. Mesothelioma currently accounts for 3200 deaths per year in the USA and about 5000 deaths in Western Europe (Henley et al. 2013; Ismail-khan et al. 2006).

In the late 1990s, it was estimated that 20% of homes and commercial buildings in the USA still contained products, e.g., shingles, cement pipes, and insulation, made from chrysotile asbestos (Alleman and Mossman 1997). Deaths due to mesothelioma

are expected to increase by 5–10% per year in most industrialized countries until about 2020, and asbestos has also been shown to cause asbestosis, pleural fibrosis/plaques, as well as lung and laryngeal cancer (Carbone et al. 2012). Notably, the incidence of mesothelioma has continued to increase despite various measures implemented in the 1970s and 1980s to reduce (U.S.) or eliminate (countries of the European Union) the use of products containing asbestos.

Both epidemiological studies and experimental work performed in vitro and in rodents have shown a strong link between mesothelioma and exposure to crocidolite asbestos, a needlelike (amphibole) form of asbestos, and erionite, a needlelike type of zeolite. Other forms of amphibole asbestos, such as tremolite, have also been associated with the development of mesothelioma, although the risk appears to be lower than for crocidolite fibers. Whether other amphibole types or the serpentine (snakelike) asbestos fiber, chrysotile, causes mesothelioma is still debated; however, the World Health Organization's International Agency for Research on Cancer (IARC) has concluded that all forms of asbestos can cause mesothelioma (IARC 2009; http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-11.pdf).

Given that asbestos is virtually an inescapable carcinogen in industrialized societies, almost everyone may have some level of exposure. Although it has been hypothesized that there is a threshold level of exposure above which risk of developing mesothelioma increases significantly, the threshold is unknown, and individual genetic susceptibility likely influences this threshold (Testa and Carbone 2016). There does not appear to be a linear dose-response relationship between asbestos exposure and development of mesothelioma, and in addition to genetic differences, tumor risk may depend on the type of mineral fiber inhaled and exposure to certain cofactors.

Interestingly, while billions of dollars per year are spent on asbestos-related litigation and asbestos abatement, progress in understanding mesothelioma pathogenesis has been hampered by limited research funding—due in part to its lower incidence than other types of cancer, such as lung and breast carcinomas, but also because of the mistaken belief by some that the disease is disappearing. In fact, the incidence of mesothelioma in the USA has remained constant since the mid-1990s. Alarmingly, in countries that produce and/or are expanding their use of asbestos, including India, China, Russia, Zambia, Colombia, and Kazakhstan, a surge in disease incidence is expected to occur in these countries (see Chap. 4 by Røe and Stella in this volume), particularly in countries such as India, where little or no precautions are being taken to prevent exposure of workers (Burki 2010). In Western countries, exposure to high levels of asbestos in the workplace has been largely abolished, but the number of workers exposed to low, but above-background, levels of asbestos has increased; furthermore, use of asbestos in some products continues in the USA (Carbone et al. 2012).

In addition to mesothelioma, asbestos was shown to act as a carcinogen in lung carcinoma, and the combination of cigarette smoking and asbestos greatly increased the risk of lung cancer (Barrett et al. 1989). Moreover, inhalation of asbestos fibers was also found to induce other occupational lung diseases, including benign pleural plaques as well as two potentially deadly diseases: asbestosis, marked by chronic

inflammation and scarring of the lungs, and a form of pneumoconiosis, a respiratory disease that restricts lung expansion. More recently, a comprehensive review by the IARC determined that there is *sufficient evidence* for the carcinogenicity of all forms of asbestos (chrysotile, crocidolite, amosite, tremolite, actinolite, and anthophyllite) and that exposure to asbestos can cause not only mesothelioma and lung cancer, but also cancer of the larynx (IARC 2009; http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-11.pdf). Additionally, IARC noted that positive associations have been observed between exposure to asbestos and cancers of the ovary and stomach.

Since asbestos has been shown to be the major cause of mesothelioma, with a history of asbestos exposure being documented in about 80% of individuals diagnosed with the pleural form of the tumor (Robinson and Lake 2005), and since no safe lower threshold of exposure has been identified, asbestos products have been banned in all the countries of the European Union, beginning January 1, 2005 (http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-11.pdf; EU 1999). Moreover, in addition to those exposed occupationally, family members can be at risk, e.g., as a result of washing contaminated work clothes, or simply by living in proximity to mining or asbestos cement processing factories (Magnani et al. 2001; Musti et al. 2009).

Patients with peritoneal mesothelioma, which comprise approximately 20% of all cases, tend to be younger than patients with pleural mesothelioma; moreover, a higher proportion of peritoneal mesothelioma cases, mostly women, are long-term survivors (Kindler 2013). Among patients eligible for surgery, a locoregional approach consisting of cytoreductive surgery and perioperative intraperitoneal chemotherapy—introduced over the last decade—achieved an overall 5-year survival rate of 30–60% (Mirarabshahii et al. 2012). Malignant pleural mesothelioma, on the other hand, is almost uniformly resistant to treatment. Cancer-directed surgery for malignant pleural mesothelioma is associated with a 5-year survival rate of only 15% (Wolf and Flores 2016), and chemotherapy-naive patients who were not eligible for curative surgery had a median survival of only about 12 months when treated with pemetrexed plus cisplatin, the current standard chemotherapeutic regimen (Vogelzang et al. 2003).

1.3 Outline of Monograph Contents

To understand how clinical outcomes may be improved in the future, it is necessary to better comprehend the biology of the disease. In recognition of the continuing global use of asbestos and its deadly legacy, this volume includes reviews on the various forms of asbestos and their relative carcinogenic potential, the epidemiology and biology of mesothelioma, and the current therapeutic options for this aggressive, therapy-resistant malignancy. In Chap. 2, Wylie describes the physical and chemical attributes of a group of very narrow fibrils that form bundles of parallel fibers characteristic of the “asbestiform habit.” Included in this chapter are

numerous photographs of the various types of asbestiform amphiboles, such as crocidolite, as well as the serpentine group of minerals that include chrysotile, the most widely used type of asbestos. Erionite, a fibrous zeolite, is also discussed.

Chapters 3, 4, and 5 discuss various aspects of the epidemiology of malignant mesothelioma, particularly in connection with exposure to asbestos or erionite. In addition to asbestos and other carcinogenic mineral fibers, Moolgavkar and coworkers point out that there is evidence for idiopathic mesotheliomas, i.e., those that arise spontaneously or from an obscure or unknown cause, as well as for other contributing factors, including germline and acquired, age-related gene mutations. Other risk factors, such as ionizing radiation, and the impact of non-occupational low levels of fiber exposure are also reviewed. Røe and Stella review the history of asbestos usage and its connection with mesothelioma causation as well as current unresolved questions and controversies regarding the epidemiology and biology of this dreaded disease. Additionally, these authors review recent studies indicating that man-made carbon nanofibers could pose dangers similar to those of asbestos in the coming years, and thus they urge regulatory bodies to be proactive in ensuring thorough evaluation of novel substances before commercial use. Emmett and Cakouros describe a diverse group of communities that have a high incidence of malignant mesothelioma and other asbestos-related diseases. They highlight lessons from communities where there is an elevated risk of mesothelioma due to asbestos mining, processing, and manufacturing as well as regions such as Cappadocia, Turkey, where asbestiform erionite occurs naturally in the local environment. They also describe a wide assortment of issues, including shortcomings in the regulatory definition of asbestos, diffuse administrative responsibilities, diverse community attitudes about disease risk and prevention, as well as difficulties in quantifying exposures and justifying remediation actions.

In Chap. 6, Pavlisko et al. describe in detail the gross pathology of mesothelioma arising from pleura, peritoneum, pericardium, and the tunica vaginalis. The authors provide an overview of the histomorphologic growth patterns, ranging from epithelioid to sarcomatoid, and discuss the importance of immunohistochemical stains in helping to assure the diagnosis of malignant mesothelioma. They also review the value of BAP1 immunohistochemistry together with fluorescence in situ hybridization for detection of homozygous loss of the gene encoding p16INK4A in distinguishing benign/reactive from malignant mesothelial proliferations.

Chapters 7, 8, 9, 10, and 11 present overviews of various biological processes important in the development and progression of malignant mesothelioma. Thompson and Shukla review the role of asbestos-induced inflammation in mesothelioma, fibrosis, and other lung diseases. They discuss the possibility that early inflammatory gene "signatures" might be exploited as novel predictive biomarkers and therapeutic targets to aid in early diagnosis and treatment of mesothelioma, respectively. Cheung and colleagues highlight our current understanding of the role of both germline and acquired (somatic) mutations in human malignant mesothelioma, as well as lessons learned from experimental studies of asbestos-exposed rodent models of mesothelioma. The authors review the body of literature about relevant genes, particularly the tumor suppressor genes *BAP1*, *CDKN2A* and *NF2*,

which are frequently mutated somatically in human mesotheliomas and may serve as "drivers" of this lethal disease. They also explore recent research about familial risk of mesothelioma due to germline mutation of *BAP1* and potentially other genetic factors that may play a role in tumor predisposition (Testa et al. 2011). Evidence for gene–environment interaction, i.e., the convergence of germline *BAP1* mutation and exposure to asbestos fibers in the same individual, is also highlighted. De Rienzo et al. discuss recent efforts to discover gene signatures that might hold promise for personalized therapeutic decisions, with the goal of improving clinical outcome in patients with mesothelioma. They summarize findings using several different technologies such as sequencing, expression, and methylation arrays, and they discuss current challenges, including the need for large-scale validation before gene signatures can be implemented into the clinic. Mossman provides an overview of cell signaling and epigenetic mechanisms critically involved in the transformation of a mesothelial cell into a malignant mesothelioma. She reviews integrated genomic and proteomic analyses of mesothelioma, which have uncovered recurrent activation of multiple cell signaling cascades and transcription factors, as well as epigenetic mechanisms, with an emphasis on research that links such changes to key cell survival and proliferative pathways in tumor formation. Broaddus and coworkers discuss the value of three-dimensional, multicellular spheroid models for investigating mechanisms of cell survival in mesothelioma. They highlight areas in which in vitro multicellular spheroids and ex vivo tumor fragment spheroids have advanced the understanding of mesothelioma cell survival and other processes. As compared to conventional two-dimensional (monolayer) cultures, their findings with spheroid models appear to more closely mimic the therapeutic response in the actual tumor and could offer novel insights that can be subsequently tested in the clinic.

The review by Mesaros et al. (Chap. 12) focuses on recent advances in the identification of biomarkers of response to asbestos exposure, with the ultimate goal being to promote early diagnosis and timely clinical intervention. They evaluate various potential biomarkers of response to asbestos exposure, including the High Mobility Group Box 1 (HMGB1) protein, which has a regulatory role in inflammatory immune responses. Preliminary work has revealed that increased nonacetylated HMGB1 in serum may serve as a biomarker of asbestos exposure, whereas acetylated serum HMBG1 was associated with progression to mesothelioma. The potential merit of combined use of a multiplexed serum lipid biomarker panel with serum protein biomarkers is also discussed.

Chapters 13, 14, 15, and 16 contain comprehensive overviews of state-of-the-art therapies for mesothelioma. Wolf and Flores describe current surgical approaches for mesothelioma. They point out that although the role of surgical resection in malignant pleural mesothelioma is controversial, surgery has yielded long-term survivors, with a 15% 5-year survival in eligible patients. The authors summarize preoperative, perioperative, and postoperative management of mesothelioma patients as well as results of studies evaluating the two operations developed for surgical resection, extrapleural pneumonectomy and radical or extended pleurectomy/decortication (P/D), with the authors advocating the better tolerated P/D procedure for

most pleural mesothelioma patients. Simone et al. discuss the role of both technologically sophisticated ionizing radiotherapy and non-ionizing radiotherapy (photodynamic therapy—a procedure that combines a photosensitizer, light, and oxygen) in both the palliative and definitive treatment of pleural mesothelioma, particularly in providing durable local control. The authors outline the mechanistic and logistical basics of radio- and photodynamic therapies and their use in the multidisciplinary care of mesothelioma patients. They also discuss the potential for future improvements in the use of these therapies. Zauderer summarizes standard chemotherapeutic approaches as well as clinical trials of novel molecularly targeted agents for malignant mesothelioma. She reviews challenges in conducting large randomized clinical trials in mesothelioma, including the scarcity and geographic distribution of patients, the intrinsic chemoresistance of the malignancy, as well as the limited interest and modest financial support from pharmaceutical companies and various funding agencies. Despite these drawbacks, standard cytotoxic chemotherapeutic regimens have been established, and clinical trials with multiple novel agents are ongoing. Thomas et al. review immunotherapeutic strategies to inhibit immune checkpoints and their ligands in mesothelioma. Furthest along currently are clinical investigations of the tumor differentiation antigen mesothelin, with immunotherapies developed that include immunotoxin, tumor vaccine, chimeric antigen receptor T cell, and antibody-based approaches. The authors also describe current work aimed at understanding the antitumor responses to immune-based approaches and ways to identify prospectively those patients most likely to respond to immunotherapy.

In addition to understanding the etiology, biology, and treatment of mesothelioma from a scientific and medical perspective, understanding the disease from the vantage point of the patient is critical. Thus, the final section of this volume focuses on the patient experience. Mesothelioma patients face enormous medical, stress-related, and financial challenges as emphasized in Chaps. 17 and 18. Hartley and Hesdorffer present an overview of medical and legal aspects of the disease, in particular lawsuits intended to seek compensation for patients who develop a mesothelioma potentially caused by exposure to asbestos fibers. Factors to consider when seeking legal advice—and the qualifications of prospective law firms—are presented. Pretrial discovery processes are discussed in detail, including possible requests for genetic testing to determine if an underlying heritable factor may have contributed to development of the disease. The authors also summarize new developments at the intersections between medicine and law, i.e., the possible use of molecular biomarkers, as well as genetic and epigenetic signatures, as potential indicators of asbestos exposure. Buchholz provides a compassionate overview of the complex experience of the mesothelioma patient. He delves into the psychological, sociological, and communicative elements of the individual patient's experience, with the aim being to help medical caregivers comprehend and better respond to that experience. Through interesting case studies, the author illustrates that mesothelioma patients are under great stress that is often unrecognized, but which may be alleviated, at least in part, when the nature of suffering is identified and integrated into a comprehensive treatment strategy.

Finally, the Editor thanks all of the chapter authors for their invaluable contributions to this volume on asbestos and mesothelioma. In the interest of transparency, the publisher has requested that all authors include a brief conflict of interest statement, because a diagnosis of mesothelioma often results in litigation, and many investigators are consulted about matters concerning disease causation—often with very different perspectives on such issues. In any case, the views and opinions expressed by authors of individual chapters do not necessarily reflect those of the Editor.

Acknowledgements The Editor is grateful to the many talented laboratory colleagues and collaborators he has been privileged to work with over the years in a collective effort to unravel the pathogenesis of mesothelioma. He gives special thanks to Fox Chase Cancer Center, NIH, and the Local #14 of the International Association of Heat and Frost Insulators and Allied Workers for their sustained financial support over the last three decades.

References

Alleman JE, Mossman BT (1997) Asbestos revisited. Sci Am 277:70–75

Barrett JC, Lamb PW, Wiseman RW (1989) Multiple mechanisms for the carcinogenic effects of asbestos and other mineral fibers. Environ Health Perspect 81:81–89.

Burki T (2010) Health experts concerned over India's asbestos industry. Lancet 375:626–627

Carbone C, Ly BH, Dodson RF et al (2012) Malignant mesothelioma: facts, myths and hypotheses. J Cell Physiol 227:44–58

Henley SJ, Larson TC, Wu M et al (2013) Mesothelioma incidence in 50 states and the district of Columbia, U.S., 2003–2008. Int J Occup Environ Health 19:1–10

International Agency for Research on Cancer (2009) Chrysolite, amosite, crocidolite, tremolite, actinolite, and anthophyllite. In: IARC monographs. arsenic, metals, fibres and dusts. International Agency for Research on Cancer, Lyon, pp 147–167

Ismail-Khan R, Robinson LA, Williams CC Jr et al (2006) Malignant pleural mesothelioma: a comprehensive review. Cancer Control 13:255–263

Kindler HL (2013) Peritoneal mesothelioma: the site of origin matters. Am Soc Clin Oncol Educ Book 33:182–188

Magnani C, Dalmasso P, Biggeri A et al (2001) Increased risk of malignant mesothelioma of the pleura after residential or domestic exposure to asbestos: a case-control study in Casale Monferrato, Italy. Environ Health Perspect 109:915–919

Mirarabshahii P, Pillai K, Chua TC et al (2012) Diffuse malignant peritoneal mesothelioma—an update on treatment. Cancer Treat Rev 38:605–612

Musti M, Pollice A, Cavone D et al (2009) The relationship between malignant mesothelioma and an asbestos cement plant environmental risk: a spatial case-control study in the city of Bari (Italy). Int Arch Occup Environ Health 82:489–497

Robinson BW, Lake RA (2005) Advances in malignant mesothelioma. N Engl J Med 353:1591–1603

Testa JR, Cheung M, Pei J et al (2011) Germline BAP1 mutations predispose to malignant mesothelioma. Nat Genet 43:1022–1025

Testa JR, Carbone M (2016) Mesothelioma. In: Schwab M (ed) Encyclopedia of cancer, 3rd edn. Springer, Heidelberg

Vogelzang N, Rusthoven JJ, Symanowski J et al (2003) Phase III study of pemetrexed in combination with cisplatin versus cisplatin alone in patients with malignant pleural mesothelioma. J Clin Oncol 21:2636–2644

Wagner JC, Sleggs CA, Marchand P (1960) Diffuse pleural mesothelioma and asbestos exposure in the North Western Cape province. Br J Ind Med 17:260–271

Wolf AS, Flores RM (2016) Current treatment of mesothelioma: extrapleural pneumonectomy versus pleurectomy/decortication. Thorac Surg Clin 26:359–375

Chapter 2
Asbestos and Fibrous Erionite

Ann G. Wylie

Abstract Very narrow fibrils forming bundles of parallel fibers characterize the asbestiform habit. The width of fibrils varies among asbestos types and among occurrences of the same type. The known asbestiform amphiboles have the composition of anthophyllite, tremolite-actinolite-ferroactinolite (prieskaite), cummingtonite-grunerite (amosite and montasite), magnesioarfvedsonite-arfedsonite, magnesioriebeckite-riebeckite (crocidolite), winchite (Libby amphibole), richterite, and fluoro-edenite-edenite. Amphiboles are common rock-forming minerals that normally occur in a prismatic or massive habit and are not asbestos. The most widely exploited type of asbestos is chrysotile, a member of the serpentine group of minerals. Erionite is a fibrous zeolite; when asbestiform, it is called woolly erionite. This chapter describes the characteristics of these minerals as they occur in an asbestiform habit.

Keywords Asbestos • Tremolite-asbestos • Actinolite-asbestos • Ferroactinolite-asbestos • Anthophyllite-asbestos • Amosite • Crocidolite • Edenite-asbestos • Winchite-asbestos • Richterite-asbestos • Chrysotile-asbestos • Woolly erionite

2.1 Introduction

Asbestos is a naturally occurring, heat-resistant, and chemically inert silicate material that can be readily separated into long, thin, strong fibers with sufficient flexibility to be woven. It may be formed from a number of different minerals that belong to the amphibole or serpentine mineral groups. For thousands of years, the unique properties of asbestos have made it a valuable commodity that has found applications in ceramics, whitewash, paint, fireproof fabrics, reinforced cement, insulation, brake pads, filters, and roofing tiles.

The author has served as a consultant on mineral occurrence, identification, and characterization.

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J.R. Testa (ed.), *Asbestos and Mesothelioma*, Current Cancer Research,
DOI 10.1007/978-3-319-53560-9_2

In the mid-twentieth century, it became clear that the inhalation of asbestos and asbestiform erionite could induce mesothelioma, stimulating extensive research into their physical and chemical characteristics and occurrences in nature. The research focused on relationships between the association of elevated levels of mesothelioma and (1) the size of fibers in the dust cloud, (2) mineral make-up of the fibers, including mineral alterations, intergrowths, and impurities, (3) the biodurability of the various fibers, (4) surface chemistry, particularly iron content, (5) surface area, and (6) reactivity in vivo. The research has demonstrated that all these characteristics can affect mesotheliomagenicity and that there is considerable variation in carcinogenic potential among asbestiform minerals.

While asbestos and erionite with asbestos-like dimensions are relatively rare, the minerals that form them exist most commonly in a form that is not asbestos. They are common rock-forming minerals and may also be found in soils. Amphiboles and serpentine are found in 6–10% of the land area of the USA and are probably similarly common elsewhere in the world (Wylie and Candela 2015). Erionite is found in geological environments that are common in the western USA and elsewhere; it is only rarely asbestiform (Van Gosen et al. 2013). When disturbed by recreational activities, mining, and excavation for road and building construction, both fragments and fibers of these minerals may become airborne. This chapter will describe the mineralogical characteristics thought to have relevance to biological activity of the major occurrences of commercially exploited amphibole- and serpentine-asbestos, of asbestiform erionite, and of unexploited naturally occurring asbestos and erionite.

2.2 Discussion of Terminology

In modern usage, *asbestos* is applied to a set of minerals from the amphibole and serpentine silicate mineral groups that were mined during the twentieth century and sold as asbestos. The term is also used for asbestiform amphibole that has not been exploited commercially, but is identified as asbestos because of its similarity in habit to commercially exploited asbestos. This would include, for example, the Na-Ca amphiboles that make up the asbestos gangue in the vermiculite deposit at Libby, Montana, some standard reference samples of asbestos, and many museum samples.

The formation of friable mineral fiber is restricted to particular physical and chemical conditions that are limited in their geographical extent. A discussion of geologic occurrences of asbestos in the USA has been provided by Van Gosen (2007). Rock must have been of the appropriate composition and subsequently altered by hot water-rich fluids, dissolving the mineral components until changing conditions resulted in crystallization of secondary minerals in a fibrous form. The *asbestiform habit* describes flexible mineral fibers, formed from parallel or nearly parallel bundles of very thin single crystals, called *fibrils* that are not otherwise regularly aligned. In asbestos, fibrils range in width from about 0.01 to about 0.5 μm. These very small fibrils give a silky luster to asbestos. Fibrils combine to

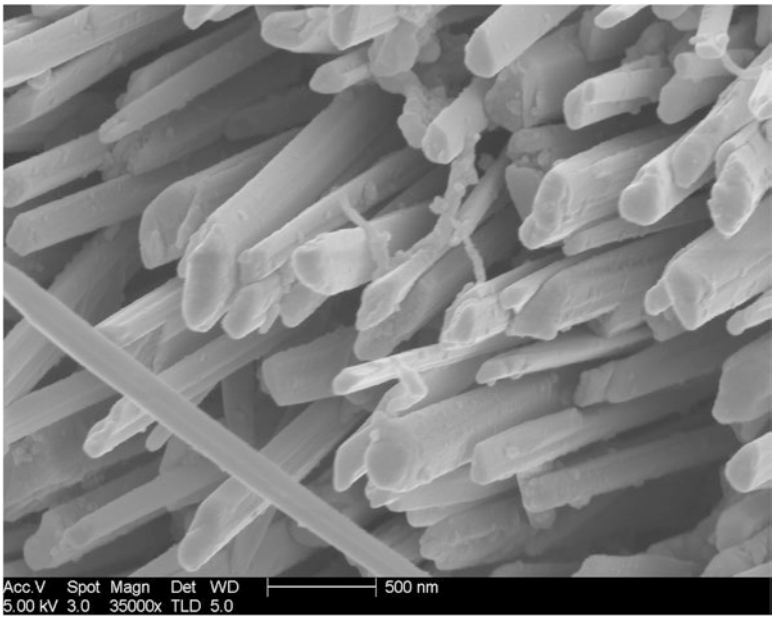

Fig. 2.1 Field emission scanning electron microscopy (FESEM) micrograph of fibril bundle of tremolite-asbestos from North Carolina. Note typical irregularity of the cross section. Photo courtesy R.J. Lee Group

form *fibers* (Fig. 2.1). Asbestos and asbestiform erionite fibers are easily separable with hand pressure, but the ease of *disaggregation* or *separation* into individual fibrils varies among occurrences (Fig. 2.1).

Glassy, brittle fibrils, with width of about 0.5–10 μm or more may accompany asbestos and asbestiform-erionite, or may occur separately. Such glassy brittle fibers of amphibole are referred to as *byssolite* and brittle fibers of serpentine are sometimes referred to as *picrolite* (Fig. 2.2).

In the USA, *regulatory criteria* for counting airborne particles as "fibers" during exposure monitoring are: (1) longer than 5 μm, (2) an aspect ratio of at least 3:1, and (3) visible by optical microscopy. Some portion of a population of airborne asbestos fibers will meet these criteria, but a large portion is below the resolution of the light microscopy (≈0.25 μm) or is ≤5 μm in length. A portion of airborne fragmented amphibole, erionite and serpentine particles will also meet these criteria. The National Institute of Occupational Safety and Health has recently clarified that what is being measured are optically visible *Elongated Mineral Particles* (EMP), which are not necessarily fibers in the mineralogical sense (NIOSH 2011). An *EMP* is, therefore, any particle with a length to width ratio of at least 3:1 whether it is a fiber or fragment; for purposes of occupational exposure monitoring, EMPs must be >5 μm.

In this chapter, the term "*fiber*" means an EMP that is a single or twinned crystal bounded by growth surfaces or *crystal faces* (a fibril) or a bundle of such crystals (*fiber bundle*). The term "*fragment*" applies to a particle that is bounded by broken

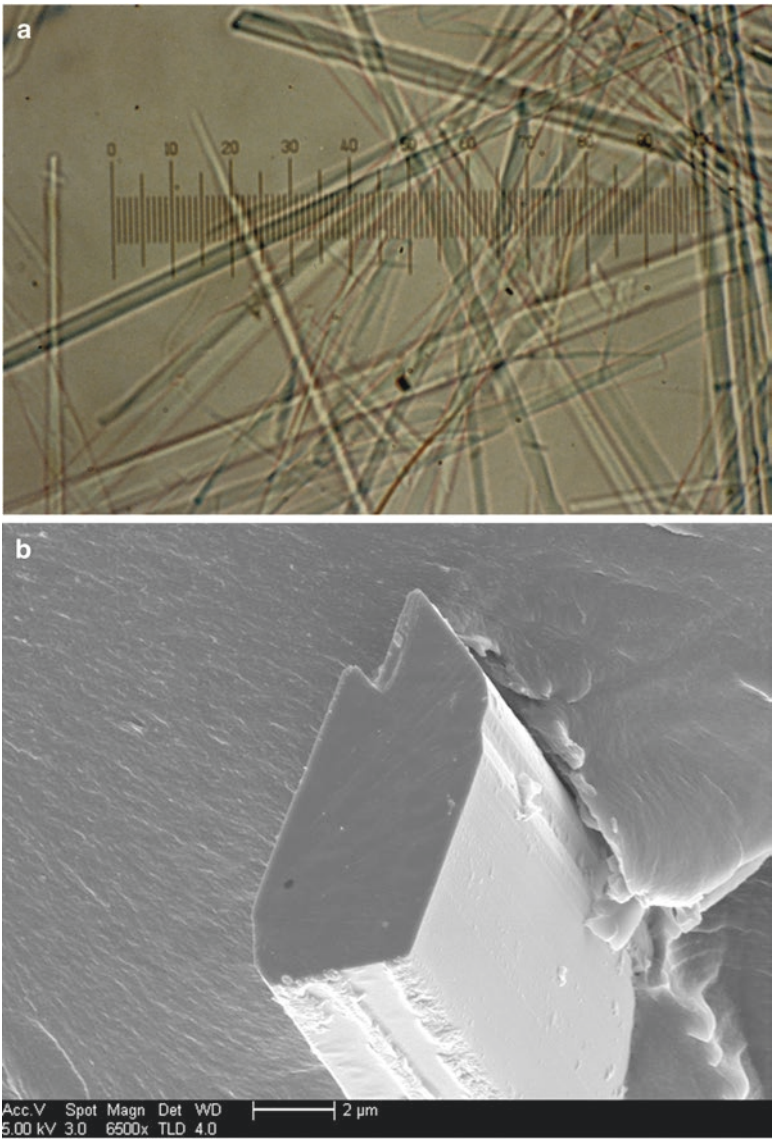

Fig. 2.2 Micrographs of actinolitic byssolite fibers from Austria. **(a)** Photograph of fiber sizes (smallest scale division = 2 µm). **(b)** FESEM micrograph of single fiber (Courtesy R.J. Lee Group). The largest prismatic surfaces that flatten the fiber are {100}

surfaces, originating when rock or brittle fiber is crushed. Fragments may be shaped by geometrically related planes if they possess *cleavage*, defined as the regular way a mineral breaks. Cleavage planes are planes of weakness within the ordered atomic structure of a mineral. In amphiboles, perfect *cleavage* in two directions forms prismatic EMPs, called *cleavage fragments*. Because cleavage arises from weak

structural bonds, the potential for cleavage is the same in every sample of a given mineral. *Parting* resembles cleavage, but the planes of weakness arise from structural defects or inclusions, which are not necessarily present in every sample.

2.3 Amphiboles

There are many *amphibole* minerals, but all are built on double chains of Si_4O_{11} groups linked to each other by a variety of cations. Amphiboles occur in one of two crystal systems: monoclinic and orthorhombic. For both, modern nomenclature is based on the atomic proportions of the major elements assigned to the A, B, C, and T structural sites, following the rules of Leake et al. (1997, 2004) and Hawthorne et al. (2012). The general formula for amphibole is: $AB_2C_5T_8O_{22}(OH)_2$ where A = □,[1] Na, K; B = Na, Ca, Mg, Fe2+, Mn2+ Li and rarer ions of similar size; C = Mg, $Fe^{2+,}$ Mn^{2+}, Li, Fe^{3+}, Al, Mn^{3+} Cr^{3+}, Zr^{4+}, Ti^{4+}; T = Si, Al, Ti^{4+}; and (OH) may be replaced by F, Cl, and O. The A-site is in 10–12-fold coordination, the B- and C-sites are octahedrally coordinated, and the T-site is tetrahedrally coordinated. The structure of amphibole suggests that the A-, B-, and T-sites come in contact with bodily fluids, which would have only limited access to C cations. For this reason, the amphibole formulae in this chapter are written to make the distinctions between A, B, C, and T.

Other systems of nomenclature have been used in the past. The earliest relied primarily on optical properties. Despite changes, there is general agreement among all nomenclature systems used for the last 50 years, although there are notable exceptions, such as the nomenclature of Na-Ca amphiboles, the chemical boundary between tremolite and actinolite, and the nomenclature within the large group of amphiboles generally known as hornblende. Because nomenclature is now strictly tied to crystal system and chemical composition, it may be useful to refer to amphibole-asbestos within solid solutions as, for example, tremolitic-asbestos instead of tremolite-asbestos or actinolitic-asbestos instead of actinolite-asbestos when the exact composition is inferred from qualitative or semi-quantitative chemical analyses or optical properties.

Amphibole minerals and mineral solid solutions known to have formed asbestos are: magnesioriebeckite-riebeckite (crocidolite), cummingtonite-grunerite (amosite and montasite), magnesioarfvedsonite, tremolite-actinolite-ferroactinolite, winchite, richterite, fluoro-edenite-edenite, and anthophyllite. Sometimes, dynamic physical and chemical conditions result in the formation of fibers with several amphibole compositions from the same location. For example, at Libby, MT, and Biancaville, Italy, winchite-asbestos, richterite-asbestos, tremolite-asbestos and edenite-asbestos have been reported (Meeker et al. 2003; Gianfagna et al. 2007). Actinolite-asbestos and crocidolite occur together in South Africa.

Not all amphibole compositions can form asbestos. In particular, Al substitution for Si in the T-site >0.5 atoms per formula unit (apfu) appears to limit the development

[1] $A_□$ means the structural site A is empty.

of the asbestiform habit. The highest ^{T}Al is found in the fluoroedenite-asbestos fibers from Sicily, a region of active volcanism and high heat flow. The generally low ^{T}Al in asbestos is likely due to the requirement of a temperature for its incorporation into the structure higher than is common in most environments where asbestos forms (Dorling and Zussman 1987).

Amphiboles are well studied, and much is known about their occurrences and the natural variability they show in chemical composition and atomic structure. The optical properties of the common amphiboles are also well known. The reader is referred to major reference works for detailed discussions. These include Hawthorne et al. (2007), Guthrie and Mossman (1993), and Deer et al. (1997).

2.4 Amphibole Fibers and Fragments

Fibers form in open, often fluid-filled spaces or from hydrothermal alteration of preexisting material in low-pressure environments. Fiber surfaces are often striated from vicinal faces associated with the rapid growth and metastability that arise from rapid precipitation from supersaturated hot water-rich fluids. Prolonged favorable conditions during growth or slow nucleation and crystal growth may result in larger fibril widths. Most fibrils of high quality amphibole asbestos range from 0.03 to <0.5 μm in width. In some asbestos occurrences, there are several generations of fibril growth, some of which are byssolite fibers of several micrometers in width. Some occurrences of asbestos may be referred to as *mountain leather* or *mountain cork*, when they have been subject to weathering on the earth's surface for long periods of time.

Fibrils are irregular in cross section, only occasionally displaying the expected crystal faces, {110}, {100} and {010},[2] as is evident in Fig. 2.1. However, many analysts report that amphibole fibers encountered in transmission electron microscopy (TEM) and optical studies are frequently flattened near {100}. A general relationship between width and thickness of fibers of crocidolite and amosite was established by Wylie et al. (1982) from TEM and scanning electron microscopy (SEM) measurements of fibers. It predicts that a fiber 0.1 μm in width would have a thickness of about 0.06 μm, while one that is 0.5 μm in width would have a thickness of about 0.2 μm.

Amphibole fragments are generally smooth as they are bounded by perfect {110} cleavage. They may also be bounded by {010} and/or {100} parting planes; offsets of faces parallel to cleavage are common (Fig. 2.3).

Structural studies of amphibole asbestos have shown that chain width defects parallel to {010} (e.g., a triple chain instead of the double chain characteristic of amphibole), known as Wadsley defects, and twinning or stacking faults parallel to {100} are both common. These are particularly well developed in anthophyllite-asbestos but have been reported in all amphibole asbestos and in many samples of common amphibole. Defects may explain the development of large {100} surfaces

[2] Miller Indices, e.g., {110}, are used to designate the orientation of planes within a crystal structure. A detailed discussion can be found in Bloss (1971) or other mineralogy textbooks.

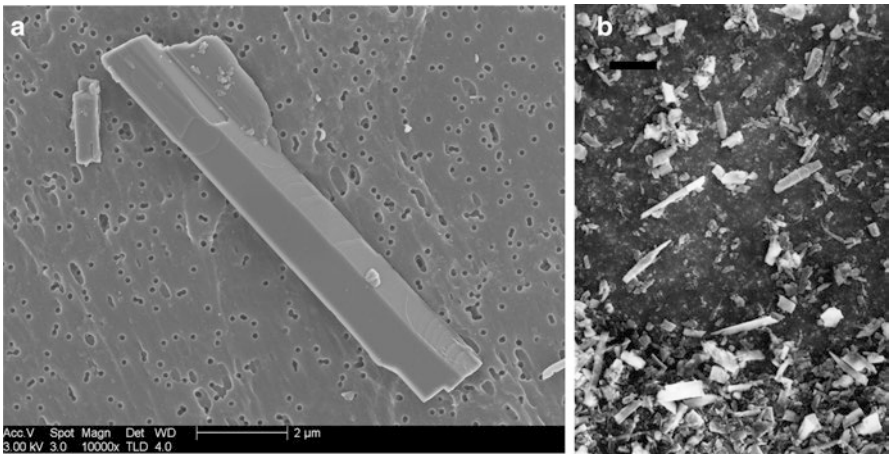

Fig. 2.3 **(a)** FESEM micrograph of a cleavage fragment of tremolite from Shininess, Scotland (Courtesy R.J. Lee Group). The EMP is formed by perfect {110} cleavage. Note offsets on prism surfaces and notched terminus. **(b)** SEM micrograph of cleavage fragments of grunerite from Homestake Mine, South Dakota (scale bar = 10 µm)

on fibrils. When defects are abundant, parting on {100} and {010} develops, enhancing the elongation (aspect ratio) of cleavage fragments.

Amphibole surfaces react to some extent with lung fluids, providing varying amounts of Ca, Na, Mg, K, Fe, and Si to the fluid. Some small chemical alterations have been observed on fibers retained in the human lung and there is some evidence for preferential dissolution on {100}. However, dissolution rates are very slow and fibers persist in the lung many years after exposure. In general, iron and aluminum reduce amphibole solubility in neutral to acidic solutions. Armoring by other minerals, such as talc, might also reduce solubility. In contrast, chrysotile is very soluble in lung fluid (Hume and Rimstidt 1992).

All amphiboles and serpentine would be expected to have tensile strength enhanced by the stable silicon-oxygen chains or sheets that characterize them. However, tensile strength has been shown to increase as the diameter of a fiber decreases (O'Hanley 1986); thus, given its extremely small fibril widths, it is not surprising that the tensile strength of crocidolite from Cape Asbestos Belt in South Africa and from the Hamersley Range in Western Australia has been measured at about 25–48,000 kg/cm^2 (Hodgson 1979) at room temperature; Hodgson (1979) reports tensile strength for amosite as 20–25,000 kg/cm^2. These compare to the tensile strength of steel piano wire, which is usually given as 25,000 kg/cm^2. The measured tensile strength of other amphibole-asbestos varies widely, and measurements of tremolitic, actinolitic, and anthophyllite-asbestos, which characteristically have fibrils wider than crocidolite, are usually much lower than that of crocidolite, amosite, and chrysotile. In addition to fibril size, a high frequency of planar defects may also result in an increase in tensile strength.

Surface area of amphibole-asbestos used in manufacturing is quite high, approaching 90,000 cm^2/g as measured by nitrogen absorption, while unprocessed ore may have a surface area an order of magnitude smaller. After ore is mined, it is normally

"fiberized" in the mill to differing degrees, depending on its intended use. Fiberization liberates fibrils, affects fiber size, and increases surface area. In comparing lung fibrosis after exposure to Cape crocidolite, Hamersley crocidolite, amosite, and Paakkila anthophyllite-asbestos, Lippmann and Timbrell (1990) have concluded that it is the surface area of inhaled fibers that controls the degree of lung fibrosis, not mineral type per se, so surface area is an important variable in characterizing asbestos.

The magnetic properties of asbestos have been studied by Timbrell (1975). Amphiboles are paramagnetic and will align in a magnetic field if suspended in air or a liquid. The higher the iron content, in general the lower the field strength required for alignment. Crocidolite, chrysotile, and other fibers generally align with fiber axis parallel to the field. These are referred to as P-fibers. Amosite fibers may be P fibers, but some may align perpendicular to the magnetic field, referred to as N-fibers. Magnetite does not account for the alignment in amphiboles, although it does for some chrysotile. Timbrell reported that a synthetic fluoro-amphibole aligned with its fiber axis transverse at a definite acute angle to the magnetic field (T-fibers), but the relevance to natural mineral fiber is unknown. Variations from P-type fibers might be explained by structural defects such as twinning or by intergrowth of a second mineral phase.

Amphibole fibers and fragments carry a negative charge on their surfaces and a positive charge at their ends. Repulsive forces between fibers, however, are small and settled fibers form an open latticework with many voids. Because surface charge has been shown to be a function of aspect ratio, long narrow fibers will carry a higher charge than shorter or wider ones.

The optical properties of minerals occurring in an asbestiform habit are normally anomalous. Fibrils smaller than about 0.25 μm are not individually resolvable by polarized light microscopy, so it is the properties of a bundle that are observed. In their common form, amphiboles, serpentine, and erionite are birefringent with three principal indices of refraction: *gamma*, *alpha*, and *beta*. Because of the fibrillar habit of asbestos, however, only two indices of refraction can be measured, one parallel and one perpendicular to the fiber axis. Because of this, asbestos is characterized by *parallel extinction* or near parallel extinction. In monoclinic nonasbestiform amphiboles, the vibration directions make an angle with the axis of elongation; they are said to have *oblique extinction*. The anomalous optical properties are described in more detail by Wylie (1979) and by Verkouteren and Wylie (2002).

Generally speaking, each occurrence of amphibole has a distinct chemical composition and has experienced a distinctive geologic history, which determined its habit and the particle sizes it forms when disaggregated (asbestiform habit) and/or fragmented (common mineral forms). Habit and composition of the same mineral can be similar across locations, e.g., crocidolite from Western Australia and the Cape Asbestos Belt of South Africa, but they are more commonly quite different, e.g., crocidolite from other locations differ in both composition and size of fibrils. For occurrences of asbestos of tremolite-actinolite-ferroactinolite composition, the range in properties is quite large. In summary, with few exceptions, generalizations about the nature of asbestos across occurrences and among types without specifying the source location should be made with great care.

2.5 Amphibole-Asbestos

2.5.1 Sodic Amphibole Group

Riebeckite-magnesioriebeckite is a solid solution in the sodic group of amphiboles represented by the end member formula $^{A}\square^{B}Na_2\ ^{C}(Mg, Fe^{2+})_3\ ^{C}Fe^{3+}{}_2\ ^{T}Si_8O_{22}(OH)_2$, where the following apfu restrictions apply to substitutions: $^{T}Al < Fe^{3+}$, $^{B}Na > 1.5$, $^{A}(Na + K) < 0.50$, $Si > 7.5$, $Al < 0.5$, and $(Mn^{2+} + Mn^{3+}) < {}^{C}(Al + Fe^{3+} + Fe^{2+} + Mg)$, $Li < 0.5$. If $^{A}(Na + K) > 0.50$, the amphiboles are called *magnesioarfvedsonite-arfvedsonit*e. $Mg/(Mg + Fe^{2+}) = 0.5$ separates magnesioriebeckite from riebeckite and magnesioarfvedsonite from arfvedsonite. Magnesioriebeckite-riebeckite and magnesioarfvedsonite-arfvedsonite are normally blue in color.

The asbestiform variety of magnesioriebeckite-riebeckite is known as crocidolite, or blue asbestos. Cross fiber veins have been mined in the Hamersley Range, Western Australia, and in the Cape Asbestos Belt, north central South Africa. Cross fiber crocidolite has also been mined from the Transvaal Asbestos Belt, northeast South Africa, and from Cochabamba, Bolivia (Redwood, 1993). Crocidolite from any locality may be expected to be accompanied by small amounts of magnetite, iron-rich biotite, carbonate, and quartz. In the mines in the Transvaal, kerogen has been reported.

Crocidolite mines in Hamersley Range and Cape Asbestos Belt have provided most of the world's crocidolite; in both places, its composition is riebeckite. Fibril widths <0.1 μm are characteristic as illustrated by Fig. 2.4a and by the frequency distribution of width from the mining and milling aerosol in Fig. 2.4b. The smallest fibrils are on the order of 0.02 μm in width, but rarely 0.5 μm single fibrils occur. The high frequency of airborne fibers of all lengths with widths <0.1 μm is unique among the varieties of commercially important amphibole-asbestos (Table 2.1). Cape and Hammersley crocidolite disaggregates into component fibrils readily, as reflected by the insensitivity of modal width to length (Table 2.1; Shedd 1985). Frequency distributions derived from bulk samples of long fiber products may be quite different from that of aerosols, reflecting either sampling protocols, removal of the finest fibrils during air processing, or sample preparation protocols, as illustrated in Fig. 2.4c.

Transvaal crocidolite fibers are coarser and harsher than Cape fiber. Compositionally, they are riebeckite but in some ore, grunerite (amosite) asbestos fiber may be intergrown. Cochabamba crocidolite fibers are typically light blue, long, and silky. Compositionally, they are magnesioriebeckite, but small amounts of another amphibole may be found intergrown. Frequency distributions of the width of crocidolite fibers from the Transvaal or from Cochabamba are more likely to resemble those of amosite (Fig. 2.5) than the crocidolite depicted in Fig. 2.4. They contain a smaller proportion of fibers less than 0.25 μm and widths extend over a wider range. Modal fiber widths are approximately 0.5 μm and 0.3 μm for Cochabamba, and Transvaal crocidolite, respectively (Shedd 1985).

Massive, nonfibrous, common riebeckite is found in the rock that encloses crocidolite veins in the asbestos mining regions of South Africa, the Hammersley

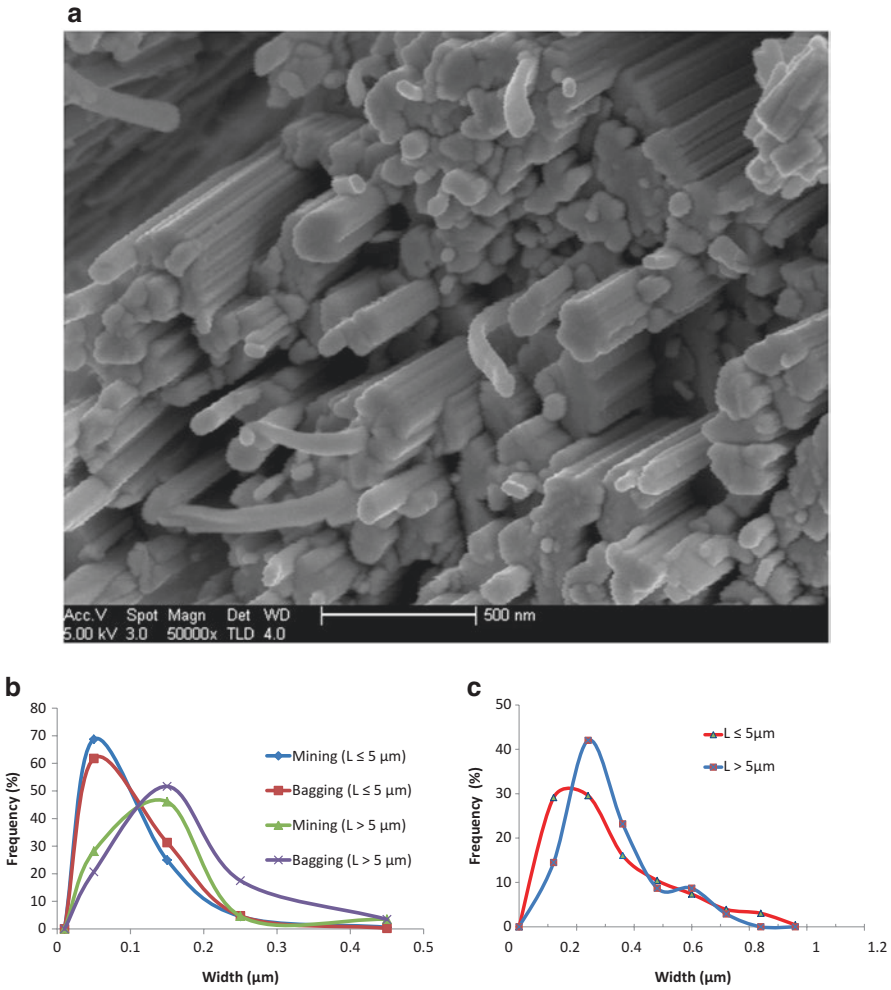

Fig. 2.4 Crocidolite characteristics. **(a)** FESEM micrograph showing fibrillar structure of crocidolite from the Cape asbestos province, South Africa (Courtesy R.J. Lee Group). **(b)** Frequency of width of airborne crocidolite EMPs from the mining and milling environments. Data are taken from Gibbs and Hwang (1980). Magnitude of the largest category of width (w >0.3 µm) is plotted at 0.45 µm. Lengths range from ≤2.5 to 10 µm: 96% of the fibers from mining and 93% of the fibers from bagging are less than 5 µm in length; the modal length for both mining and bagging is ≤ 2.5 µm. **(c)** Frequency of width of EMPs from bulk crocidolite used as a Standard Reference Material (SRM) by the National Institute of Standards and Technology (NIST). Data are from TEM measurements by Beard et al. (2007); sampling protocol is described by Harper et al. (2008). 23% of fibers measured are ≤5 µm. The range is 2 – 28 µm, and the modal length is 9.5 ± 2 µm. Note that the fibers measured in the bulk material are slightly wider and much longer than those found in the mining and milling aerosol

Range of Australia, and Cochabamba, Bolivia. It is also associated with certain igneous rocks in the western USA and elsewhere. Dimensional characterizations of common riebeckite can be found in Wylie (in press).

Table 2.1 Selected length and width measurements of amphibole-asbestos and amphibole cleavage fragments

	(a) Amosite and crocidolite				(b) Tremolite-ferroactinolite asbestos				
							Asbestos mine[a]		Construction[a]
	Airborne amosite[b]		Airborne crocidolite[c]		Asbestos mine[d]	Asbestos mine[b]	raw-NIST SRM	Asbestos mine[b]	raw-NIST SRM
	Electrical Co.	Shipyard	Mine	Bagging	Tremolite	Tremolite	Tremolite	Prieskaite	Actinolite
					Korea	India	CA	South Africa	VA
$L \leq 5$ µm > =1									
Number measured	90	406			788	125	129	371	91
Width mode (µm)	0.20 ± 0.05	0.20 ± 0.05	<0.06	0.15 ± 0.05	0.07 ± 0.02	0.22 ± 0.06	0.48 ± 0.06	0.22 ± 0.06	0.72 ± 0.06
Mean width ± SD (µm)	0.31 ± 0.22	0.31 ± 0.22			0.20 ± 0.19	0.36 ± 0.21	0.68 ± 0.28	0.30 ± 0.15	0.71 ± 0.25
$5 < L \leq 10$ µm									
Number	121	265			396	30	77	34	32
Width mode (µm)	0.30 ± 0.05	0.35 ± 0.10	0.15 ± 0.05	0.15 ± 0.05	0.07 ± 0.02	0.33 ± 0.06	1.50 ± 0.24	0.22 ± 0.06	0.66 ± 0.12
Mean width ± SD (µm)	0.40 ± 0.23	0.41 ± 0.24			0.26 ± 0.33	0.71 ± 0.44	1.48 ± 0.57	0.45 ± 0.20	1.06 ± 0.48
$10 < L \leq 15$ µm									
Number measured	55	70			136	3	19	9	9
Width mode (µm)	0.30 ± 0.05	0.20 ± 0.05	0.15 ± 0.05[e]	0.15 ± 0.05[e]	0.14 ± 0.05	Undefined	Undefined	Undefined	1.14 ± 0.06
Mean width ± SD (µm)	0.42 ± 0.29	0.47 ± 0.35			0.39 ± 0.42	1.12 ± 0.64	2.55 ± 0.64	0.45 ± 0.18	1.28 ± 0.52
	(c) Amphibole-asbestos from Libby Montana				(d) Airborne fragments of common amphibole				
	Airborne	Extracted		Extracted	Stone quarry	Taconite mine	Gold mine	El Dorado Co.	
	town[f]	Mine products[g]		Exfoliation products[g]	VA[b]	Mn[b]	SD[b]	CA[h]	
$L \leq 5$ µm > =1									
Number measured	1448	245		311	236	58	202	1545	
Width mode (µm)	0.25 ± 0.05	0.16 ± 0.06		0.16 ± 0.06	0.55 ± 0.06	0.55 ± 0.06	0.55 ± 0.06	0.3 ± 0.1	

(continued)

Table 2.1 (continued)

	(a) Amosite and crocidolite				(b) Tremolite-ferroactinolite asbestos				
							Asbestos mine[a]		Construction[a]
	Airborne amosite[b]		Airborne crocidolite[c]		Asbestos mine[d]	Asbestos mine[b]	raw-NIST SRM	Asbestos mine[b]	raw-NIST SRM
	Electrical Co.	Shipyard	Mine	Bagging	Tremolite	Tremolite	Tremolite	Prieskaite	Actinolite
					Korea	India	CA	South Africa	VA
Mean width ± SD (μm)	0.35 ± 0.20	0.28 ± 0.23		0.27 ± 0.19	0.71 ± 0.32	0.70 ± 0.29	0.77 ± 0.29	0.59 ± 0.31	
$5 < L \leq 10$ μm									
Number measured	1044	83		151	128	23	126	1080	
Width mode (μm)	0.25 ± 0.05	0.28 ± 0. 06		0.28 ± 0.06	1.16 ± 0.06	Undefined	1.10 ± 0.06	0.7 ± 0.1	
Mean width ± SD (μm)	0.59 ± 0.40	0.51 ± 0.33		0.47 ± 0.28	1.48 ± 0.80	1.59 ± 0.44	1.28 ± 0.54	1.29 ± 0.67	
$10 < L \leq 15$ μm									
Number measured	429	34		49	40	2	27	367	
Width mode	0.25 ± 0.05	0.27 ± 0.06		0.27 ± 0.06	Undefined	Undefined	Undefined	2.5 ± 0.1	
Mean width ± SD (μm)	0.73 ± 0.56	0.49 ± 0.22		0.54 ± 0.30	2.32 ± 0.93	2.05 ± 1.34	1.91 ± 0.76	2.17 ± 1.14	

[a]Beard et al. (2007)
[b]Wylie et al. (2015)
[c]Gibb and Hwang (1980)
[d]Jenny Verkouteren (personal communication)
[e]The mode is for fibers between 10 and 20 μm in length
[f]EPA (2006)
[g]Atkinson et al. (1981)
[h]Ecology and the Environment (2005)

2.5.2 *Magnesium-Iron-Manganese-Lithium Amphibole Group*

2.5.2.1 Cummingtonite-Grunerite

Cummingtonite-grunerite is a solid solution in the magnesium-iron-manganese-lithium group of monoclinic amphiboles represented by the end member formula $^{A}\square^{B}(Mg, Fe^{2+})_2\ ^{C}(Mg, Fe^{2+})_5\ ^{T}(Si)_8O_{22}(OH)_2$; the following restrictions to substitutions apply: $^{B}(Ca + Na) < 1.0$, $^{B}(Mg, Fe, Mn, Li) \geq 1.0$, $^{B}Li < 1.00$, $Si > 7.0$. $Mg/(Mg + Fe^{2+}) = 0.5$ divides cummingtonite from grunerite. Cummingtonite-grunerite is light to dark brown in color.

The asbestiform variety of cummingtonite-grunerite is known as *amosite* or *brown asbestos*. The silky variety is sometimes called *montasite*. The name amosite

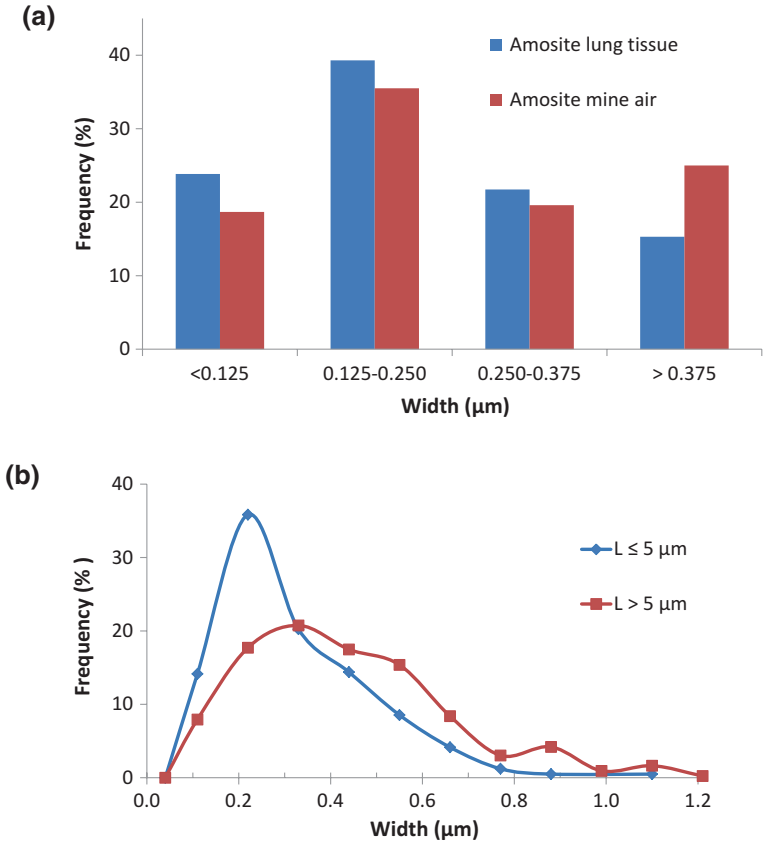

Fig. 2.5 Characteristics of amosite. **(a)** Frequency of width of amosite EMPS from lungs of miners and the mine aerosol, Transvaal, South Africa. Data for fibers of all lengths are taken from TEM measurements of Pooley and Clark (1980). Fibers ranged from <1 to >10 µm in length. Modal length is 2-3 µm, with 8-9% >10 µm and with 32% of airborne and 40% of lung burden fibers longer than 4 µm. (**b**) Frequency of width of amosite EMPS from shipyard aerosol. Fibers range from about 1.5 to >100 µm. Modal length is 2.5 ± 1 µm and about 23% are longer than 5 µm. Particle measurements can be found in Wylie et al. (2015). Many more long fiber bundles are found in the aerosol surrounding the construction of ships than in the mine

is not a proper mineral name; it was derived from the ***A***sbestos ***M***ines ***o***f ***S***outh Africa located in the Transvaal Asbestos Belt. These mines have been the only important source of amosite worldwide.

Small amounts of ferroactinolite-asbestos, sometimes referred to as prieskaite, occur in association with amosite in the Transvaal. Magnetite and quartz are common accessory minerals, and minor biotite, pyrite, carbonate, stilpnomelane, kerogen, graphite, and magnesite have been reported in raw asbestos.

Amosite is sometimes described as "harsh." When the Bureau of Mines was trying to reduce the size of amosite in an air jet mill, the amosite blew a hole through hard-surfaced stainless steel (Campbell et al. 1980). Harshness results when fibrils resist disaggregation, forming larger fibers with less flexibility. Some level of coherence or semi-coherence in the amphibole structure across fibril boundaries has been observed in amosite, and sheet silicates, such as iron-rich talc, serpentine, and chlorite, are normally intergrown with the fibrils; these likely increase amosite's resistance to disaggregation.

Like crocidolite, frequency distributions of the width of amosite fibrils found in lung tissue and the air of mines and mills normally display a single modal value, as depicted in Fig. 2.5a. Modal widths reported in the literature range from about 0.15 μm for short fibers up to 0.5 μm for fibers longer than 5 μm. Unlike Cape and Hammersley crocidolite, there is a prominent tail on the distribution extending toward larger fiber widths. Such a tail is consistent with fibrils that adhere to one another, resisting disaggregation and resulting in wider fiber bundles, particularly for longer fibers. Of course, amosite may undergo varying degrees of fiberization during processing for different applications, which would be reflected in the size and structure of the tails; some distributions may be multimodal as illustrated in Fig. 2.5b, which shows the frequency of width of amosite fibers in the aerosol of a shipyard. The distribution displays the characteristic increase in the width of longer fibers formed from the bundles of many smaller fibrils.

2.5.2.2 Anthophyllite

Anthophyllite is a solid solution in the Mg-Fe-Mn-Li group of orthorhombic amphiboles represented by the endmember formula $^{A}\square^{B}(Mg, Fe)_2{}^{C}(Mg, Fe)_5Si_8O_{22}(OH)_2$. Iron-rich anthophyllite is rare. The following restrictions apply to atomic substitutions: $^{B}(Mg,Fe^{+2}, Mn^{+2}, Li) \geq 1.50$, $^{B}Li < 0.50$, $^{T}Si > 7.0$. The largest anthophyllite-asbestos mine is found at Paakkila, Finland. Smaller deposits have been mined in the USA, Sweden, Russia, India, and Pakistan. The risk for mesothelioma from anthophyllite-asbestosis generally is considered to be among the lowest among amphibole-asbestos exposures, and its mineralogical characteristics readily distinguish it from crocidolite and amosite.

Unlike amosite and crocidolite, anthophyllite-asbestos does not normally occur in cross-fiber veins. It is found in pods, masses, and clusters of fibers. Within clusters, parallel fibrils form bundles, but the clusters are not aligned. Its mode of formation results in a less homogeneous material than is characteristic of cross fiber veins.

Talc is always present with anthophyllite-asbestos. It is intergrown in such a way that its structural elements are parallel to those of anthophyllite (the growth is said to be *epitaxial*), and fibers composed only of the mineral talc are commonly associated with anthophyllite-asbestos. Talc is so pervasive that most fiber surfaces are covered