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RESEARCH ARTICLE



The presence of erionite in North American geologies and the estimated mesothelioma potency by region

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ABSTRACT

Objective: Erionite is a naturally occurring fibrous mineral found in soils in some geographical regions. Known for its potency for causing mesothelioma in the Cappadocia region of Turkey, the erionite fiber has attracted interest in the United States due to its presence in a band of rock that extends from Mexico to Montana. There are few toxicology studies of erionite, but all show it to have unusually high chronic toxicity. Despite its high potency compared to asbestos fibers, erionite has no occupational or environmental exposure limits. This paper takes what has been learned about the chemical and physical characteristics of the various forms of asbestos (chrysotile, amosite, anthophyllite, and crocidolite) and predicts the potency of North American erionite fibers.

Materials and Methods: Based on the fiber potency model in Korchevskiy et al. (2019) and the available published information on erionite, the estimated mesothelioma potency factors (the proportion of mesothelioma mortality per unit cumulative exposure (f/cc-year)) for erionites in the western United States were determined.

Results and Discussion: The model predicted potency factors ranged from 0.19 to 11.25 (average ~3.5), depending on the region. For reference, crocidolite (the most potent commercial form of asbestos) is assigned a potency factor ~0.5.

Conclusion: The model predicted mesothelioma potency of Turkish erionite (4.53) falls in this same range of potencies as erionite found in North America. Although it can vary by region, a reasonable ratio of average mesothelioma potency based on this model is 3,000:500:100:1 comparing North American erionite, crocidolite, amosite, and chrysotile (from most potent to least potent).

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Introduction

Erionite is a naturally occurring fibrous mineral series that belongs to the zeolite group. Zeolites are hydrated aluminosilicates of alkali and alkaline earth metals (Mumpton 1999; Virta 2003; Ilgren, Ortega Breña, et al. 2008; Van Gosen et al. 2013). Approximately 40 natural zeolites have been identified to date. The most common include analcime, chabazite, clinoptilolite, erionite, mordenite, and phillipsite (Virta 2003). Most zeolites rarely occur in pure form and, as such, are typically associated with other zeolite minerals. Zeolites have valuable adsorption, cation exchange, dehydration-rehydration, and catalytic properties, which make them suitable for a variety of chemical, industrial, and commercial applications (Mumpton 1999).

Historically, erionite was used as a catalyst in petroleum refining processes (Mumpton 1999), and it was one of four commercially important zeolites that were mined and marketed in the U.S. for commercial purposes beginning in the 1960s and continuing through the 1970s (International Agency for Research on Cancer (IARC) 1987a). As of 1987,

erionite was no longer mined or marketed for commercial uses and has been replaced by synthetic non-fibrous zeolites (International Agency for Research and Cancer [IARC] 1987c; International Agency for Research on Cancer [IARC] 1987b; US Environmental Protection Agency [EPA] 1988; Dogan and Dogan 2008).

Erionite is a tectosilicate belonging to the ABC-6 group of zeolites and can be formed under a few different types of conditions (Giordani 2017). Erionite can occur naturally as a hydrothermal alteration product, commonly due to the reaction of volcanic ash with groundwater (Berry et al. 2019). It has also been found that large quantities of erionite can be formed in cavities of magnesium and iron-rich volcanic rock under low pressure and low temperature (Bish and Ming 2018).

Erionite was first identified in an opal mine in Durkee, Oregon, by Eakle (1898) and was considered a very rare mineral until Deffeyes (1959) identified several deposits in Wyoming, Nevada, and South Dakota. Since then, deposits of erionite have been discovered around the world, including Antarctica, Austria, Canada, Czechoslovakia, Faroe

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Islands, France, Georgia, Germany, Iceland, Italy, Japan, Kenya, Korea, Mexico, New Zealand, Russia, Scotland, Tanzania, and Turkey (Papke 1972; Dogan and Dogan 2008; Ilgren, Ortega Breña, et al. 2008; Ilgren, Pooley, et al. 2008; Van Gosen et al. 2013; Ortega-Guerrero and Carrasco-Nunez 2014; Saracci 2015).

The carcinogenic potency of erionite found in Turkey has been documented, and, in one study, it has been reported in rats to be 500–800 times more tumorigenic than chrysotile asbestos. In that same study, crocidolite asbestos was 30–60 times more tumorigenic than chrysotile (Coffin et al. 1992). Erionite's role in the mesothelioma-ridden villages in Turkey, especially in the 'houses of death' (as locals have called them), brings concern about its potential health threat in other countries where it is present (Carbone et al. 2007). In fact, Ilgren, Ortega Breña, et al. (2008) reported that '[i]t has thus been known for more than 25 years that fibrous erionite from parts of the world outside Turkey possess the same extreme carcinogenic potential as that originally noted in Central Anatolia' (Ilgren, Ortega Breña, et al. 2008). However, little work has been done to determine whether the North American erionite deposits have similar potency to that in Turkey and whether the deposits pose a real health threat to populations. It is possible, even probable, that the erionite deposits in North America could be a source of adverse health effects if there was much human exposure to the airborne fibers.

This article discusses the location and chemical compositions of North American erionite and describes a model to assess the possible health risks posed by environmental exposure to these fibers. To address the differences in potencies between elongated mineral particles (EMPs or fibers), Korchevskiy et al. (2019) offered a formula that estimated the mesothelioma potency factor (as defined by Hodgson and Darnton (2000)) of fibers. The potency factor, as discussed in this article, is the mesothelioma mortality as a proportion of expected mortality per unit cumulative exposure (f/cc-year). The formula for the model was derived by comparing the relationship between mesothelioma potency factors, fiber length, and chemical composition of various minerals, such as chrysotile, crocidolite, amosite, anthophyllite, and erionite (Korchevskiy et al. 2019). The same formula derived by Korchevskiy et al. was used in this article to predict the differences (or similarities) in potency between the Turkish erionite and the erionite deposits in North America, as well as the major commercial forms of asbestos (chrysotile, amosite, and crocidolite).

Properties of the various erionites

Chemical

To address the significant chemical variability in the various zeolites called erionite, they have been further classified into three sub-species: erionite-Na, erionite-Ca, and erionite-K (Rezvani and Bolduc 2014; Giordani et al. 2017). This categorization separates erionite compounds based on the most abundant extra-framework (EF) cations within the erionite cavities (Giordani et al. 2017). In erionite-Na, sodium is the

most abundant EF cation, and the proportion of tetrahedron sites occupied by silicon atoms must be in the range of 0.74–0.79. Erionite-Ca contains a majority of calcium EF cation, and the proportion of tetrahedron sites occupied by silicon atoms must be in the range of 0.68–0.79. Erionite-K may contain significant quantities of sodium, calcium, and magnesium; however, potassium must make up at least 58% of EF cations, and the proportion of tetrahedron sites occupied by silicon atoms must be in the range of 0.74–0.79 (Rezvani and Bolduc 2014). These are all found in parts of North America.

Morphological

In addition to the chemical differences within the different formations of erionite, there can be variations in the morphology and structures, ranging from rigid prismatic to asbestiform (fibrous) (Giordani 2017). According to what was found in the literature, the precise definitions for what differentiates prismatic from acicular have yet to be established. For this article, and in accordance with much of the literature, the morphological terms will be used as generally discussed in the USGS (US Geological Survey) asbestos fact sheet, where prismatic crystals are slightly elongated, acicular crystals have significantly longer length than width, and 'extremely long' fibers are asbestiform (US Geological Survey (USGS) 2001). Generally, the more fibrous erionite minerals have long fibers of smaller diameters. These fibers have been shown to be a potent carcinogen. Erionite crystals that are more prismatic and acicular may be less potent, as the diameter of the fibers is generally greater than 2 microns.

All erionite compounds are fibrous, but not all forms are able to produce the extreme chronic toxicity that results in diseases, such as mesothelioma. To distinguish harmful erionite fibers from those that lack toxicity, one needs to be able to recognize the difference between fibers termed asbestiform (or wooly, as termed by A. S. Eakle (1898), because of the white, wooly appearance of the fibers (Deffeyes 1959)) and those that are non-asbestiform (often called cleavage fragments). The official classification of erionite as wooly is the same classification used to identify asbestos fibers during exposure monitoring. The fibers must meet the following criteria: '(1) longer than 5 μm , (2) an aspect ratio of at least 3:1, and (3) visible by optical microscopy' (Wylie 2017). They also need two or more of the following characteristics: parallel fibers in bundles, fiber bundles with plied ends, matted masses of individual fibers, or fibers showing curvature (Wylie 2017).

Comparison with offretite

Another naturally-occurring zeolite with which erionite is often confused is offretite. Offretite is very similar in structure to erionite and has recently been of interest in some toxicity studies (Mattioli et al. 2018). In fact, offretite is so similar to erionite morphologically that many methods of identifying fibers cannot differentiate between the two; even

with the use of X-ray powder diffraction, it can be difficult to distinguish the two (Passaglia et al. 1998). The chemical composition of offretite mimics erionite in that potassium, sodium, and calcium are commonly found in cages (e.g. the chemical structure). Today, a skilled analytical chemist should not have a problem differentiating if they are aware of the presence of both.

The extra framework Mg/(Ca + Na) ratio distinguishes the two, where offretite can have values greater than 0.7, and erionite has values lower than 0.15 in most cases (Gualtieri et al. 1998). Offretite also has been found to form acicular and prismatic crystals and occasionally can crystallize with asbestiform habit (Mattioli et al. 2018). There are no epidemiology studies on offretite; thus, it has not been classified, one way or another, as a human carcinogen.

Comparison with asbestos

As noted previously, the first specimen of erionite identified by Eakle (1898) was described as 'wooly.' 'Erionite' is derived from the Greek word for wool, 'eiros'. Erionite can occur as a short or long fiber form or as rod-like crystals ranging from 2 to 200 µm in length and 0.1 to 10 µm in diameter (Dogan et al. 2008; Van Gosen et al. 2013). Like asbestos, erionite can be broken into respirable fibers and presents an inhalation hazard.

Baris et al. (1978, 1979) first identified a cluster of mesotheliomas in Turkey with no known exposure to asbestos. In their follow-up study, Baris et al. (1981) established a link between exposures to fibrous erionite and the incidences of mesothelioma. The airborne concentration of erionite fiber, which they measured, was 2–3 orders of magnitude lower than concentrations prevalent in asbestos occupational settings at that time (Baris et al. 1981). The authors hypothesized that erionite fibers may have enhanced carcinogenicity (Baris et al. 1981). This was confirmed in several animal studies (Maltoni et al. 1982; Wagner et al. 1985; Davis et al. 1991; Carthew et al. 1992). The relative carcinogenicity and tumorigenicity of erionite estimated from intrapleural experiments were more than two orders of magnitude greater than crocidolite (Hill et al. 1990; Carthew et al. 1992; Dogan et al. 2008). In intraperitoneal experiments, erionite was 7–20 times more potent for mesothelioma than crocidolite (Carthew et al. 1992; Dogan et al. 2008). Of course, the intrapleural experiments are a better reflection of the inhalation hazard because the majority of fibers are expected to accumulate and cause mesothelioma in this sack, which surrounds the lung (the pleura).

The mechanism of asbestos and erionite toxicity is still under considerable research. Many scientists believe that the role of reactive oxygen species (ROS) is significant; however, results have shown that erionite produced the same or lesser amount of ROS compared to crocidolite asbestos (Baris et al. 1981; Mossman and Sesko 1990; Leanderson and Tagesson 1992; Nejjar et al. 1993; Eborn and Aust 1995; Ruda 2007). Some studies have shown that erionite's physiochemical properties substantially impact its toxicity (Timblin et al. 1998; Fach et al. 2003).

Erionite had very little commercial value and was, therefore, less economically important than asbestos. Thus, most epidemiological studies of erionite have been based on environmental exposures rather than occupational (Baris et al. 1978; Artvinli and Baris 1979; Baris et al. 1979; Baris et al. 1981; Artvinli and Baris 1982; Saracci et al. 1982; Baris et al. 1987; Baris 1991; Karakoca et al. 1997, 1998; Timblin et al. 1998; Metintas et al. 1999; Fach et al. 2003; Dikensoy 2008; Metintas et al. 2010; Ortega-Guerrero and Carrasco-Nunez 2014; Saracci 2015). This has led researchers to wonder whether certain occupations (e.g. miners and farmers) may have elevated exposures to airborne erionite due to their work activities. For example, Baris et al. (1981) and Baris et al. (1987) measured airborne concentrations of erionite in farming fields and at a Turkish stone quarry in an attempt to characterize the extent of occupational exposure. From a study in North Dakota, road maintenance/gravel pit workers, farmers/ranchers, and frequent drivers over gravel roads were found to have a high potential for exposure to erionite (Ryan, Dihle, Griffin, Partridge, Taylor, et al. 2011). While these studies identified the potential for occupational exposure, there remains a significant information gap regarding the epidemiology of mesothelioma due to outdoor exposure.

Differences in erionite-induced tumors and asbestos-induced tumors

Although the tumors induced by asbestos and erionite are morphologically similar, some slight differences suggest that the biological activity differs. These differences have been thoroughly examined by Johnson et al. (1984). In this study, they obtained 'pleural tumors... from seven rats exposed to erionite [from Rome, Oregon] by inhalation for 12 months'. These tumors were analyzed using various techniques to find differences in erionite-induced tumors and tumors from other asbestiform fibers in Wagner (1983) (Johnson et al. 1984).

In this study, from nearly 40 years ago, it was found that a primary difference between erionite and asbestos is that erionite-induced tumors possessed more prominent fibrosarcomatous elements, whereas asbestos predominately produced epithelial forms of tumors (Wagner 1983; Johnson et al. 1984). Additionally, the inhalation of erionite produces tumors much faster and more frequently than asbestos (Wagner 1983; Johnson et al. 1984). Interestingly, where asbestos produces more tumors *via* intraperitoneal injections than intrapleural injections, erionite produces more tumors *via* intrapleural injections (Johnson et al. 1984). Further studies replicating these results would improve the certainty of these conclusions.

Erionite deposits in the Western United States

For purposes of this article, we focused on clusters of erionite deposits in the western United States. These clusters have been grouped into five areas for ease of discussion (Figure 1).

Some forms of erionite have been found in almost all western states, and it is most 'abundant in southeast California, northern and central Nevada, and southeastern Oregon' (Sheppard 1996). Samples of the rock contained anywhere from 'trace to nearly 100% erionite' (Sheppard 1996). They noted that the "most voluminous" deposit of erionite occurred in the continental Cenozoic silicic tuffs of the western United States (Sheppard 1996). In this tuffaceous sedimentary, the erionite existed in prismatic, acicular, and fibrous forms with lengths ranging from 2-200 μm and diameters of 0.1-10 μm (Sheppard 1996).

The erionite deposits in Rome, Oregon, have been among the most studied areas in North America with regard to erionite toxicity. Erionite-K has often been found in the Rome, Oregon area (Dogan et al. 2006; Dogan and Dogan 2008; Dogan et al. 2008; Croce et al. 2015). However, Berry et al. (2019) found significant Calcium peaks in samples taken from Rome, Oregon that would indicate erionite-Ca may be present as well. This illustrates that depending on the area where a sample is taken, the results can be quite different (which seems true for most mined materials).

Appendix I provides more detailed descriptions of the available information at each location.

Airborne concentrations of erionite

It has been known for decades that, in the workplace, the primary hazard posed by all respirable fibers are *via* inhalation.

Numerous articles have documented environmental exposures to erionite and the associated health effects (Baris

et al. 1979; Artvinli and Baris 1982; Artvinli and Baris 1985; Baris et al. 1987; Dogan 2003a; Dog 2003; Gulmez et al. 2004; Carbone et al. 2011; Ortega-Guerrero and Carrasco-Nunez 2014; Ortega-Guerrero et al. 2015; Saracci 2015). While erionite fibers have been identified and documented even prior to the 1900s (Eakle 1898), the link between erionite exposure and pleural diseases was not established until the 1980s (Baris et al. 1978, 1979, 1981).

Exposures to the public

In Karain, Turkey, Baris et al. (1981) reported that three airborne samples (out of 8) taken in school playgrounds, fields during work, and stone-cutting areas had airborne fiber concentrations of 0.2-0.3 f/cc which were ~80% erionite fibers. Seven out of 11 samples during indoor cleaning operations in the cave homes in Karain, Turkey, had airborne fiber concentrations between 0.03 and 1.38 f/cc (Baris et al. 1981).

Erionite-containing geological formations in North Killdeer and Dunn County, North Dakota, were being used for gravel in roads since the 1980s (Carbone et al. 2011). Airborne erionite concentrations were measured during different activities in Dunn County (Carbone et al. 2011). The authors reported a mean concentration of 0.022 f/cc by PCME (phase contrast microscopy equivalent) (0.235 s/cc by TEM (transmission electron microscopy)) in vehicles (cars and school buses) during travel over erionite-containing gravel roads. The mean concentration measured during a short-term sampling period (a peak sample) while sweeping in a road maintenance garage was 0.061 f/cc by PCME (0.207 s/cc by TEM) (Carbone et al. 2011).

Carbone et al. considered airborne erionite concentration in Karain, Sarihidir, Tuzkoy, Karlik, and Boyali in Turkey as a comparison to erionite concentrations measured in Dunn County, North Dakota. The stationary outdoor samples in Dunn County exceeded the fiber concentration of all of the roadside samples collected along the main town roads in Turkish villages that exhibited elevated mesothelioma rates (Carbone et al. 2011). The mean outdoor streetside stationary samples obtained in the Turkish villages ranged from 0.0000 to 0.0017 f/cc by PCME (0.0000 to 0.0091 s/cc by TEM) compared to 0.012 f/cc (0.108 s/cc by TEM) in Dunn County (Carbone et al. 2011). Erionite concentrations measured during outdoor activities in the Turkish villages ranged from 0.0000 to 0.1398 f/cc by PCME (0.0411 to 0.4464 s/cc by TEM) compared to 0.0004 f/cc (0.003 s/cc by TEM) measured in Dunn County. Indoor concentrations measured during cleaning activities in the Turkish villages ranged from 0.0000 to 1.737 f/cc by PCME (0.0431 to 7.817 s/cc by TEM) compared to 0.0575 f/cc (0.1750 s/cc by TEM) in Dunn County (Carbone et al. 2011).

Exposures in the workplace

Few studies have conducted quantitative measurements of erionite fibers in the workplace. Zeolites have been used in various products, including animal litter, animal feed, odor control, cement, water purification, wastewater treatment,

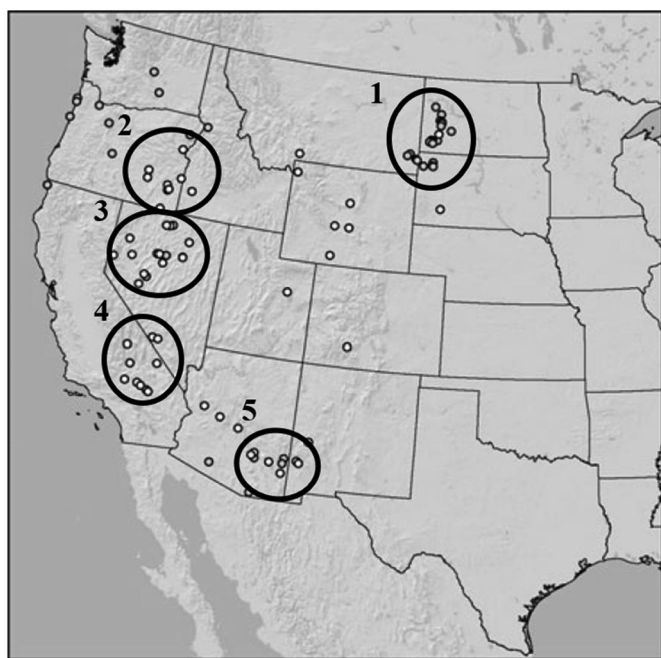


Figure 1. Modified from Van Gosen et al. (2013), this figure depicts the approximate locations of natural erionite from Sheppard (1996) and Van Gosen et al. (2013). (1) The Killdeer Mountain area, North and South Dakota; (2) Rome, Oregon; (3) Lander County, Nevada; (4) San Bernardino County, California; (5) Bowie, Arizona.

and more (Virta 2013). The commercial value of natural zeolites, including erionite, increased from 2000 to 2015, but they were gradually replaced by synthetic zeolites beginning in 2005 (Virta 2003, 2006, 2013). Zeolite deposits that were used commercially contained mixtures of species and, as a result of contamination, exposure to erionite could occur (International Agency for Research on Cancer (IARC) 1987a). Isolated data for erionite could not be identified.

Several studies have identified agricultural activities and the associated production of suspended soil particles as a potentially important source of exposure to erionite (Ilgren, Ortega Breña, et al. 2008; Ilgren, Pooley, et al. 2008; Ryan, Dihle, Griffin, Partridge, Hilbert, et al. 2011; Ortega-Guerrero and Carrasco-Nunez 2014; Ortega-Guerrero et al. 2015). Baris et al. (1987) measured airborne fiber concentrations in the range of 0.004 f/cc (in Karain, Turkey) and 0.007 f/cc (in Sarihidir, Turkey) in fields during a time of low agricultural activity in the summer when little to low amounts of dirt were disturbed. According to the study, most of the fibers (60% in Sarihidir and 80% in Karain), based on street samples in these villages, were zeolites. Although airborne measurements were conducted in agricultural fields, the conditions during which the measurements were taken almost certainly underestimated the airborne concentrations during standard agricultural activities. The authors noted that airborne fiber concentrations measured in the fields were lower than those measured in the streets (mean concentrations of 0.006 f/cc and 0.009 f/cc in Karain and Sarihidir, respectively) (Baris et al. 1987).

Ilgren, Ortega Breña, et al. (2008) hypothesized that erionite might cause an emerging cluster of mesothelioma cases in the state of Zacatecas in central Mexico, where mining and agricultural activities predominate. They later identified two cases of erionite-related mesothelioma in a small village in the northern part of the State of Jalisco. A lung fiber burden analysis conducted on one of the two mesothelioma cases discovered high concentrations (> 1 million fibers/gram of dry lung) of fibrous erionite in the lung specimen (Ilgren, Ortega Breña, et al. 2008; Ilgren, Pooley, et al. 2008). The authors discussed that in both cases, the persons were involved with agricultural activities for approximately the first 20 years of their lives (Ilgren, Pooley, et al. 2008).

Zeolite mining occurs in Jalisco, and zeolite-containing material may have been used in various agricultural activities (Ilgren, Ortega Breña, et al. 2008). Ortega-Guerrero and Carrasco-Nunez (2014) identified deposits of erionite in the village of Tierra Blanca de Abajo in the State of Guanajuato, Mexico, along with a high incidence of mesothelioma (Ortega-Guerrero et al. 2015). The authors stated that the main economic activity in Tierra Blanca de Abajo is agriculture (Ortega-Guerrero et al. 2015).

Ryan, Dihle, Griffin, Partridge, Hilbert, et al. (2011) identified ranchers/farmers as a group with potentially high exposures to erionite in North Dakota. However, a high-resolution CT scan analysis detected interstitial changes in only one out of six subjects in the rancher/farmer exposure category (Ryan, Dihle, Griffin, Partridge, Hilbert, et al. 2011). Although the referenced studies provided evidence of

exposure to erionite from agricultural activities, the lack of airborne concentration data and specific toxicity data limits the ability of health scientists to conduct a risk assessment.

In July 2013 and September 2014, the Health Hazard Evaluation Program visited the Sioux Ranger District of the Custer National Forest to assess the potential employee exposures to erionite mineral fibers. They performed air sampling within the Arikaree and White River rock formations to evaluate employee exposure to erionite and respirable crystalline silica during forestry activities including '... thinning, felling, and bucking trees; digging fireline; spraying invasive weed species; mowing campgrounds; using a Bobcat to masticate timber and grade roads; and reclaiming push pits' (Beaucham et al. 2015). From the July 2013 visit, they found that the airborne erionite concentrations from the task samples ranged from non-detect to 0.36 f/cc (Beaucham et al. 2015). For the visit in September 2014, they found the erionite concentrations for the full-shift exposures ranged from 0.009 to 0.096 f/cc (Beaucham et al. 2015). They reported that they collected these samples in the rain and snow, and that there could be a possibility for airborne concentrations to be higher in dry weather.

In bulk rock and soil samples, from the July 2013 visit, the laboratories that analyzed their samples '... confirmed that the fibrous minerals in each sample included erionite.' They concluded that the weight percentage of erionite was low (about 1%). For the September 2014 samples, they found the 'erionite fibers in the soil samples analyzed by PLM ranged from not detectable to approximately (5%)' (Beaucham et al. 2015).

Toxicity studies

There have been some toxicology studies that have evaluated erionite from the United States. Of the studies identified, eight are presented – four *in vitro* studies (Poole et al. 1983; Urano et al. 1991; Pelin et al. 1992; Gualtieri et al. 2018) and four *in vivo* studies (Maltoni et al. 1982; Suzuki and Kohyama 1984; Wagner et al. 1985; Davis et al. 1991). Others were of poor quality or not acceptable for various reasons.

In vitro studies

The *in vitro* studies examined the stimulation of unscheduled DNA repair synthesis (UDS), the production of ROS, anaphase aberrations, and the biopersistence of various fibers.

The study by Poole et al. (1983) found that after exposure to erionite (from Turkey and Oregon), there was an increase in the amount of morphological transformations and UDS in mouse embryo cells and the human lung cells (Poole et al. 1983). The use of DNA repair assays to detect carcinogenic/mutagenic agents has been advocated by many to be a useful method (Larsen et al. 1982) and, in this instance, suggests pure erionite can cause pleural mesothelioma tumors.

Urano et al. (1991) examined the *in vitro* production of ROS (O_2^- , H_2O_2 , and OH^-) by erionite (Urano et al. 1991). These species are often associated with metabolic and cellular disturbances (Slater 1984). One of the major cellular disturbances that

can occur is mutations of DNA if the reactive species is formed close to the DNA. Urano et al. (1991) stated that these effects can help explain ‘... the mechanism of erionite carcinogenicity observed in epidemiological surveys and experimental studies.’ Interestingly, while asbestos does not typically indicate the induction of DNA damage or mutagens *in vitro* (Chamberlain and Tarmy 1977) (suggesting it is a carcinogen only *via* inflammation), erionite has been shown to exhibit gene toxicity *in vitro* (Poole et al. 1983; Kelsey et al. 1986; Urano et al. 1991).

Pelin et al. (1992) described erionite as causing anaphase aberrations in human mesothelial cells. In terms of anaphase aberrations as a measure of toxicity, Pelin et al. (1992) found that erionite was less toxic compared to amosite, crocidolite, and chrysotile on a weight basis and again less toxic when the doses were converted to fibers instead of grams (Pelin et al. 1992). It is unclear why these results are inconsistent with other whole animal studies and epidemiology studies. They are included for the sake of completeness.

The biopersistence of mineral fibers was studied primarily by Gualtieri et al. (2018). Biopersistence is the time it takes for the mineral fibers to be cleared from the respiratory system. Any fibers that cannot be cleared are classified as biopersistent and will accumulate throughout the subject's life (Patel et al. 2022). In order to predict biopersistence, Gualtieri et al. (2018) calculated the dissolution time of various fibers (Gualtieri et al. 2018). This study examined 0.25 μm thick fibers of chrysotile, amphibole fibers, and erionite (Gualtieri et al. 2018). They showed that chrysotile had the shortest dissolution time with a range of 94–177 days, followed by amphibole fibers at 49–245 years, and finally, fibrous erionite at 181 years (Gualtieri et al. 2018).

The extreme biopersistence of erionite fibers is also supported by Scholze and Conradt (1987). Their study evaluated erionite, crocidolite, and chrysotile. They found that erionite was more biopersistent than the other two fibers (Scholze and Conradt 1987; Patel et al. 2022). They also found that *in vitro* acellular dissolution studies showed that chrysotile dissolves faster than amphibole asbestos, and that ‘erionite is much more biopersistent than crocidolite and chrysotile’ (Patel et al. 2022).

Giordani et al. (2020) analyzed the aqueous solubility of erionite, offretite, and stellerite in water with equilibrium to atmospheric carbon dioxide. The results illustrated the limited solubility of all of these three zeolites. After a week in the solution, silicon and calcium ion concentrations were slightly above the detection limit for all zeolites (Giordani et al. 2020). However, the aluminum concentration was below the detection limit for all samples. The low solubility of erionite supports those studies that found erionite to be extremely biopersistent in the lung, and this characteristic is widely believed to contribute to its chronic toxicity (Brunner et al. 2006). This is why, among other factors, chrysotile asbestos is far less toxic than amphiboles.

In vivo studies

In vivo studies have examined intrapleural, intraperitoneal, and inhalation exposure to erionite in various types of rats.

Maltoni et al.'s (1982) research involving intraperitoneal and intrapleural injection of erionite (unspecified where the erionite was sourced) found that no tumors were formed at the 53-week mark after intraperitoneal injection. It found that after pleural injections, 9 of the 40 rats tested (22.5%) developed tumors. This was very different from the crocidolite that was tested, which formed 0 pleural tumors and 12 peritoneal tumors (30%) (Maltoni et al. 1982).

In a study conducted by Suzuki and Kohyama (1984), the differences between erionite, amosite, and chrysotile were examined. They found that the percentage of malignant peritoneal tumors in rats injected with erionite at all doses was 43.8%, while amosite produced 30.2%, and chrysotile yielded 29.4% (Suzuki and Kohyama 1984). This supports the conclusion reached by Davis et al. (1991) that erionite was more carcinogenic than both amosite and chrysotile. However, it should be noted that the results of Suzuki and Kohyama (1984) are inconsistent with other studies that have shown chrysotile to be nearly nontoxic *via* peritoneal injection. Some experts have attributed that inconsistency to methodological errors.

It is known that chemical composition plays an important role in the potency of mineral fibers. However, within a species of minerals, where there are few or no chemical differences, the fiber's morphology seems to dictate toxicity. Davis et al. (1991) stated that ‘current theory suggests that fibre number, and probably the number of long thin fibres (length > 8 μm , diameter < 0.25 μm) ... rather than mass, determine carcinogenicity.’ They further noted that ‘... it appears from hazard models that erionite is only about twice as carcinogenic as chrysotile and amosite, though rather more in comparison with crocidolite’ (Davis et al. 1991). Why they found chrysotile to be potent has long put the study results in question.

Wagner et al. (1985) showed that both types of erionite (from Oregon and Turkey) produced mesothelioma tumors after intrapleural injection at a higher rate than the other mineral fibers tested (Wagner et al. 1985). The erionite from Oregon caused 40 out of 40 (100%) of the rats to develop tumors, and the Turkish erionite caused 38 out of 40 (95%) of the rats to develop tumors (Wagner et al. 1985). Comparing this to chrysotile, only 19 out of 40 (47.5%) rats develop mesothelioma, supporting a view that erionite is around twice as toxic as chrysotile after intrapleural injection (Wagner et al. 1985). This agrees with the intraperitoneal research by Davis et al. (1991) mentioned previously. Again, the biological activity of chrysotile in this study is higher than expected.

Wagner et al. (1985) also found that inhalation of erionite was extremely carcinogenic in rats exposed to dust concentration of 10 mg/m³ for 7 hours/day, 5 days a week, for 1 year. Out of the 28 rats that inhaled erionite from Oregon, 27 of them developed mesothelioma 12 months later. On the other hand, 0 of the 28 rats exposed to crocidolite developed mesothelioma, and only 1 developed another form of cancer (squamous cell carcinoma). As discussed previously, dosage is not the only factor in determining carcinogenicity (i.e., fiber dimension). Wagner et al.

(1985) explained that erionite and crocidolite had a ‘... similar range of fibre lengths and diameters ...’. To fully understand this study, one would need to measure the percentage of fibers of each fiber type according to length and aspect ratio. These data were not collected.

Methodology for estimating potency

Chemical composition and fiber length data were collected from various air samples recorded in the literature. These data were used to compare the erionite found throughout North America with the erionite responsible for the outbreak of mesothelioma in the Cappadocian region of Turkey (Baris et al. 1987). The following is the formula derived by Korchevskiy et al. (2019) that relates mesothelioma potency with chemical composition and fiber length:

$$\log_{10}(R_M) = -4.70 + 2.08\log_{10}(\text{SiO}_2) + 1.33\log_{10}(\text{AR} - 3) + 0.34\log_{10}(\text{Fe}_2\text{O}_3) - 1.51\log_{10}(\text{MgO}) \quad (1)$$

where R_M is the mesothelioma potency factor (a percent of expected mortality from mesothelioma per unit of cumulative exposure), AR is the median aspect ratio, and SiO_2 , Fe_2O_3 , and MgO are the percent compositions for the respective compounds.

$$R_M = 100 * \frac{O_M}{E_{Adj} * X} \quad (2)$$

Equation 2, originally from Hodgson and Darnton (2000) and used again in Darnton (2023), defines the mesothelioma potency factor (R_M) when it is derived from epidemiology data ‘where is the number of mesothelioma deaths, is the total expected deaths from all causes adjusted to the age of first exposure of 30, and is the mean cumulative exposure in fibers/cubic centimeter-years (f/cc-years)’ (Korchevskiy et al. 2019).

The aspect ratio and chemical composition data for erionite used in Korchevskiy et al. (2019) was derived from multiple articles (Dogan et al. 2006; Lowers et al. 2010; Carbone et al. 2011). Similar to the steps used by Korchevskiy et al., we assembled the aspect ratio and chemical composition data from multiple articles that sample from the same locations. With the exception of Table 3, which was included to compare the mesothelioma potencies of erionite to other asbestos minerals, all data were collected independent of the (Korchevskiy et al. 2019) article.

Inputs for determining mesothelioma potency

General erionites (K, Ca, and Na)

Outside the regions focused on in this article, there have been locations of erionite deposits that have yet to be as well studied and documented. When discussing erionite, it is useful to estimate the relative toxicity of the various fiber types (e.g. K, Ca, and Na). To fill this gap and compare the three general types of erionite, mesothelioma potency factors were calculated for the general chemical compositions of

Table 1. The model predicted mesothelioma potency factors for various aspect ratios of the general erionite compositions.

Erionite-Ca						
SiO ₂ :	64.91	Fe ₂ O ₃ :	0.07	MgO:	0.51	
AR	4	7	10	13	16	Mean
R _M	0.13	0.83	1.74	2.79	3.96	1.89
Erionite-Na						
SiO ₂ :	66.91	Fe ₂ O ₃ :	1.47	MgO:	0.40	
AR	4	7	10	13	16	Mean
R _M	0.56	3.54	7.46	11.98	16.99	8.11
Erionite-K						
SiO ₂ :	71.58	Fe ₂ O ₃ :	2.77	MgO:	0.87	
AR	4	7	10	13	16	Mean
R _M	0.25	1.59	3.35	5.38	7.63	3.64

The chemical composition data were determined from the standard chemical formulas of erionite-Ca, erionite-Na, and erionite-K from Dogan and Dogan (2008). As shown, the mean potency factors and the potency factors at an assumed median aspect ratio of 10 are (unsurprisingly) similar within each erionite group. For purposes of this article, the potency factors for these general erionites can be compared to erionites by region as well as the asbestos fibers in Table 3 using this same model.

erionite-Ca, erionite-Na, and erionite-K at varying aspect ratios.

These general erionite chemical compositions have been presented by Dogan and Dogan (2008). These values (converted to SiO_2 , Fe_2O_3 , and MgO) are shown in Table 1. Korchevskiy et al.’s model was used to calculate the mesothelioma potency factors at the chosen aspect ratios (Figure 2). This table should serve as a reasonable estimate of the potencies of the various types of erionite.

Rome, Oregon

Sufficient data for the median aspect ratio and chemical composition were identified in the literature for erionite from Rome, Oregon. Table 2 presents an estimate for the mesothelioma potency based on the median aspect ratio reported by Yanamala et al. (2018) and average chemical composition data from Eberly Jr. (1964) and Dogan et al. (2006).

Killdeer Mountain area

Although both aspect ratio and chemical composition data were found for the Killdeer Mountain Area, some shortcomings in the data were identified. Chemical analysis by Lowers et al. (2010) found that this erionite contained no iron of any oxidation number and recorded the percent composition as 0.00. The absence of iron is unusual, but it has been hypothesized that the iron in erionite is from impurities, and pure erionite would not contain any (Gualtieri et al. 2016). In fact, Ballirano et al. (2009) removed iron from the chemical composition of erionite, claiming it was from impurities (Ballirano et al. 2009). Korchevskiy et al.’s (2019) model that estimated mesothelioma potency factors takes the log-base-10 of the percent composition of iron oxide, and a value of zero is not computable in a logarithmic function and will result in an undefined value.

A different publication, Saini-Eidukat and Triplett (2014), evaluated the chemical compositions of 16 erionite-

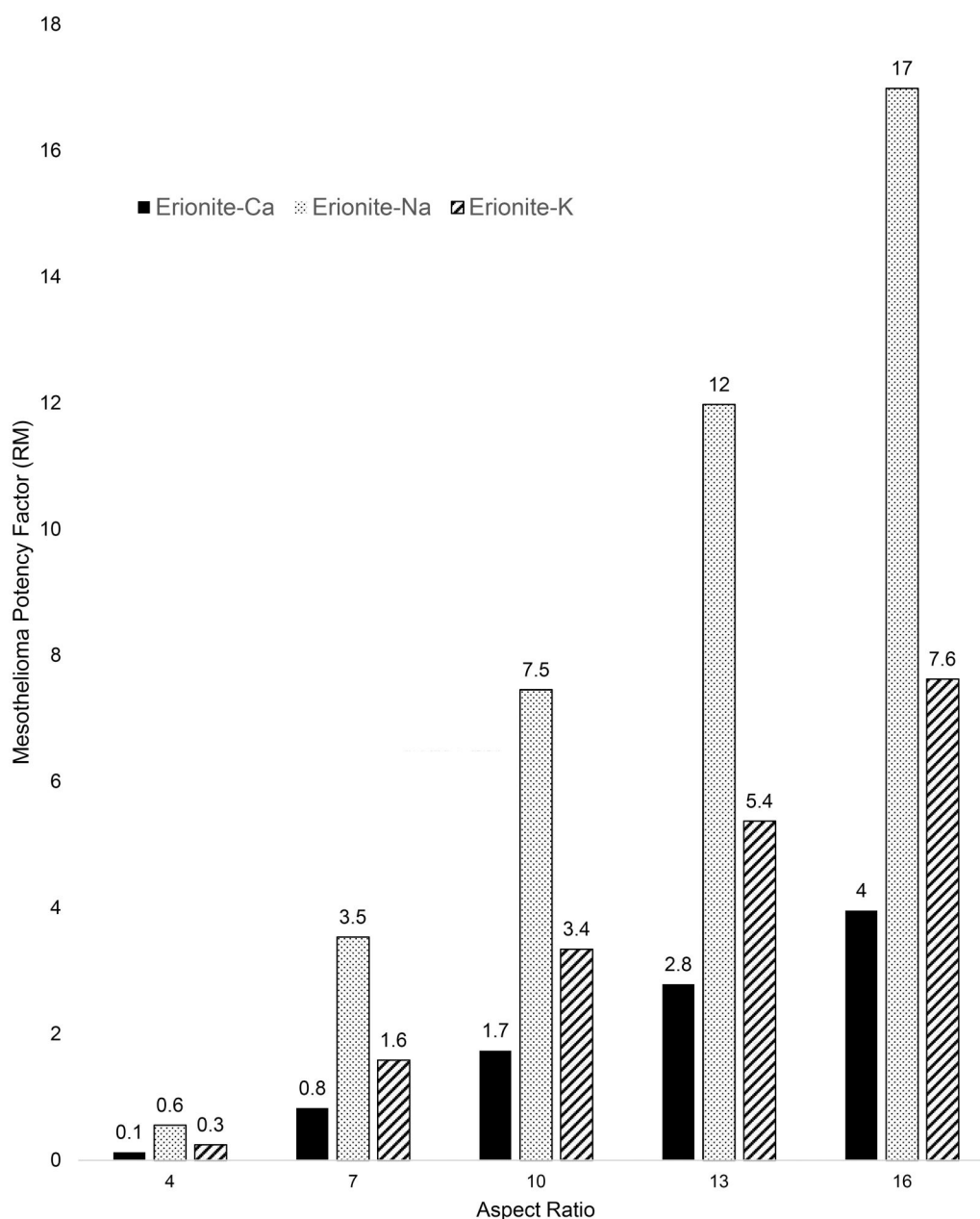


Figure 2. The model predicted mesothelioma potencies (R_M) of the various erionite types (Ca, Na, and K) discussed in Dogan and Dogan (2008) at different aspect ratios.

containing samples from the Killdeer Mountains. Erionite is often found in deposits with other zeolites, like offretite, and minerals, like quartz. The soil samples from this article had varying amounts of offretite, chabazite, heulandite, clinoptilolite, calcite, dolomite, ankerite, and quartz, in addition to erionite (Saini-Eidukat and Triplett 2014). Even so, the SiO_2 (55.48%) and MgO (1.68%) content from Saini-Eidukat and Triplett (2014) was similar compared to the SiO_2 (60.33%) and MgO (1.51%) content from Lowers et al. (2010). Saini-Eidukat and Triplett (2014) found there to be a 0.75% composition of Fe_2O_3 in samples containing erionite from the Killdeer Mountains. This value was used as the Fe_2O_3 content for the Killdeer Mountain erionite (as it appears to be a more reasonable estimate than 0.00). Carbone et al. (2011) found chemical compositions of

Killdeer erionite to be 'similar' to that of Turkish erionite, which has 1.25% Fe_2O_3 (Table 3).

Berry et al. (2019) identified the aspect ratios of two groups of samples from Dunn County (in the Killdeer Mountain area) gravel. One sample was prepared by the fluidized bed asbestos segregator (FBAS) method, and EPA collected the other through activity-based sampling (ABS). The Dunn County sample prepared by FBAS had a median aspect ratio of roughly 6.3, and the sample prepared by ABS had a median aspect ratio of 5.5 (note that these values were approximated from a graph) (Berry et al. 2019).

Another aspect ratio was identified by Carbone et al. (2011), who compared air sampling data from Dunn County, North Dakota with air sampling data from the Boyali and Karlik villages of Turkey. The study found the

chemical composition of the two erionites to be very similar, with differences in the median aspect ratio being roughly 5.83 and 11.67 for North Dakota and Turkey, respectively.

The aspect ratios from erionite in the Killdeer Mountain area, 5.5, 5.8, and 6.3, were used in Table 2 and a median aspect ratio of 5.8 was used in Figures 3 and 4 and Table 3.

Erionites in Nevada, Arizona, and California

For some of the regional erionites, published median aspect ratios of 5.8 (Killdeer Mountain erionite), 11.67 (Turkish erionite), and 12.94 (Rome, Oregon erionite) were used in this article. For Lander County, Nevada; Bowie, Arizona; and San Bernardino County, California, there were not sufficient data on the aspect ratios of erionite fibers in the respective areas. However, there was adequate chemical composition data that could be used to assess the possible potency of erionite in the region.

For these erionites, the mesothelioma potency factor was calculated at varying aspect ratios to indicate how toxic the erionite of each region may be. The standard median aspect ratios of 4, 7, 10, 13, and 16 were chosen because aspect ratios found in the literature tended to fall within this range (Lowers et al. 2010; Farcas 2015; Yanamala et al. 2018). Based on the known median aspect ratios (5.8, 11.67, and 12.94) of erionites, an assumed median aspect ratio of 10 seemed like a reasonable estimate for these erionites in which a median aspect ratio was not available in the literature. Erionite is reported to have similar dimensions to crocidolite (Wagner et al. 1985), which ranged from 9.99 to 12.6 aspect ratios (depending on region) in Korchevskiy et al. (2019).

Lander County, Nevada

Papke (1972) has corrected chemical composition data that was collected around Lander County by Sheppard and Gude (1969). Gude III and Sheppard (1981) later collected erionite samples from Reese River, which is near Lander County, and reported chemical composition data. Mattioli et al. (2016) also analyzed the chemical composition of erionite from Lander County. The Lander County samples from all three of these articles were averaged and used in Table 2 to estimate the mesothelioma potency factor of erionite in Nevada.

Bowie, Arizona

Nearby Bowie, Arizona, chemical composition data were recorded in Clifton (Greenlee County) and Thumb Butte (Graham County) by Wise and Tschernich (1976). The data from these two locations were averaged and used for the chemical composition in Table 2 to estimate the mesothelioma potency factor of Arizona erionite. This was the only instance found in the literature of an analysis that reported the chemical composition of erionite in Arizona.

San Bernadino, California

Chemical composition data of sedimentary rock were collected in the southern flank of the Cady Mountains in San Bernardino County, California, by Sheppard et al. (1965).

Erionite was one of the few zeolites identified in the chemical analysis, and the chemical composition reported in this article is used in Table 2 for the calculation of mesothelioma potency. This was the only instance of a chemical analysis that reported the composition of erionite in San Bernardino that was identified.

Results

Table 2 and Figure 3 present the estimated mesothelioma potency factors for erionite in various regions based on the fibers' chemical composition and aspect ratio. Table 3 and Figure 4 compare these mean erionite potencies to the model-estimated potencies for asbestos from Korchevskiy et al. (2019).

Discussion

To date, there has not been a cluster of mesothelioma cases in any of the western states in the U.S. despite the presence of the erionites in various soils. A few authors have suggested this must pose a mesothelioma hazard, yet due to a small sample size and a lack of lung biopsy data, one cannot causally associate any reported mesothelioma in the U. S. with exposure to erionite (Weissman and Kiefer 2011). The lack of a cluster is either because the erionite is less potent than predicted, the exposure is quite low, or the population is too small (since erionite deposits are typically in areas that are scarcely populated).

Based on Korchevskiy et al.'s (2019) model and the available published information on erionite, the estimated mesothelioma potency factors for five different erionites in the western United States range from 0.19 to 11.25, and the average was around 3.5 (around six times more potent than crocidolite).

As explained in Korchevskiy et al. (2019), it is remarkable that Coffin et al. (1992) estimated the mesothelioma potency of erionite as being 5.6 times higher than for crocidolite, based on human data. This suggests that both Korchevskiy et al.'s estimation of Turkish erionite (6.4 times more potent than African crocidolite) and our average potency of erionite are reasonable. Based on these results, the average potency ratio of North American erionite, crocidolite, amosite, and chrysotile is roughly 3000:500:100:1. Erionite potency may be highly variable, dependent on the chemistry, and aspect ratios of the inhaled fibers.

Aspect ratios

The importance of aspect ratio is apparent when one examines the mesothelioma potency factors estimated for Lander County, Nevada, which ranged from 0.09 to 2.70, as a result of changing the aspect ratio from 4 to 16. To somewhat standardize the data, one can assume a median aspect ratio of 10 in the absence of published medians. The use of the median aspect ratio was intended to limit the effect of different preparation methods and the chance that a few extremely large or small fibers may skew the

Table 2. Chemical compositions and model predicted mesothelioma potency values of erionite fibers at different locations across the western United States.

Location	SiO ₂	Fe ₂ O ₃	MgO	AR	R _M
Rome, Oregon (Eberly 1964 and Dogan 2006 for chemical composition; Yanamala et al. 2018 for AR)	60.76	3.51	0.96	12.94	3.54
Lander County, Nevada (Papke 1972)	58.79	0.69	0.96	4 7 10 13 16 Mean R _M	0.09 0.56 1.18 1.90 2.70 1.29
Bowie, Arizona (Wise and Tschernich 1976)	58.38	0.01	0.76	4 7 10 13 16 Mean R _M	0.03 0.19 0.40 0.64 0.91 0.43
San Bernardino County, California (Sheppard et al. 1965)	59.16	1.48	0.26	4 7 10 13 16 Mean R _M	0.85 5.34 11.25 18.08 25.62 12.23
Killdeer Mountain Area (Lowers et al. 2010; Carbone et al. 2011; Saini-Eidukat and Triplett (2014 for Fe ₂ O ₃ only)	60.33	*0.75	1.51	5.5 5.8 6.3 Mean R _M	0.17 0.19 0.24 0.20

When median aspect ratios were unknown, values of 4, 7, 10, 13, and 16 are presented. Mean potency factors and the potency factors at an assumed median aspect ratio of 10 are (unsurprisingly) similar within each location.

*Iron oxide was likely considered an impurity and was reported as zero in Lowers et al. (2010). This value was substituted for 0.75, the iron oxide composition of mainly erionite-containing samples from another study (Saini-Eidukat and Triplett 2014); however, these samples were known to be contaminated with other minerals.

data, which would be the case if the mean aspect ratio was used.

It is important to be aware that the potencies of any fiber may vary from the expected potencies presented in this article. This article was based on the typical chemical compositions and median aspect ratios. Commercial asbestos fibers have typically been classified and sold as different grades. Aspect ratios may vary between these grades, just as it has been shown to vary across geographical regions (Korchevskiy et al. 2019). These different variations or grades likely present different risks of mesothelioma. Specific to erionite, the median aspect ratios of those in the Killdeer Mountain area (~6) seem to be lower than those in other areas like Rome, Oregon (~13) and Turkey (~12).

Turkish vs North American erionites

Our analysis predicts that the potency of erionite in the western United States may range between roughly 20 times less potent (in the Killdeer Mountain area) to 3 times more potent (in San Bernardino County, California) than the model predicted potencies for Turkish erionite. It is important to note that this range of mesothelioma potency factors is for assumed aspect ratios of 10 for those erionites in which the median aspect ratios are unavailable (Nevada, Arizona, California). The average of the modeled potency factors of North American erionite (3.5) is roughly the same as that of Turkish erionite (4.5).

Risks associated with erionite exposures in the U.S

To provide context to the airborne concentrations of erionite in, for example, North Dakota as reported by Carbone et al. (2011) (0.061 f/cc during garage cleaning) and Custer National Forest as reported by Beaucham et al. (2015) (0.009–0.096 f/cc full shift exposures for forestry operations), possible mesothelioma risks are presented.

If one assumes that it would be plausible for a road worker, forestry worker, or farmer to be exposed to an average airborne concentration of 0.05 f/cc of erionite over an 8-h workday, then one can estimate the cancer risk. Assuming 20 years of exposure to these workday conditions, then the lifetime dose is 1 f/cc-year. Further assuming a potency factor of 3.5 (the average predicted potency factor of North American erionites in this study), a 1 f/cc-year cumulative exposure to erionite would present a theoretical 3.5% (or 35 in 1000) increased chance of dying from mesothelioma. By most standards, this would be considered an appreciable risk.

Limitations

The accuracy of Korchevskiy et al.'s (2019) model for predicting the mesothelioma potency factors seems to be reasonable for the fibers that he evaluated since the model fit the results of epidemiology studies. In order to confirm our estimated mesothelioma potency factors for the erionites in the western United States, an epidemiology study or a series of animal tests would need to be conducted. The cost of a

Table 3. Chemical composition and calculated mesothelioma potency factors using Korchevskiy et al.’s model for erionite and asbestos fibers.

Fiber classification	Location	AR	SiO ₂	Fe ₂ O ₃	MgO	R _M
Erionite	Rome, Oregon	12.94	60.76	3.51	0.96	3.54
	Lander County, Nevada	10	58.79	0.69	0.96	1.18
	Bowie, Arizona	10	58.38	0.01	0.76	0.40
	San Bernardino, California	10	59.16	1.48	0.26	11.25
	Killdeer Mountain, N and S Dakota	5.8	60.33	*0.75	1.51	0.19
	Turkey	11.67	68.09	1.25	0.67	4.53
Crocidolite	Cape Province	11.9	51.03	17.91	2.88	0.71
	Australia	9.99	52.68	18.48	3.90	0.35
Amosite	South Africa	8.59	50.23	2.89	6.01	0.065
Chrysotile	Quebec	7.09	40.20	0.50	39.90	0.0009
	Zimbabwe	7.09	39.70	0.30	40.30	0.0010
	Russia	7.09	38.10	1.40	37.70	0.0018

When median aspect ratios were unknown, erionite fibers had an assumed median aspect ratio of 10 (there were known median aspect ratios of 12.94 for Rome, Oregon, 5.8 for the Killdeer Mountain area, and 11.67 for Turkish erionite). The Turkish erionite and asbestos fiber data was taken from Korchevskiy et al. (2019).

*Iron oxide was likely considered an impurity and was reported as zero in Lowers et al (2010). This value was substituted for 0.75, the iron oxide composition of mainly erionite-containing samples from another study (Saini-Eidukat and Triplett 2014); however, these samples were known to be contaminated with other minerals.

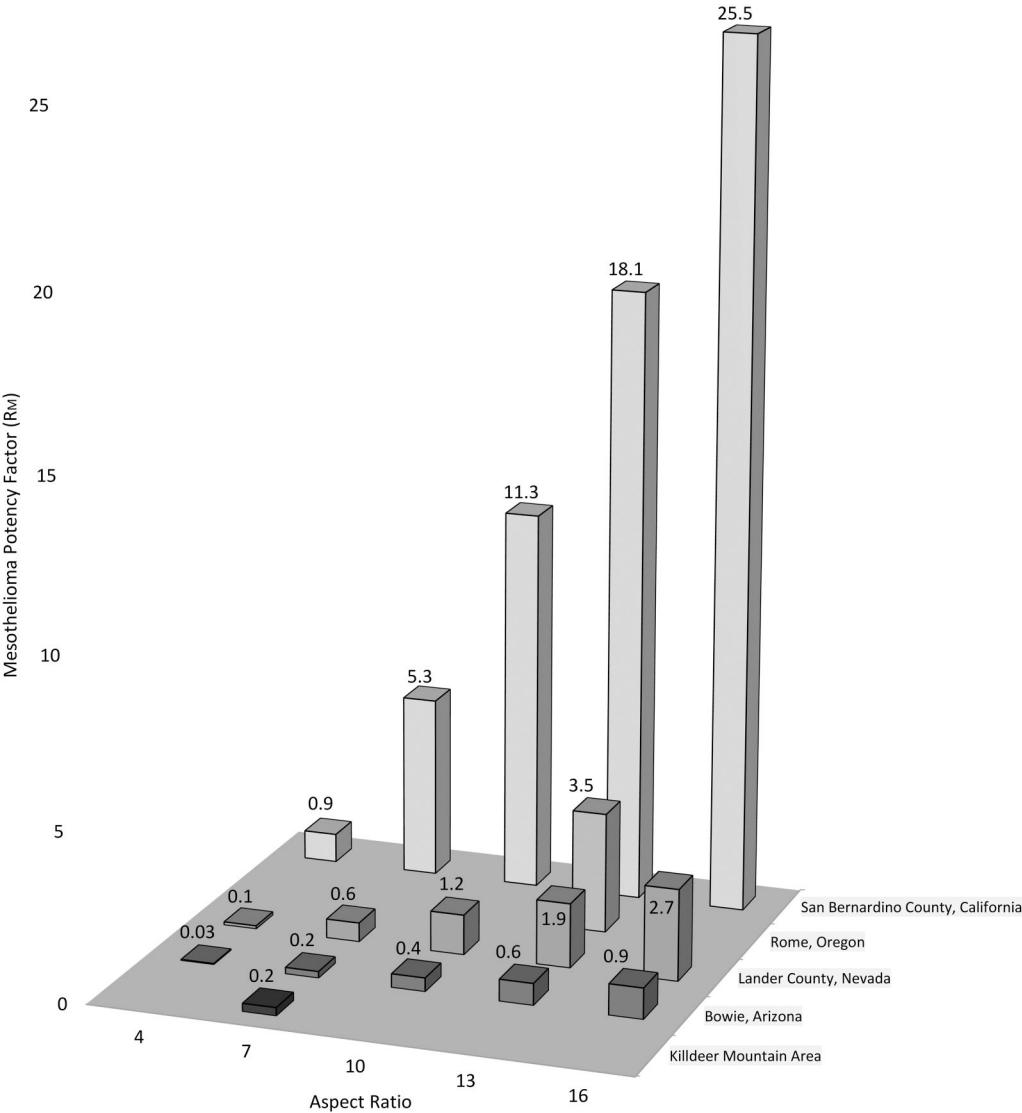


Figure 3. Mesothelioma potencies (R_M) of the erionite compounds in 5 different regions based on the model described in Korchevskiy et al. (2019) with chemical composition and aspect ratios as inputs.

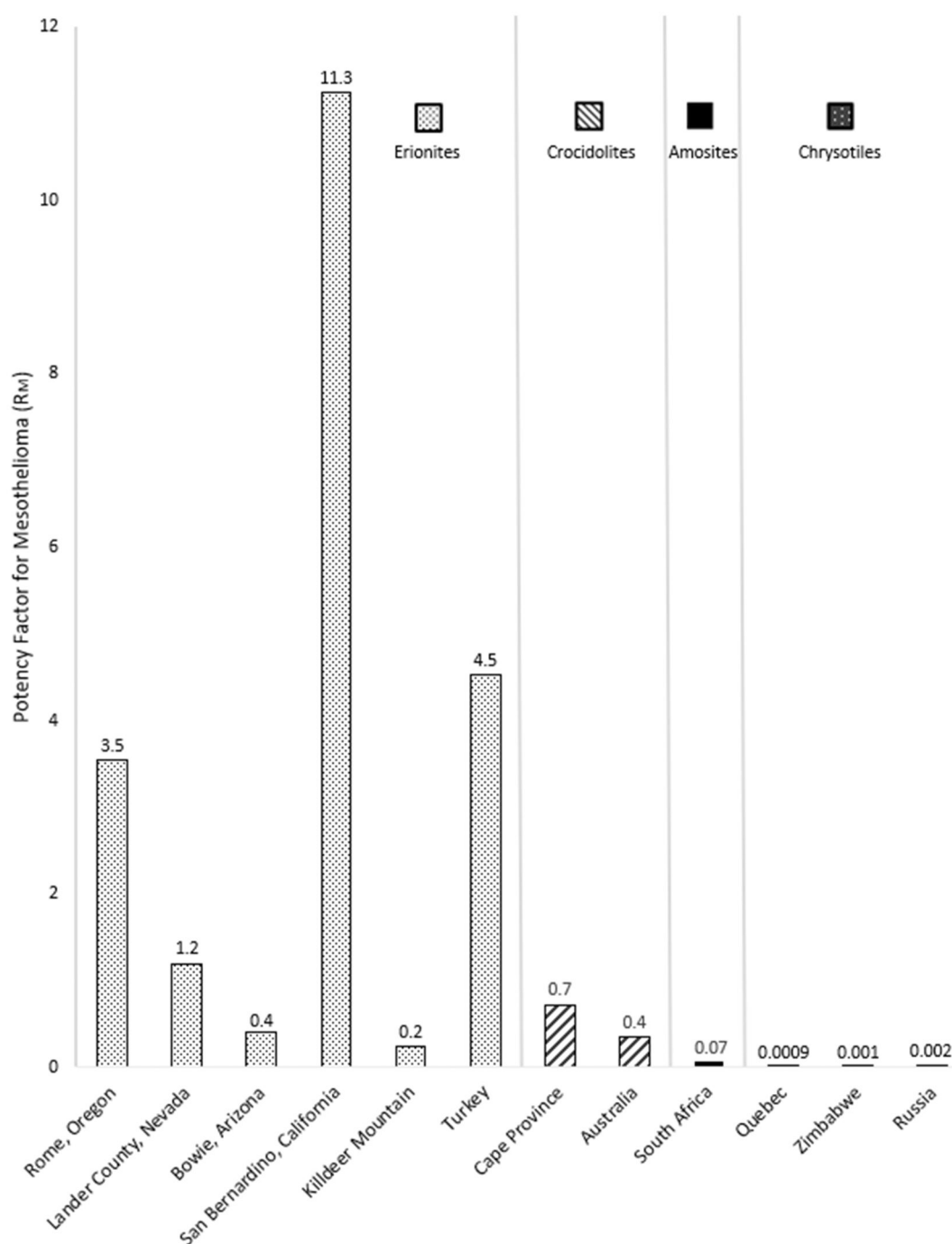


Figure 4. Mesothelioma potency factors for different types of fibers from various locations. Chrysotile (Quebec, Zimbabwe, and Russia), amosite (South Africa), crocidolite (South Africa and Cape Province, Australia), and Turkish erionite are from Korchevskiy et al. (2019). The rest were calculated by the authors of this paper. When the median aspect ratios of erionites were unknown (Nevada, Arizona, and California), they were assumed to be 10.

series of thoughtful animal studies would be so large as to likely require some amount of federal funding.

It should be noted that other factors, outside of those evaluated in this model, such as tensile strength, surface charge, and flexibility have long been known to influence the toxicity of inhalable fibers (Wylie 1979). However, these characteristics cannot be determined from phase-contrast microscopy nor transmission electron microscopy and have thus not been frequently used to characterize hazardous fibers or assess potency. Korchevskiy et al. (2019) were able to successfully predict relative fiber potency based on aspect

ratio and limited chemical composition without considering such factors.

Another issue that deserves some level of attention is the mechanism of action (MOA) for erionite's potency for producing mesothelioma. It has been hypothesized that erionite fibers cause '[potassium] binding through cation exchange after phagocytosis' or that erionite fibers absorb cytosolic calcium. Di Carlo et al. (2023) studied both of these mechanisms and found that erionite fibers will bind potassium after phagocytosis, but the evidence that they absorb cytosolic calcium is not present. This affects homeostasis and

causes excessive pulmonary toxicity. Their article is one of the few that discusses the MOA of erionite in lungs, and it has not been corroborated with any studies in actual lungs. This study only used simulated lung fluid, so more studies would need to be done to fully understand the MOA of toxicity due to erionite.

Closing thoughts

The erionite mesothelioma potency factors presented in this article were predicted based on the chemical composition and aspect ratio of the fibers. The results supported the view that some erionite deposits in the United States may have similar potency to the Turkish erionite (although precision is limited based on the available data). The mesothelioma potency factors were estimated in certain areas to approach 20 times that of crocidolite, a well-known and extensively researched human carcinogen.

Disclosure statement

The purpose of this article was to share information regarding the estimated mesothelioma potencies of various erionites found in North America. The data were obtained from various published sources. Dr. Paustenbach has served as an expert in asbestos litigation for various clients since 2000. No lawyers, nor the companies they represent, asked us to prepare this article, and none were involved in the analysis of the data or conclusions of the article. Nobody other than the author's read it prior to submission. The authors are solely responsible for the content of this article.

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Data availability statement

All data came from published and publicly available literature. All calculations are presented within the article or its Supplementary materials.

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Appendix I. Descriptions of known erionite deposits in the Western United States

Rome, Oregon

In Oregon, erionite is commonly found in Rome, Barney Lake, and Durkee (Sheppard 1996). Although erionite was first discovered in Durkee, this article focused on erionite from Rome, Oregon, the most prevalent area discussed in the literature. In Rome, there is a 550 square kilometer area called the Miocene Rome beds which contain erionite-bearing rocks (Sheppard 1996). These beds are at least 100 m thick and are most abundant in two conspicuous tuffs (Sheppard and Gude 3rd 1993; Sheppard 1996). These two tuffs are classified as the lower and upper marker tuff. The lower tuff is around 3–6 m thick and commonly consists of major amounts of erionite, nearly 100% (Sheppard 1996). This tuff has become the primary source of material used in biological experiments (Sheppard 1996) which had been studied in many of the experiments reported in this article. The erionite found in the lower tuff appears as ‘... individual acicular or rodlike crystals and as clusters of acicular crystals’ (Sheppard 1996). The upper tuffs are 6–7 m thick, but only one meter thick contains erionite and the upper part of the one meter thick area contains as much as 80% erionite (Sheppard 1996).

The erionite deposits in Rome, Oregon, have been one of the most studied areas in North America regarding erionite toxicity. Erionite-K has often been found in the Rome, Oregon area (Dogan et al. 2006; Dogan and Dogan 2008; Dogan et al. 2008; Croce et al. 2015) but Berry et al. (2019) found significant calcium peaks in samples taken from Rome, Oregon that would indicate erionite-Ca may be present as well. This illustrates that depending on the area where a sample is taken, the results can be quite different (which seems true for most mined materials).

Lander County, Nevada

Erionite in Nevada is primarily found in the central region near the Cenozoic lakes of Jersey Valley. This erionite is found in silicic, vitric tuffs and is described as ‘... common and abundant ...’ (Deffeyes

1959; Sheppard 1996). These tuffs can range in thickness from less than 1 cm to more than 1 m with the compositions of these tuffs ranging from trace amounts of erionite to nearly 100% erionite (Sheppard 1996). The beds where these tuffs occur in Jersey Valley extend for about 5.5 km and can coexist with analcime, chabazite, clinoptilolite, mordenite, and phillipsite, and (most commonly) clinoptilolite (Sheppard 1996). Papke (1972) reported that erionite has been found exposed on the sides of hills and cliffs and is occasionally on the surface layer (top 18 inches) of rock in Central Nevada (Papke 1972).

Bowie, Arizona

Erionite in Arizona has been exclusively found in a band running from the state’s center to the southeastern part of the state. The amount of erionite in this location is mainly unknown or very rare, except near Bowie, Bear Springs, and Wikieup. The main area in which erionite is found is Bowie, Arizona. In Bowie, there is a ‘zeolite deposit’ that has been mined intermittently since 1962 for chabazite (Eyde et al. 1987). This deposit is formed in tuffs that are 22–155 cm thick and crops out discontinuously for approximately 15 km (Sheppard 1996). Only the bottom 10–20 cm is mined for chabazite and erionite has been found in trace amounts in this section (Sheppard 1996). The rest of the overlying, thin-bedded portion of the deposit is not processed (Sheppard 1996). Sheppard (1996) states that ‘the erionite commonly occurs in stubby bundles in both parts of the tuff’ (Sheppard 1996).

San Bernardino County, California

Erionite in San Bernardino County is located in upper Cenozoic rocks and is usually associated with other zeolites in this area with the erionite content of the tuff being 20% or less (Sheppard and Gude 1969). Erionite is also prominent in the Cady Mountains and Lake Tecopa, where it makes up nearly 100% of certain tuffs (Sheppard 1996). Sheppard described that there is a tuff that sticks out from the rest that is especially abundant in erionite at Lake Tecopa, that crops out along the Amargosa River about 14 km (Sheppard 1996). There are also a few more areas in San Bernardino County where erionite has been identified, but mostly in trace amounts.

Killdeer Mountain Area

The Killdeer Mountain Area, for the sake of this article, will include erionite found in Custer National Forest in eastern Montana, Dunn County in western North Dakota, and Harding County in northwest South Dakota. A chemical composition analysis of samples taken from Dunn County, Killdeer Arikaree Formation, and the Custer National Forest found that soil from the Custer National Forest contained no erionite and instead consisted of offretite (Berry et al. 2019). However, samples from Dunn County and Killdeer Arikaree Formation contained predominately erionite, with a few particles of offretite (Berry et al. 2019).