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QUANTITATIVE GEOMORPHIC ANALYSIS OF ASBESTOS DISPERSION AND POLLUTION FROM NATURAL SOURCES: THE CASE-HISTORY OF THE POLLINO NATIONAL PARK, SOUTHERN ITALY

ABSTRACT: BENEDUCE P., DI LEO P., GIANO S.I. & SCHIATTARELLA M., *Quantitative geomorphic analysis of asbestos dispersion and pollution from natural sources: the case-history of the Pollino National Park, southern Italy*. (IT ISSN 0391-9838, 2012).

A multidisciplinary study has been carried out on the dispersion modalities of asbestos minerals from ophiolites outcrops in the area of the Pollino National Park (Calabria-Lucania border, southern Italy) by integrating geological and geomorphological mapping, quantitative geomorphic analysis, petrological and mineralogical analyses of outcropping crystalline-metamorphic rocks, aerosol analyses, and remote sensing investigations.

Large amount of asbestos minerals have been recognized in the ophiolitic suites outcropping at the Calabria-Lucania border. Specifically, tremolite-actinolite and chrysotile have been recognized in the metabasite and serpentinite samples by means of thin sections analyses and X-ray powder diffraction. Asbestos fibres have been also recognized in the aerosols sampled in the study area by SEM-EDS analysis.

The spreading out of ophiolite-bearing rocks in areas far away from their outcrops by natural running water (i.e. sheet wash and fluvial processes) has been evaluated by comparing different geomorphic indexes estimated for each of the seven catchment basins of the study area (i.e. the exposure index I and the morphometric parameters Tu and D). The relevant dispersion of the asbestos minerals by running water is a consequence of the cataclastic conditions of the serpentinite outcropping at the Calabria-Lucania border, although the peculiar geomorphological characteristics of each drainage basin play a crucial role in the dispersal of these minerals even far from their outcrops.

This study allowed to assess the degree of environmental hazard due to release of asbestos fibres. The comparison of natural and human factors in controlling asbestos release in areas characterized by different morphological conditions revealed that erosional (mainly fluvial) processes promoted an intense spreading of asbestos minerals, even in an area wider than the original ophiolite (mainly serpentinite) outcrops.

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KEY WORDS: Environmental Geomorphology, Asbestos minerals, Erosion estimation, Pollino National Park, southern Italy.

RIASSUNTO: BENEDUCE P., DI LEO P., GIANO S.I. & SCHIATTARELLA M., *Analisi geomorfica quantitativa della dispersione e dell'inquinamento da amianto rilasciato da fonti naturali: il caso del Parco Nazionale del Pollino in Italia meridionale*. (IT ISSN 0391-9838, 2012).

Vengono qui presentati i risultati dell'indagine geomorfologico-ambientale condotta nel territorio del Parco Nazionale del Pollino sulla dispersione e potenziale inquinamento da amianto rilasciato dalle rocce ofiolitiche del Confine calabro-lucano. Lo studio è stato basato su rilievi di terreno e telerilevamento (ai fini della redazione di cartografia geologica e geomorfologica), corroborato da campionature ed analisi di rocce, polveri e aerodispersi (per la determinazione quali-quantitativa delle fibre), e metodologicamente finalizzato all'analisi geomorfica quantitativa (per la stima dell'areale di dispersione delle pietre verdi lungo gli alvei fluviali).

Le successioni ofiolitiche al confine calabro-lucano appartenenti alle Unità Liguridi sono in parte caratterizzate da sezioni di basamento oceanico (gabbri e basalti, metabasiti, etc.) e masse serpentinizzate in cui sono contenuti minerali del cosiddetto *gruppo dell'amianto*. L'area di affioramento si estende a nord della morfostruttura carbonatica della Catena del Pollino, a formare una fascia ampia in media 10 km e lunga circa 40 km parallela alla dorsale montuosa. All'interno di questa fascia dominano le unità di copertura, in buona parte affette da metamorfismo di basso grado, ma anche gli affioramenti dei corpi serpentinitici risultano arealmente e volumetricamente significativi. Le rocce associate alla sequenza ofiolitica sono rappresentate da peridotiti serpentinizzate e metabasiti verdine o azzurrine in affioramenti di dimensioni variabili da qualche metro ad una decina di metri. Le prime contengono olivina, ortopirosseno, serpentino, lizardite, spinello, granulazioni di magnetite e rara clorite in vene, le seconde – caratterizzate da una tessitura cataclastico-milonitica che conserva parte dell'originaria struttura magmatica – presentano un assemblaggio mineralogico costituito da plagioclasi albitizzati e sericitizzati, epidoto, clorite, titanite, a luoghi glaucofane e lawsonite.

L'analisi mineralogica mediante diffrattometria di raggi X di alcuni campioni di metabasiti e di serpentiniti, provenienti dalla dorsale de La Fagosa, ha permesso di accertare la presenza di tremolite e actinolite, oltre a pumpellyite, phrenite, clorite e quarzo. Anche l'analisi quantitativa al SEM degli aerodispersi, campionati nei dintorni degli abitati di San Severino Lucano e Viggianello, rivela una concentrazione di fibre di amianto superiore ai valori massimi previsti dalle norme vigenti.

Il calcolo di alcuni parametri geomorfici (area del bacino **A**, densità di drenaggio **D**, numero di anomalia gerarchica **Ga**, indice di anomalia gerarchica **Da**, deflusso torbido unitario medio annuo **Tu**) e l'indicizzazione degli affioramenti delle successioni ofiolitiche ricadenti in diversi bacini idrografici hanno permesso di stabilire una relazione tra il deflusso superficiale e la diffusione del materiale proveniente dallo smantellamento erosivo delle rocce contenenti amianto, sia lungo le valli fluviali che in zone distanti dai luoghi sorgente. Del resto, l'utilizzo di tecniche di *remote sensing* aveva già confermato, grazie al riconoscimento della firma spettrale delle serpentiniti, la presenza in misura significativa di tali materiali lungo gli alvei fluviali, oltre a consentire agevolmente l'individuazione di masse serpentiniche, quando deprivate della copertura pedologica e del manto vegetazionale (Tramutoli & *alii*, 2002; Beneduce & *alii*, 2008).

La distribuzione delle litologie a maggior pericolosità di rilascio di fibre di amianto a ridosso della Catena del Pollino e la dispersione dei materiali detritici lungo le aste fluviali e in ambiente aereo su un areale ancora più vasto suggerisce la necessità dell'intensificazione del monitoraggio geoambientale nell'area del confine calabro-lucano, anche a causa del massiccio utilizzo antropico di inerti provenienti da affioramenti di serpentiniti.

TERMINI CHIAVE: Geomorfologia Ambientale, minerali dell'Amianto, stima dell'erosione, Parco Nazionale del Pollino, Italia meridionale.

TABLE 1 - «Greenstones» classification based on the amount of asbestos minerals contained in ophiolite rocks

Lithotype	Main minerals
serpentinite	antigorite, **chrysotile**, olivine, ortho- and clyno-pyroxenes, **amphibole tremolite**, talc, dolomite, garnet, spinel, chromite and magnetite
prasinite	feldspar, albite, epidote. amphibole **tremolite-actinolite**, glaucophane, clyno-pyroxenes and white mica
eclogite	monoclinic pyroxene, garnet, rutile, amphibole glaucophane
amphibole	horneblende, plagioclase, zoisite, chlorite, **anthophyllite**-gedrite
actinolite schists	**actinolite**, talc, chlorite, epidote, olivine
chlorite schists, talcosis and serpentinous	talc, chlorite, dolomite, **tremolite**, **actinolite**, serpentine, **chrysotile**, rutile, titanite, garnet
ophicalcite	talc, antigorite, **chrysotile**, **tremolite**, dolomite, calcite, olivine

INTRODUCTION

Asbestos is a term commonly used to refer to those silicate minerals showing a typical fibrous *habitus* and belonging to the serpentine and amphibole mineral groups. Monoclinic amphiboles, i.e. tremolite and actinolite (also known in their fibrous arrangement types as amphibole-asbestos) and fibrous serpentine, i.e. chrysotile (well known as serpentine-asbestos or «white asbestos») are the most common asbestos minerals.

Asbestos fibres dispersion in the environment is extremely dangerous because they may cause many kinds of cancer pathologies when inhaled (Cattaneo & *alii*, 2006, and references therein). Asbestos fibers can easily get into the atmosphere and hydrosphere due to their very small size fragmentation. Besides, their high resistance to heat and to chemical and biological agents also induces them to persist for a very long time in the environment. For all these reasons the Italian legislation set the limit of maximum concentration of asbestos fibres in the environment to 2 ff/l (fibres/litre).

At present, the Italian laws considers only tremolite, actinolite, anthophyllite, grunerite (amosite), riebeckite (crocidolite) and chrysotile as potential environmental pollutants. However, others fibrous and non-fibrous minerals with an asbestiform *habitus,* such as balangeroite, carlosturanite, antigorite, and diopside (Compagnoni & *alii*, 1983, 1985; Compagnoni & Groppo, 2006, among others), should be also considered among the asbestos fibres potentially dangerous if inhaled. A «natural» potential polluting source of asbestos fibres is represented by the mafic and ultramafic components of an ophiolitic suite. For this reason, the Italian legislation (D.M. 14/05/1996) has produced a classification of the so-called «greenstones» based on the amounts of the asbestos minerals carried by every rock-type (table 1).

Monitoring of asbestos pollution in air as well as in ground and surface waters has gathered momentum in the recent years. Discharging of materials containing asbestos fibres in the upstream of drainage basins and natural releases from rock outcrops in the headwater of rivers are considered the main causes inducing water pollution by asbestos fibres in the Balangero district, northern Italy (Buzio & *alii*, 2000). On the other hand, it has been demonstrated that human activity in mine operations from northern Greece contributes stronger than natural erosion to atmosphere pollution by asbestos fibers (Anastasiadou & Gidarakos, 2007). Indeed, human activity has strongly contributed, especially in the last century, to accelerate the geomorphic processes responsible of landscape evolution (Schiattarella & *alii*, 1998; Berglund, 2003). In urbanized areas «mankind» can be considered, similarly to natural processes, a geomorphic factor which intensity reaches a magnitude two to four times greater (Rivas & *alii*, 2006).

The present study deals with the dispersion analysis of material containing asbestos fibres from ophiolitc rocks in an area located in the Pollino National Park, at the Calabria-Lucania border (southern Italy), where they largely crop out. By integrating geological and geomorphological mapping, quantitative geomorphic analysis, sampling followed by petrological and mineralogical analyses of sampled rocks and aerosols, dispersion of material containing asbestos fibres has been monitored and natural to atrophic factors responsible of asbestos release have been compared.

In order to estimate the degree of environmental pollution caused by the natural release of asbestos-shaped fibres in the urbanized areas and in the whole catchments, the arrangement of ophiolite-bearing rocks and their spreading by runoff have been evaluated by means of a morphometric analysis in seven drainage basins (Sinni, Noce, Mercure, and Sarmento rivers and Frido, Rubbio, and Torno streams). Thin section and X-ray powder diffraction (XRD) analyses of rock samples have been carried out to identify rocks bearing asbestos minerals. Scanning Electron Microscopy (SEM-EDS) analysis of aerosols has been done to identify and quantify asbestos fibres dispersed in the atmosphere. Spectral signature processing by remote sensing based on a Multispectral InfraRed and Visible Imaging Spectrometer (MIVIS) has been previously performed to identify the spatial distribution of serpentinite bodies in the whole area of the Pollino National Park (Tramutoli & *alii*, 2002; Beneduce & *alii*, 2008).

GEOLOGY AND GEOMORPHOLOGY OF THE STUDY AREA

The study area is located at the Calabria-Lucania border in southern Italy, between the positive carbonate morphostructures of Lauria Mts and Pollino Ridge to the south-west and the Pliocene-Quaternary Sant'Arcangelo satellite basin to the north-east (fig. 1). This sector is mainly constituted of ophiolite-bearing successions («internal units») thrust on the Campania-Lucania platform carbonates (fig. 1) and forming the uppermost tectonic element of the southern Apennines (Knott, 1987; Bonardi & *alii*, 1988). The Pliocene north-verging out-of-sequence thrusting has carried the Mesozoic carbonate on the Liguride Units (Schiattarella 1996, 1998, and references therein). Toward the north-west, the lateral continuity of the Pollino carbonate ridge is interrupted by the Mercure intermontane basin (fig. 1) generated by Quaternary faulting (Schiattarella & *alii*, 1994; Schiattarella, 1996).

The Liguride Units, also known as «internal units» for their palaeogeographic and structural arrangement in the southern Apennine chain, are made of two main groups of terrains. The first group is represented by the Frido Unit, Cretaceous-Oligocene in age, and is composed of polydeformed metamorphic rocks with associated blocks of ophiolite-bearing and continental-type rocks. It is divided in two tectonic subunits (Monaco & *alii*, 1995; Schiattarella & *alii*, 2011), both affected by very low-grade metamorphism (Di Leo & *alii*, 2005). The ophiolitic rocks are tectonically interbedded in the Frido Unit, and are mainly represented by serpentinized peridotite and metabasite (Vezzani, 1968, 1970). Dark-green cataclastic serpentinite and associated metabasite rocks are made of lenticular bodies (fig. 2), which mark the tectonic contact between the phyllite and calc-schist subunits (Di Leo & *alii*, 2005). The second group is represented by a sedimentary succession constituted by a turbiditic sequence tectonically covered by the Frido Unit, and is composed, from the bottom to the top, of Crete Nere, Saraceno and Albidona Fms (Cilento Unit). Continental-type rocks like granofels, garnet gneiss, biotite gneiss are also present in the study area. Amphibolites gneiss, amphibolites schist, biotite light gneiss crossed by pegmatite and meta-diabase dikes also crop out

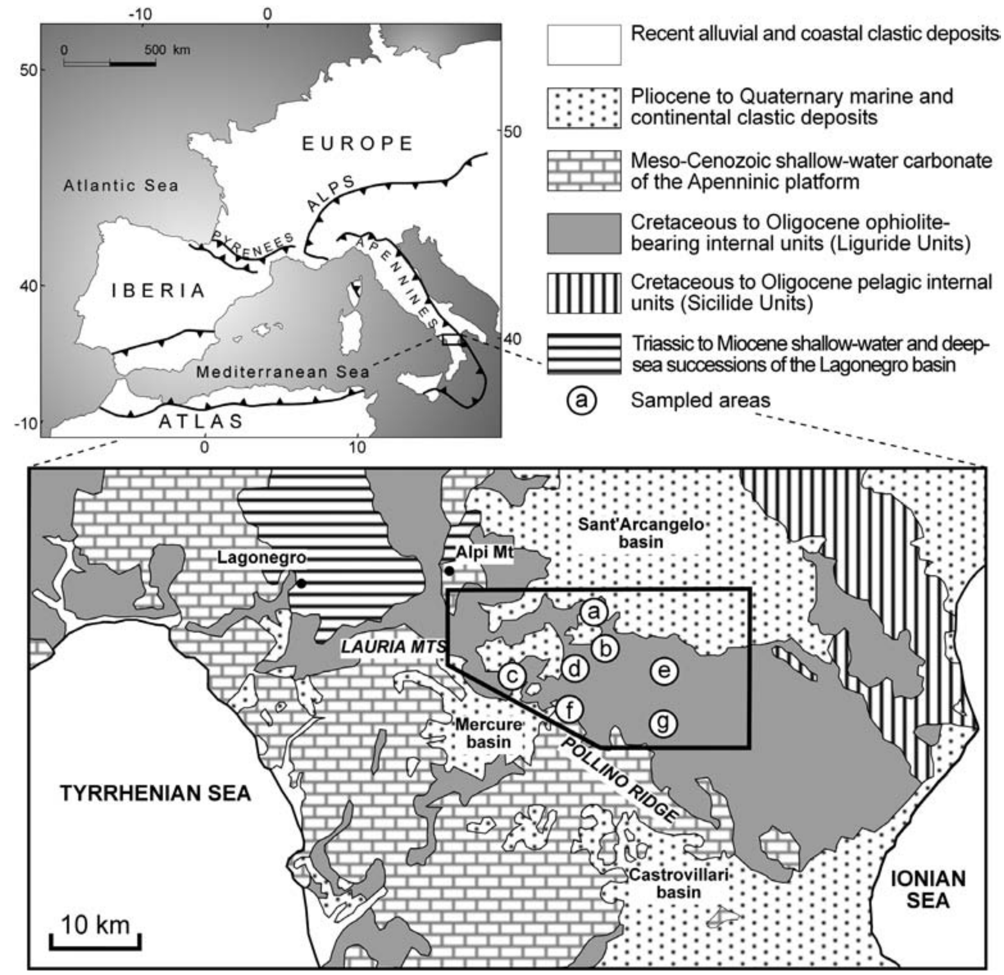

FIG. 1 - Geological sketch map of the Calabria-Lucania border. Sampled areas are included in the black frame. Toponyms: a) Pietrapica quarry; b) Timpa della Guardia; c) La Fagosa Ridge - Madonna dell'Alto; d) San Severino Lucano village; e) Mt Caramola - Timpa del Castello; f) Torno area; g) Timpa delle Murge.

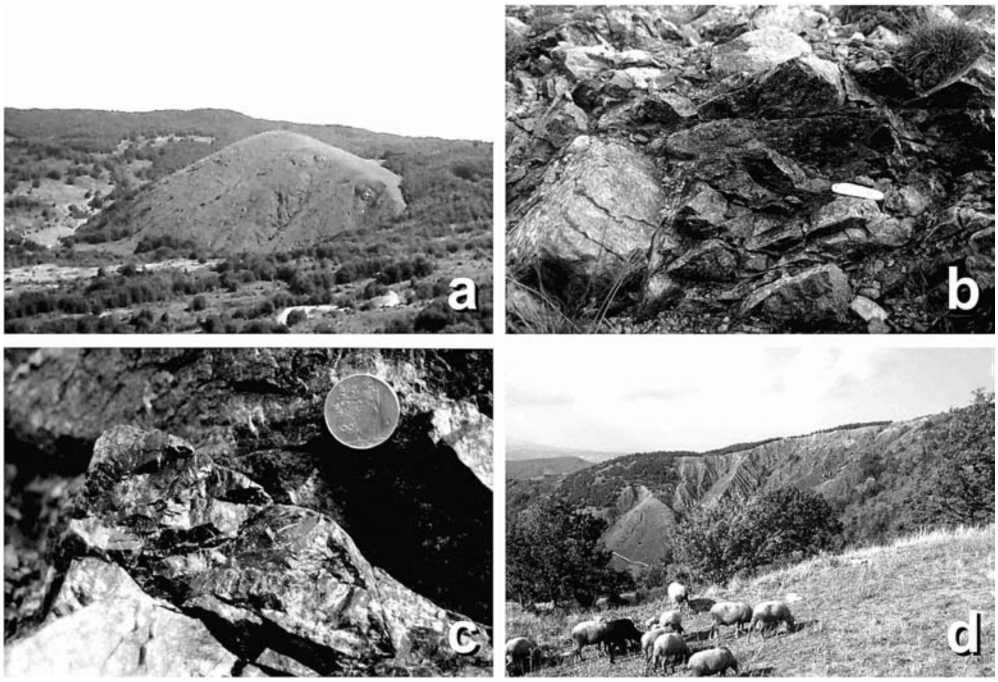

FIG. 2 - a) Serpentinite body of Mt. Pelato, tectonically embedded in the meta-phyllite of the Frido Unit; b) Timpa della Guardia cataclastic serpentinite near San Severino Lucano village; c) detail of the serpentinite shown in the previous photo; d) pseudo-badland landform in cataclastic serpentinite cropping out near the San Severino Lucano village.

in the area, although to a lesser degree. Marine to continental Pliocene-Pleistocene coarse-grained and pelite successions of the Sant'Arcangelo basin (Giannandrea & Loiacono, 2003; Schiattarella & *alii*, 2011, and references therein) unconformably overlay the previous tectonic and stratigraphic units in the northern portion of the Calabria-Lucania border (fig. 1).

The Frido Unit contains T-MORB-type basalts which underwent HP-LT conditions (P > 6 Kbar up to 8-10 Kbar; T < 400-450°). Rapid exhumation was inferred by aragonite relicts within calc-schists (Spadea, 1994). Among the North-Calabrian Unit, the Crete Nere Fm shows very low grade metamorphic conditions (cf. sub-greenshist facies of the Calabro-Lucano Flysch, after Monaco & *alii*, 1995). New constraints on the thermobaric evolution of the Liguride complex of the southern Apennines are provided by inorganic and organic thermal indicators (Invernizzi & *alii*, 2008). The phyllite Frido sub-unit underwent temperatures in the range of anchizone (250-300°C), according to data derived from both clay mineralogy and fluid inclusion microthermometry. Pressure estimates by white mica b_0 parameter are typical of accretionary wedges and in the range of 6-8 kbar. These data helped to better constraint the thermal evolution of the units belonging to the Liguride complex with respect to the timing of final exhumation at 5-6 My, as suggested by apatite fission tracks data (Invernizzi & *alii*, 2008).

Landscape evolution of the study area is strongly controlled by both lithology and structure. Rough landforms, sculptured on carbonate and crystalline-metamorphic rocks, contrast with the gentle slope and gully landforms modelled in clayey rocks. Seven drainage fluvial basins can be identified in the area (Sinni, Noce, Mercure, and Sarmento rivers and Frido, Rubbio, and Torno streams; fig. 3). Widespread landslides features occur in all these drainage basins. Summit of reliefs show relics of planation surfaces, Pleistocene in age or more ancient. Mesas sculptured in Pliocene to Pleistocene clastic successions mainly characterize the drainage basin of the Sinni River.

Watershed between Sinni River (a in figure 3) and Noce River basins and between Mercure River and Frido Stream basins (b and c in figure 3), included within the altimetric range 2005-2248 m, represents a fragment of the south-Apennine chain divide, which drives surface run-off to Tyrrhenian or Ionian seas.

The studied drainage basins undergo a Mediterranean climate regime: the stream-river water discharge is controlled by short and time-concentrated rainfall during Fall-Winter and Spring-Summer transitions. Fluvial patterns of Sinni, Sarmento, and Rubbio catchments are dendritic-type whereas Noce, Mercure, Frido, and Torno catchments show rectangular-type patterns. The latter are strongly

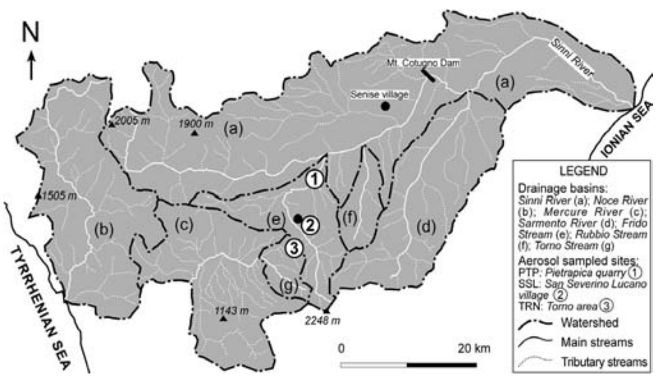

FIG. 3 - Drainage basins and aerosol sampled sites of the study area.

controlled by the geological arrangement of carbonate and crystalline-metaphorphic rocks.

The valley floor of the Sinni River is a plain surface, interrupted only by scarps bounding several Late Pleistocene to Holocene fluvial terraces. Moreover, its actual floodplain is formed by a braided channel morphology. V-shaped valley are present in the Noce, Mercure, Sarmento, Rubbio, Frido, and Torno catchment basins and are strongly controlled by both faults and fracture systems. A discordant drainage, i.e. antecedent or transverse drainages, can also be observed in the high valley of the Frido Stream, in the lower valley of Noce River, and in the lower course of Mercure River.

MATERIALS AND METHODS

Indexing of ophiolite-bearing rocks and quantitative geomorphic analysis

Quantitative geomorphic analysis of fluvial and other landforms has been considered an useful tool for the evaluation of natural hazards (Del Monte & *alii*, 2002; Vergari & *alii*, 2011). It has been here applied in estimating the dispersal of asbestos-bearing rocks along the main hydrographic basins of the Pollino National Park, where ophiolite suites widely crop out. Since these units represent a potential natural source of asbestos pollution, the precise estimation of their exposure area and the evaluation of the spreading out of serpentinite clasts in areas far away from main bodies are needed in order to determinate the hazard of environmental pollution.

Using the new official geological map (Schiattarella & *alii*, 2011), the outcropping areas of ophiolite-bearing units (including talus cover and weathering mantles) have been delimited and the relative exposure area (expressed in square kilometres) has been estimated for each of the seven drainage basins identified in the study area. This allowed precisely knowing the extension and the arrangement of such potentially polluting bodies within each physiographic or anthropic entity (fig. 3). The wideness of ophiolite outcrops has been related to the extension of each catchment basin by the following equation:

$$I = \frac{AE}{A} ‰$$

where A represents the area of a single catchment basin, AE corresponds to the exposure area of ophiolite rocks outcropping in the basin.

The complete study of the modalities of asbestos fibres dispersal by means of fluvial runoff and sheet washing, even in areas far away from their source, has required a quantitative geomorphic analysis of the fluvial network in the study area (fig. 3). Quantitative morphometric parameters are in fact quite good in environmental monitoring of those areas that are notably considered non-subjected to asbestos contamination because localized far away from the asbestos source.

For each drainage basins of the rivers and streams present in the study area the following morphometric parameters have been estimated (Horton, 1945; Strahler, 1957; Avena & *alii*, 1967): drainage density (D), hierarchic anomaly number (Ga), hierarchic anomaly index (Δa), and suspended sediment yield (Tu), the latter being an expression of the strength of the fluvial erosion. Their estimation also enabled the calculation of erosion rates and of the suspended sediment yield (Tu, after Ciccacci & *alii*, 2003, and references therein; recent advances in Della Seta & *alii*, 2007; see also Ta, after Schiattarella & *alii*, 2004) within each single basin.

Mineralogical and petrographic analyses

The identification of asbestos minerals in samples of serpentinite, metabasite, metagabbro and gneiss collected from the study area has been carried out by means of thin sections analysis, using a polarised microscope, and by X-ray powder diffraction (XRD) analysis of random mounts, using a Rigaku Miniflex diffractometer (CuK_a radiation, variable slit, sample spinner). Mineral phases have been recognised by using the *MacDiff* software (4.2 version), which adopts a mineralogy database based on JCPDS cards. Metamorphic rocks have been sampled in seven different sites (fig. 1), so that fourteen thin sections (two for every sample) have been analysed from a petrographic point of view.

Atmospheric aerosols analyses

Asbestos fibres release in the air has been monitored by collecting aerosols in different sites from the Pollino National Park area. Asbestos fibres have been identified in the atmospheric aerosol by SEM (Scanning Electron Microscope), equipped with an EDS (Energy Dispersive Scanning) spectrometer. The sites of aereosol sampling (fig. 3) are labelled with acronyms as follows: PTP (Pietrapica site), SSL (San Severino Lucano village), TRN (Torno area). The PTP sampling site is situated in a cataclastic serpentinite quarry not far from San Severino Lucano village. The TRN sample site is set on the slope to the north of the Torno village. The SSL sample comes from the urbanized area of San Severino Lucano. The latter sampling site was specifically chosen because this village, due to the presence of a fault zone in the serpentinite and of a large amount of cataclastic bodies, may represent one of the areas with a higher risk of natural asbestos pollution.

Multispectral analyses from remote sensing

The multispectral analyses in the visible and infrared spectral bands, with data acquisition by MIVIS platform processing by means of the Spectral Angle Mapper (SAM) technique, has resulted to be quite suitable in regional-scale geo-environmental studies on asbestos dispersion and pollution (Tramutoli & *alii*, 2002; Beneduce & *alii*, 2008). This technique, by using the raw MIVIS spectral response curves, allowed discrimination of serpentinite from carbonate rocks and from vegetation. Remote sensing in a test-site where such rocks crop out without any vegetation or soil cover allowed a good definition of the spectral response curves. MIVIS data used were acquired during flights carried out over the whole Lucanian area of the Pollino National Park. The dimension of ground resolution cells ranges between 5.8 and 13.5 m (Tramutoli & *alii*, 2002).

RESULTS AND DISCUSSION

Geomorphic parameters

All the ophiolite outcrops fall in the drainage basins of Sinni, Noce, Mercure and Sarmento rivers, and of Frido, Rubbio, and Torno streams (fig. 3). The main parameters used for indexing of ophiolite outcrops (i.e. the area of a single catchment basin A, expressed in km^2), the exposure area of ophiolite rocks outcropping in each basin AE (expressed both in km^2 and in %), and the exposure index of the basins I (expressed in ‰) are reported in figure 4.

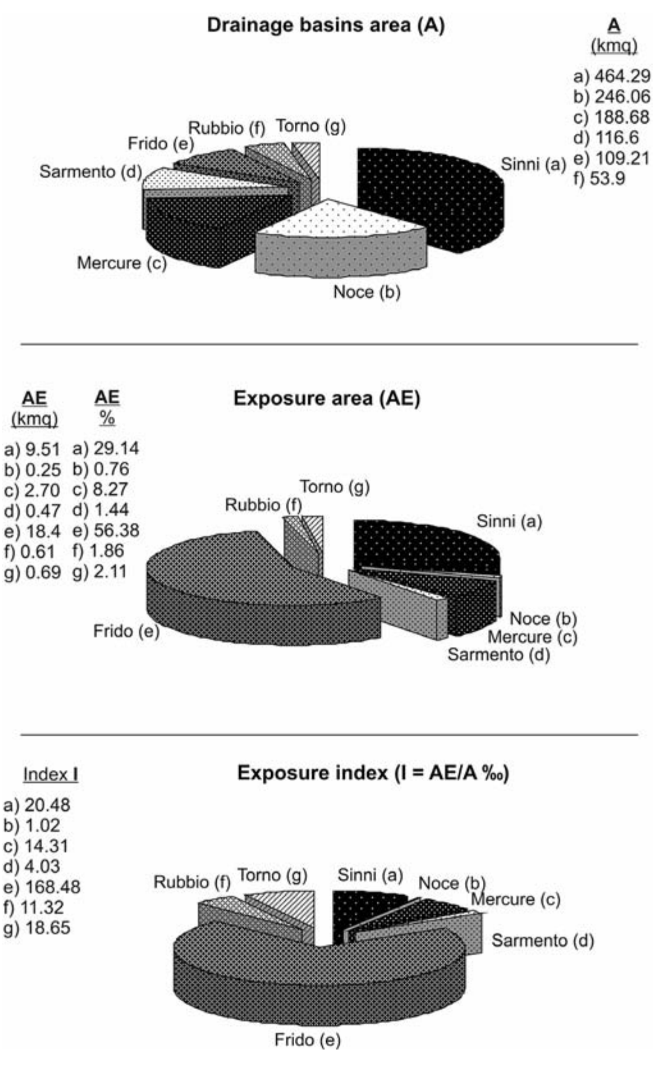

FIG. 4 - Arrangement of morphometric parameters of all the drainage basins of the study area. Labels: catchment area (A), exposure area (AE, expressed in kmq and %), and exposure index (I).

Within the entire study area (~1,215 km^2) only a small portion (extending over 32.63 km^2) is occupied by ophiolite outcrops. About the 93.8% of these outcrops fall within the drainage basins of Frido Stream and Sinni and Mercure rivers, with the most extended ophiolite outcrops placed into the Frido Stream basin (corresponding to the highest I value of the fig. 4). The remaining 6.2% of the ophiolite-bearing outcropping area fall in the others drainage basins, with a minimum in the Noce River (fig. 4). The quite high value of I observed for the Frido catchment basin (fig. 4) is due, besides the remarkable extension of ophiolitic rocks with respect to the total extension of the basin, to the high runoff potential and, consequently, high fluvial transport of material from ophiolite-bearing rocks. The Frido catchment basin can be thus looked at as an area with an high dispersal potential of asbestos minerals (by both air and running water) compared to Sinni and Mercure rivers, and Torno and Rubbio streams. The latter indeed exhibits lower values of I index (ranging from 11-20; fig. 4), and therefore only a moderately risk of asbestos dispersion is likely predictable. On the other hand, Noce River and Sarmento Stream, as suggested by the low value of the index I, are likely to exhibit low or no potential environmental hazard.

The complete selection of geomorphic parameters is reported in table 2. Tu (suspended sediment yield) value appears to be steady around 70-90 $t/km^2/y$ for almost all the studied drainage basins, with the exception of the Sarmento River basin in which Tu exceeds the average value (about 144 $t/km^2/y$), and of the Rubbio Stream basin, in which it reaches the minimum value of 45 $t/km^2/y$. This clearly suggests that the dispersal of elements from the main serpentinite bodies due to fluvial transport can be considered relevant in all the drainage basins. Further, it should be noted that a significant amount of badlands developed in Pleistocene sandy clays of the study area, particularly in sites *a* and *d* (fig. 3). Such features occupy about 380-400 km^2 (i.e. about 30%) of the entire catchment, corresponding to about 60% of the area in the site *a* (Sinni River main basin) and to about 50% of the area in the site *d* (Sarmento River basin). Therefore, erosion processes may be locally more intense in these two areas, but not in dismantling ophiolite outcrops.

The comparison between the drainage density (D) of each drainage basin and the area of ophiolite outcrops

TABLE 2 - Geomorphic parameters of the investigated catchment basins. D: drainage density, Ga: hierarchic anomaly number, Δa: hierarchic anomaly index, Tu: suspended sediment yield

Drainage basins	D (km^{-1})	Ga	Δa	Tu ($t/km^2/y$)
Sinni River	1.68	24	0.40	90
Noce River	1.28	20	0.57	70.32
Mercure River	1.41	18	0.50	75.78
Sarmento River	2.17	16	0.66	144.28
Frido Stream	1.56	8	0.47	84.16
Rubbio Stream	0.68	2	0.66	45.75
Torno Stream	1.5	8	0.16	71.81

within the drainage basin (AE) clearly suggests that the highest percentage of fluvial erosion of the «greenstones» occurs in the catchment basins of the Sinni and Mercure rivers as well as of the Frido Stream (figs. 4 and 5). On the other hand, the high erodibility of the rocks outcropping in the Sarmento River basin, as suggested by the high D and Tu values calculated (fig. 5 and table 2), does not represent a problem because of the minimal percentage of the ophiolite outcrops if compared to the entire area of the basin (i.e. low I value; fig. 5). Therefore, the Sarmento River basin is in any case an area where the risk for dispersal of asbestos minerals is low. Further, the comparison among the exposure index (I), the suspended sediment yield (Tu), and the drainage density (D) has shown that despite the high values of I observed for the Frido Stream catchment basin, the high value of Tu does not reach the one calculated for the Sarmento River basin (fig. 5), because of a lower drainage density and a lower erodibility of rock outcrops.

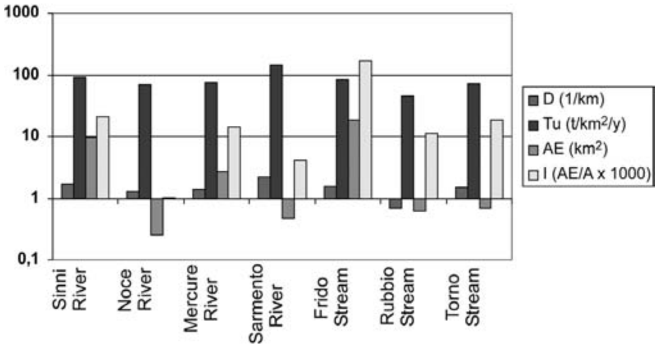

FIG. 5 - Comparison of drainage density (D), suspended sediment yield (Tu), exposure area (AE), and exposure index (I) values for all the drainage basins of the study area.

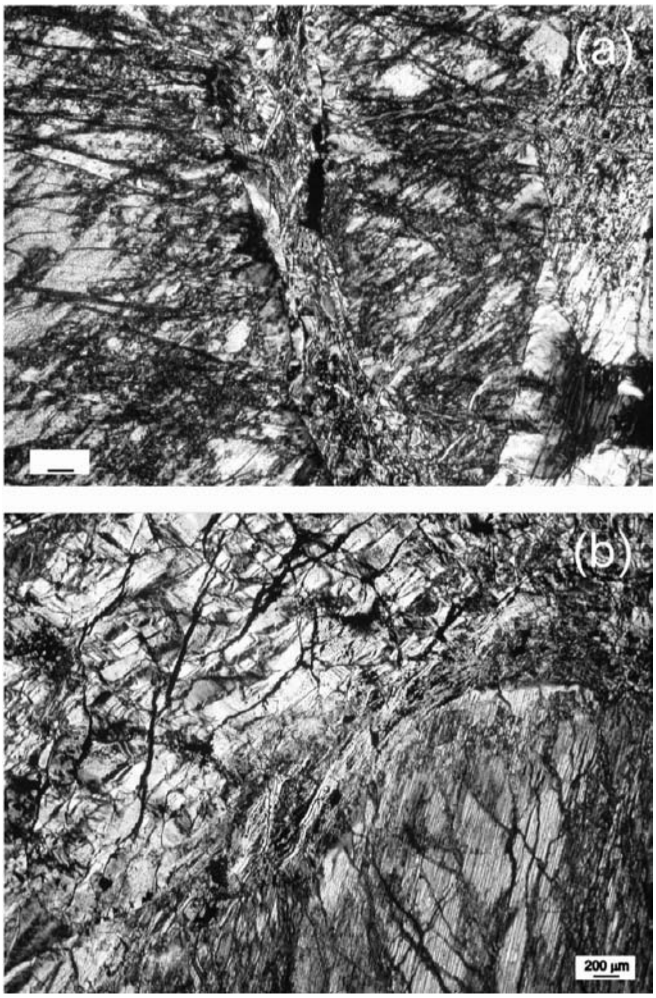

FIG. 6 - Thin sections of serpentinite rocks from Monte Caramola (a) and Timpa della Guardia (b) sites; a) serpentinite rock (4x magnification; crossed polarized light, XN) showing a relic of clinopyroxene containing a vein with fibrous minerals; b) serpentinite rock (4x magnification; crossed polarized light, XN) showing fibrous and mesh structures, and a relic of clinopyroxene with tremolite fibres at the edges.

Mineralogy and petrography

Thin sections of serpentinite rocks, deriving from *b* and *e* sampled areas (fig. 1), show fragment relics of clinopyroxene, orthopyroxene, olivine, chrome spinel (picotite) embedded in a groundmass with serpentinite texture. Pseudomorphic serpentine minerals are placed on the larger relic forms of pyroxene crystals. A few sample is entirely affected by serpentine and chlorite veins. Modal analysis of relic minerals suggests a provenance from lherzolite rocks (fig. 6).

Thin sections of metabasite samples from site *b* (fig. 1) show a porphyritic structure composed of plagioclase phenocryst relics transformed into a sericite-epidote aggregate (fig. 6). Middle-size crystals of pyroxene and reddish amphibole are imbedded into a microcrystalline matrix formed by crystals of idiomorphic plagioclase and a sericite+epidote+chlorite mineralogical association. Some metabasites have been affected by foliation and differentiated layering. They show a corrugated lamination of the included fine-grained minerals, which are constituted by pyroxene porphiroclasts. The latter display a rounded morphology and are replaced by a chlorite+actinolite+epidote+titanite pseudomorph aggregate. The groundmass is composed of epidote+actinolite+chlorite+albite minerals, and some veins cutting the foliation of the metabasites are formed by pumpellyite+actinolite+chlorite minerals and locally by pyrite and titanite.

Thin sections of metagabbro rocks sampled in the site *e* (fig. 1) show a coarse-grained mineralogical assemblage formed of clinopyroxene+orthopyroxene+plagioclase, which represents the former paragenesis of gabbro rocks. In these rocks, moreover, pyroxenes represent a cumulite phase, and plagioclases an intercumulus phase. Sometimes the plagioclases are transformed into sericite, epidote, and albite aggregates, and rare small crystals of lawsonite. Pyroxene crystals occasionally show chlorite and actinolite edges. Finally, chlorite veins affect the sample.

The gneiss samples deriving from site *e* (fig. 1) are strongly weathered and are formed from garnet and biotite felsic gneisses with a nodular texture. Fractured and chloritized garnet phenocrysts, foliated and locally cataclastic groundmass with re-crystalised quartz minerals are also present. The felsic part of the samples is composed of partially weathered plagioclase and quartz. The biotite crystals are decoloured and chloritized, and are sometimes transformed into oxides and stilpnomelane. Furthermore, albite veins affect any samples. Asbestos group minerals are also observed in these samples, at the weathered edge of pyroxene, quartz and chloritized biotite crystals.

X-ray powder diffraction analyses have show that asbestos group minerals such as chrysotile (fibrous serpentine), known as serpentine asbestos or «white» asbestos, is largely present in the serpentinite samples (fig. 7a), and that monoclinic amphibole (i.e. tremolite and actinolite) is also present in metabasite samples (fig. 7b). Beside, mineralogical and petrografical analyses suggest a paragenesis typical of high-pressure metamorphism. Indeed, the metabasite samples are confined in P/T stage of stability of the pumpellyite+actinolite+chlorite (Pmp+Act) mineralogical assemblage, with a temperature range between 250-350 °C, and with a pressure range between 6-8 kbar (for further explanation see the P/T diagram in figure 8; cf. also Frey & Robinson, 1999).

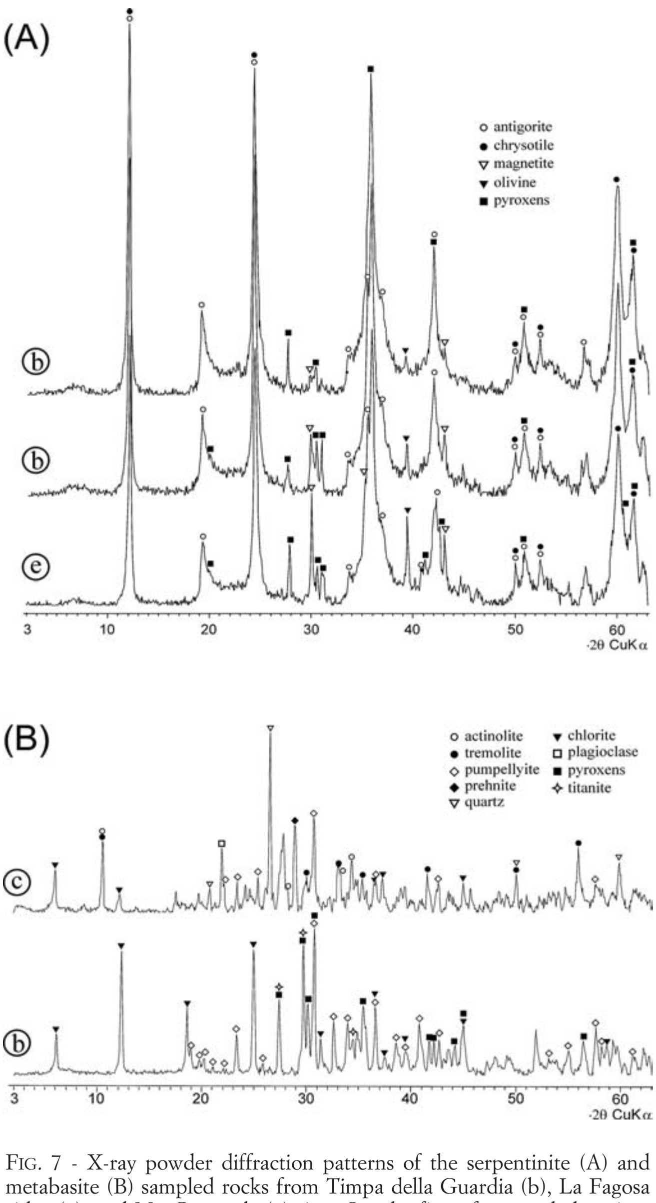

FIG. 7 - X-ray powder diffraction patterns of the serpentinite (A) and metabasite (B) sampled rocks from Timpa della Guardia (b), La Fagosa ridge (c), and Mt. Caramola (e) sites. See the fig. 1 for sample location.

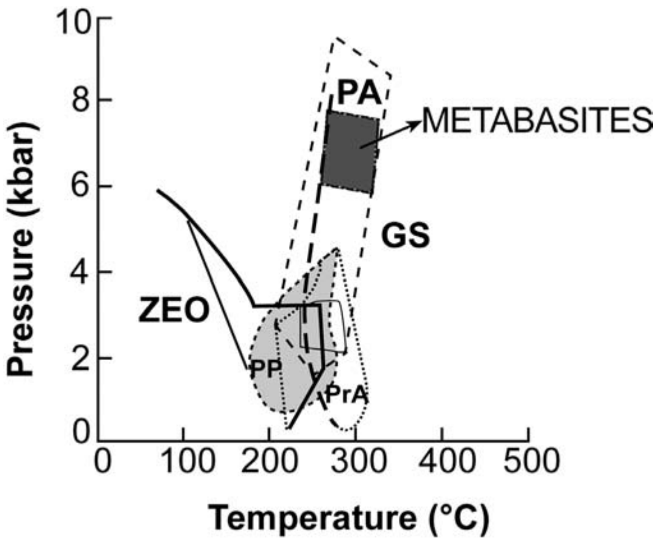

FIG. 8 - P-T diagram of low-grade metabasites (after Frey and Robinson 1999). ZEO: zeolite, PrA: prehnite+actinolite, PP: prehnite+pumpellyite, PA: pumpellyite+actinolite, GS greenschist facies.

Atmospheric aerosols

Number of samples, types of minerals and range of asbestos fibres contained in each aerosol sample are reported in table 3. For location of aerosols sampling sites see figure 3. The concentration of asbestos fibres contained in almost all samples is below 2 ff/l (fibres/litre), which represents the maximum tolerance limit accepted by current Italian legislation. Instead, samples 1, 3 and 4 from SSL site show a value of fibres concentration in the aerosols higher than the accepted tolerance limit, thus implying that asbestos pollution has interested the area of San Severino Lucano village (table 3). On the other hand, in the PTP site a continuum monitoring of asbestos fibres is suggested according to the estimated concentration asbestos fibres in aerosols near the maximum tolerance limit (samples 2 and 3, table 3). The complete absence of asbestos fibres in aerosols samples collected from TRN site is a clear evidence of unperturbed landscape conditions (i.e. close to a *naturality* state) in the Torno village area.

TABLE 3 - Quantitative analyses of asbestos fibers by SEM/EDX analysis of the aerosol samples

Sample Sites	Samples	Main asbestos mineral	Range fibres/litre (ff/l)
PTP (Pietrapica quarry)	1	Tremolite	0.028 - 0.840
	2	Tremolite	0.009 - 1.930
	3	Tremolite	0.009 - 1.930
SSL (San Severino Lucano village)	1	Tremolite	0.140 - 2.020
	2	Tremolite	0.006 - 1.290
	3	Chrysotile/Tremolite	0.380 - 2.690
	4	Tremolite	0.140 - 2.020
TRN (Torno area)	1	unknown	0.000 - 0.850
	2	unknown	0.000 - 0.850

Remote sensing data

The map of the different spectral signatures of both vegetation and rocks has been realised by Tramutoli & alii (2002) and reported also by Beneduce & alii (2008). After having selected a bounded key area where serpentinite crops out and recognized its spectral signature, it was possible to analyse the distribution of these rocks in a quite large area and rapidly. This was possible because of the absence of a pedogenic and vegetation mantle on the serpentinite. According to Tramutoli & *alii* (2002) the remote sensing analysis, using a simple and robust technique that allows to automatically identify surface materials by using Multispectral InfraRed and Visible Imaging Spectrometer (MIVIS) radiances, can be applied for the indirect recognition of serpentinite elements in the alluvial sediments of the fluvial network. Sedimentological (source areas) and geomorphological (amount of fluvial carriage) information can be therefore obtained by using such an approach together with the classical tools of the quantitative geomorphic analysis (Beneduce & *alii*, 2008).

CONCLUDING REMARKS

The multidisciplinary study on asbestos release from ophiolite-bearing units outcropping in the area of the Pollino National Park, at the Calabria-Lucania border (southern Italy), has allowed to assess the degree of the related environmental hazard. The comparison of natural and human factors in controlling asbestos release in areas characterized by different morphological conditions revealed that erosional (mainly fluvial) processes promoted an intense spreading of asbestos minerals, even in an area wider than the original ophiolite (mainly serpentinite) outcrops.

In the Pietrapica village area (PTP site), where strongly weathered garnet and biotite gneiss crops out in tectonic contact with serpentinite, aerosols samples contain asbestos fibres (mainly tremolite) up to 1.93 ff/l. The possible source of asbestos fibres has been identified in the ophiolite-bearing rocks, frequently used in the recent past to make roadbeds crossing the area of the National Park. The asbestos fibres concentration close to the limit tolerated by the Italian legislation (i.e. 2 ff/l) suggests that an *in continuum* monitoring of the site is needed.

In the San Severino village area (SSL site), where rocks containing asbestos minerals largely crop out, aerosol samples contain tremolite and chrysotile fibres and the total asbestos fibres concentration, reaching the maximum value of 2.69 ff/l, indicates pollution in progress. This can be related to the presence of a fault gauge which likely represents an important natural asbestos source and may play a crucial role in causing asbestos pollution of shallow, and underground, circulating fluids via leaching of «greenstones» without vegetable covering.

Absence of asbestos fibres in the aerosols sampled in the Torno village area (TRN site) indicates landscape conditions close to the «wildness». This area, characterised by the presence of vegetation and scarce human activities, represents a good example of a non-contaminated site.

The spreading out of ophiolite-bearing rocks in areas far away from their outcrops by natural running water (i.e. sheet wash and fluvial processes) has been evaluated by comparing the different geomorphic indexes estimated for each of the seven catchment basins of the study area (i.e. the exposure index I and the morphometric parameters Tu and D). It has to be pointed out that the wide dispersion of the asbestos minerals by running water in the Pollino National Park area is clearly a consequence of the cataclastic conditions of the serpentinite outcropping at the Calabria-Lucania border. A crucial role in the dispersion of these minerals even far from their source outcrops is also played by the peculiar geomorphological characteristics of each drainage basin in which the ophiolite-bearing rocks crop out.

Specifically, the highest I index evaluated in the Frido drainage basin indicates the widest distribution of rocks containing asbestos minerals (fig. 4). Taking into account the relevant values of Tu and D parameters calculated for this area, it can be concluded that the spreading out of the rocks containing asbestos occurred in an area much wider than the original outcrops. The area of the Frido River basin can be thus considered as the one with the highest risk of spreading out of asbestos minerals far away from outcropping areas. On the other hand, the comparison among geomorphic parameters also suggests that the area of the Sarmento drainage basin exhibits a low risk of asbestos spreading out by sheet washing and fluvial transport far away from the original outcrops. Despite the high D and Tu values estimated for this basin (fig. 3 and table 2), the low I value clearly indicates a low extension of ophiolite outcrops, and therefore low risk of asbestos contamination. It is important to underline that all suspended sediment yield of the Sarmento River as well as from the Frido Stream is redistributed, and therefore largely «diluted», in the wider Sinni River drainage basin.

Catchment basins of the Torno and Rubbio streams and Mercure and Sinni rivers represent areas where the risk of dispersal of asbestos minerals far from outcropping areas is only moderate (fig. 5 and table 2), whereas the Noce River drainage basin can be considered an area where the risk of asbestos dispersion by fluvial erosion is low due to the small amount of rocks containing asbestos (i.e. low value of the I index; fig. 5 and table 2).

On this basis, it can be concluded that the dispersal of the asbestos group minerals is not confined to the areas close to the outcrops of ophiolite rocks, which represent the main source of asbestos fibres in the Pollino National Park. In fact, mainly because of runoff, serpentinite and metabasite materials are widespread in areas far away from their outcrops, as far as the Mt. Cotugno dam, near the town of Senise (fig. 3). As a consequence, monitoring the asbestos pollution in the Pollino National Park has to take into account not only routine analyses of aerosols dispersal of fibers but also quantitative evaluations of the diffusion of asbestos minerals by running waters. Therefore, hazard studies on these topics should regard the whole catchment basins in which ophiolite rocks are dispersed as a component of alluvial beds.

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