

SYNTHESIS REPORT

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TITLE : DEVELOPMENT OF EXPLORATION AND INDUSTRIAL
TECHNOLOGY TO EXPLOIT NEW SOURCES OF
WOLLASTONITE IN EUROPE

PROJECT

COORDINATOR : DESARROLLO de **RECURSOS GEOLÓGICOS, S.A.**

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INSTITUTE of GEOLOGY and MINERAL EXPLORATION (Athens)
EUROMIN srl.

ALBATROSS MINERALS

CONSIGLIO NAZIONALE delle RICERCHE -

ISTITUTO per il TRATTAMENTO dei MINERALI (Rome)

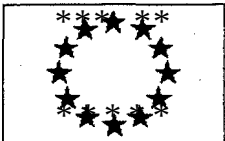
CENTRE NATIONAL de la RECHERCHE SCIENTIFIQUE (Paris)

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2. TITLE:

DEVELOPMENT OF EXPLORATION AND INDUSTRIAL TECHNOLOGY TO EXPLOIT NEW SOURCES OF WOLLASTONITE IN EUROPE

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3. ABSTRACT

Wollastonite is one of the newest fibrous materials incorporated into the industrial sector of production of new materials, ceramics, plastics, composites, paints, medical materials, etc., and as a substitute for the prohibited asbestos.

There are very few” deposits in production in the world and there is very little knowledge to act as a guide for the **prospection** and evaluation of this mineral. The specifications for commercial wollastonite products and the industrial processing involved in their preparation are largely secret. However, the steady growth in the use of wollastonite seems to have **converted** it into a strategic raw material for many new materials.

Several wollastonite deposits located in **three** areas of Europe; Spain, Greece and Sweden, have been studied and **technologically** and economically **evaluated**. To this end it has been necessary to develop different methodologies and the broad know-how **needed** for the **prospection** and **beneficiation** of the mineral of these deposits, as **well** as for its use in certain products in the ceramics sector.

4. INTRODUCTION

Wollastonite (CaSiO₃) is a mineral of relatively new use. It has only been produced on art industrial scale for the last fifty years, and production has only reached an important volume over the last two decades.

The positive characteristics of wollastonite most commonly divulged are: low chemical reactivity, capacity of exfoliation in minute needles, high brightness and an extremely low loss on ignition (LOI), as well as an average pH of 9.9 in a 10% hydrous slurry.

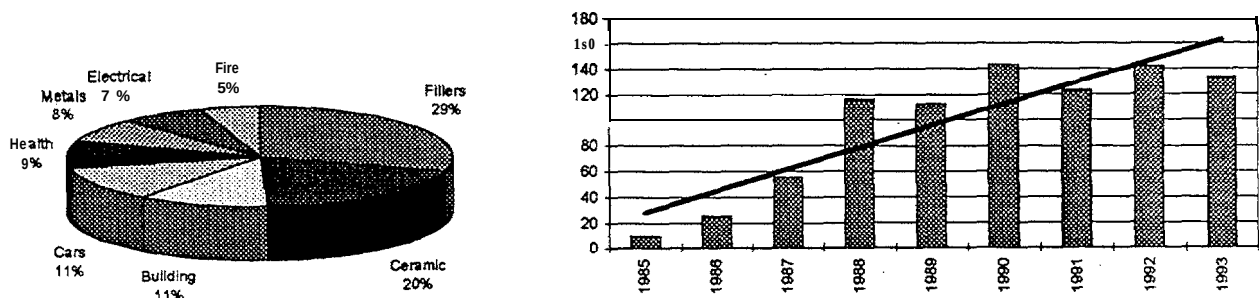
The skärn-type deposit produced by metasomatism in contacts of limestone rocks with igneous intrusions is recognized as being the most common model.

The exact figures for production and distribution for different uses are not well known, the most recently published estimates being those found in *Raw Materials for Pigments, Fillers & Extenders* (2nd Edition, 1995) by Industrial Minerals, which are a sum of 10 producers of natural wollastonite (464,000 t) and some 10,000 t of synthetic wollastonite produced mainly in Europe.

Wollastonite producers	
Company/country	Production capacity (tpa)
Majors	
NYCO, USA	200,000
R.T. Vanderbilt, USA	40,000
Lishu Wollastonite Mining Industry Co., China	70,000
Wolkem, India	60,000
Partek Minerals, Finland	30,000
Minors	
Eprom, Chile	1,182 (1993 production)
Minerales y Maquilas del Norte SA de CV, México	11,000 (1993 production)
General de Minerales 5A, México	19,000 (1993 production)
Namaqua Wollastonite Pty Ltd, South Africa	1,500
Black Mountain (Pvt) Ltd, Pakistan	32,000 (1991 production)

Over the last eight years the market for this mineral has more than doubled, and the indications are that it will continue to grow with its extension to new applications in materials with large-scale production, particularly in the plastics sector and as a substitute for asbestos.

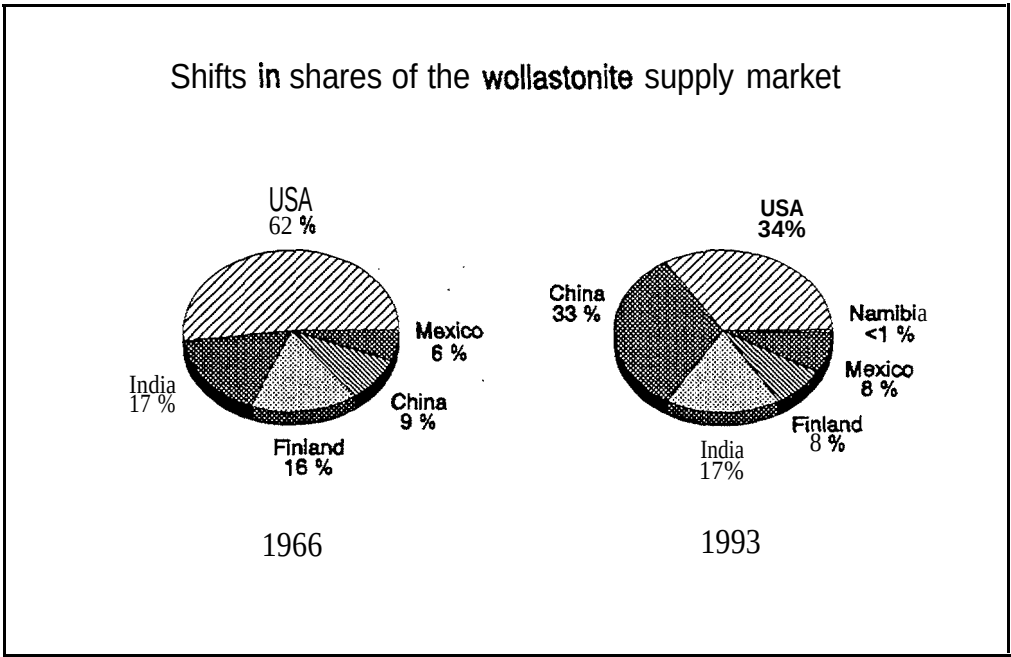
SUMMARY OF MAIN PATENTS OF WOLLASTONITE USE



STN database search performed for Albatross Minerals

The EU is the most important world consumer (approximately one third of total world consumption), while the only European producer is Finland (as a by-product of a calcium carbonate operation) and which is losing its relative importance percentage-wise as raw mineral from China is gradually being introduced into the market.

Shifts in shares of the wollastonite supply market



Raw Materials for Pigments, Fillers & Extenders, Industrial Minerals (1995)

Whilst there are some 12 producers on the market, in practice only two can be considered to have the technological capacity to develop products of high added value.

In this respect, it is also important to note that there is practically no information available on the specifications of the wollastonite products currently on the market and, naturally, on their production processes. It is therefore impossible to establish effective guidelines for **prospection**, many **exploration** projects all over the **world** having come to nothing in recent years.

There are at present about twenty projects at a relatively advanced stage, but only a few (3 or 4) would appear to have any chance of producing commercial wollastonite.

A fair percentage of these failures seem to be directly related to the reduced size of the estimated reserves. Wollastonite deposits are not a geological rarity, but those which reach a sufficient dimension to justify development for exploitation and the adaptation or innovation of the appropriate technologies to achieve products with valuable specifications are much scarcer.

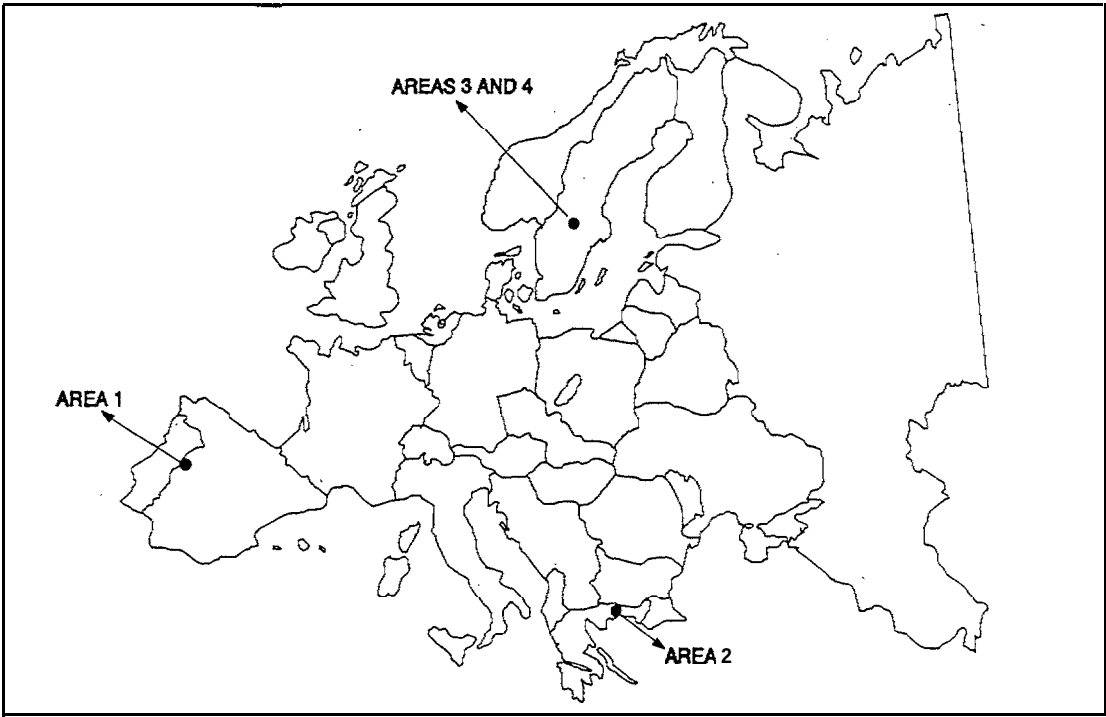
The important volume of mineral, little processed - if at all, put on the market recently by China (as was already the case with India) is the consequence of the circumstantial exploitation of extremely cheap labour and frequently entails serious problems of quality and continuity of supply.

5. TECHNICAL DESCRIPTION

The present project was **presented** by a consortium made up of eight partners from six EU countries, including **SMEs**, large state institutions and manufacturing industries. Three of these partners are the holders of the **rights** to four important wollastonite occurrences in Spain, Sweden and Greece, and while they maybe potential competitors in the future, they were aware that the evaluation of their deposits would reveal common **problems** of lack of know-how and technology which would fully **justify** cooperation and the exchange of experiences as well as **benifitting from** the collaboration with various research centres.

Three work zones in three different **countries** at a considerable distance from each other, and the corresponding plurality of methodologies has meant that from the start there have been virtually three **sub-projects**, and though the tasks in the Work **Programme** were designed in common for the study of the four original deposits, it is worth noting the practical differences in approach. In **Spain** work has centred on one large deposit from a strictly industrial point of view and in Sweden the tasks have been carried out on several smaller, relatively close-together deposits. In Greece, **while** economic objectives have not been forgotten, a genetic model to provide a guide for **prospection** has been sought.

Consequently, many results from the completed tasks must be considered individually, due both to the **necessary** adaptation to local **geological** and geographical characteristics and to the different nuances in orientation mentioned above. However, the know-how developed during the project has logically been shared by all.



Location Map

AREA 1

Area 1 corresponds to the deposit known as "Ilustración", property of Desarrollo de Recursos Geológicos, S. A., located on the Spanish-Portuguese border in the province of Salamanca, Spain.

The materials which form the study zone are fundamentally metasedimentary and granitic, with a light covering of quaternary.

Most of the material belongs to the "schist-graywacke complex" pre-Ordovician formation, which is composed of:

Biotitic mica-schists with light-dark bands alternating with quartzitic, felspathic and meta-graywackic bands; the width of the bands varies from a few millimetres to several centimetres.

They have been interpreted as sediments accumulated on oxygen-deficient floors in a shore environment, alternating storm episodes with still ones which mixed material of diverse grain size.

These materials alternate with levels of

Laminated calcsilicates which correspond to the mineralized series. Lamination consists of the alternation of white wollastonite bands with other siliceous, felspathic and calcitic bands grey and green in colour. There are also occasional intercalations of biotitic schists. Some of the wollastonite bands have associated diopside and idocrase.

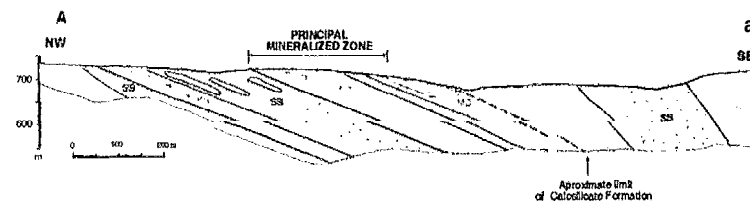
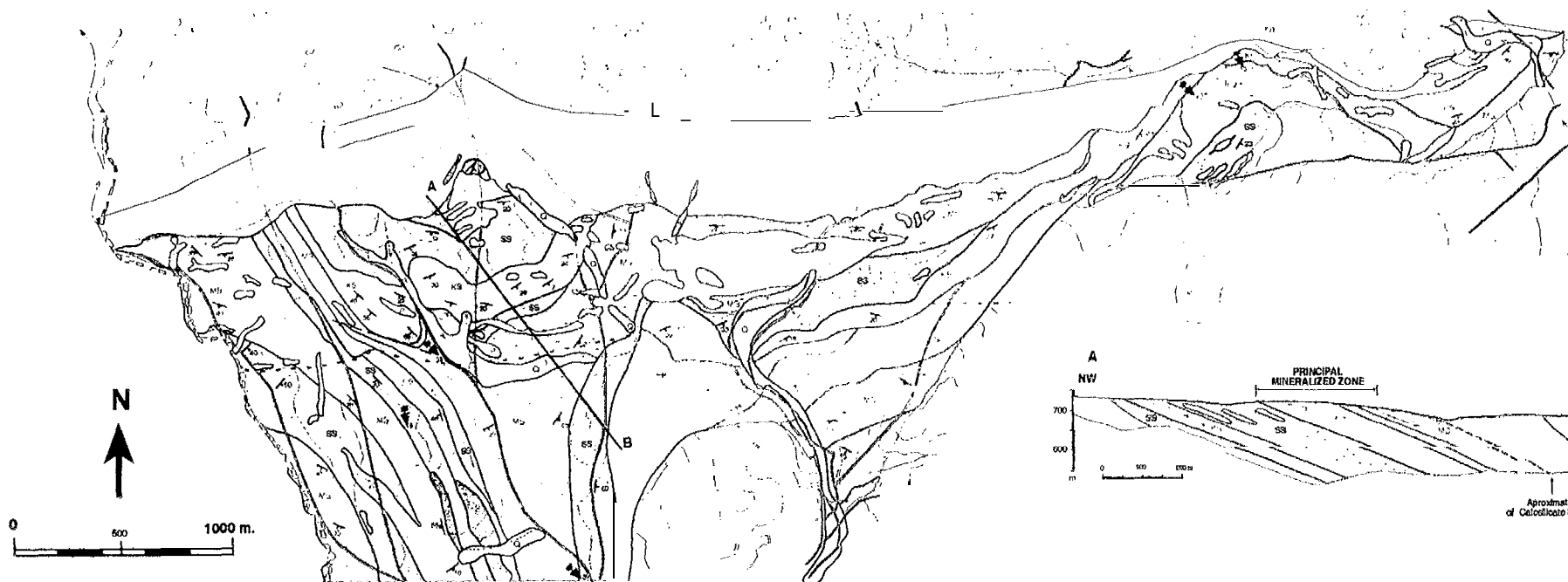
The whole Northern zone of the study zone belongs to the "Guarda Batholith" of Hercynian age, which consists of a porphyritic non-foliate biotite granite. The porphyritic texture is determined by the presence of feldspar-phenocrysts, with a grain size oscillating between 3-7 cm.

In zones near the granite, there are minor intrusive (dykes and stocks) made up of fine to medium grain leucogranite, fine-grain two mica granite, pegmatites and aplites.

Quartzite dykes are found on the border between the two zones with varying percentages of ferruginous material. The length varies from some hundreds of metres to kilometres and the width is between 30-50 m.

In tectonic terms, the materials of the "schist-graywacke complex" are affected by various phases (pre-Hercynian and Hercynian). The main cleavage observed in the rock corresponds to S_1 , developed exclusively in the most pelitic materials, since it has not been observed in the carbonatic bands. In the schist bands this cleavage is very intense, with the phyllosilicates having preferred orientation, giving rise to a "slate-cleavage". The lineation of this first phase (L_1) strikes 160° , and dips $20-25^\circ$ SE.

These schist bands were crenelated by action in the third Hercynian "phase, which caused a third cleavage (S_3) parallel to the axial plane of the microfolds developed on S_1 . The



LEGEND

GEOLOGY

SEDIMENTS

Q Recent Alluvium / Eluvium

HYDROTHERMAL ROCKS

Q Quartz vein<, ferruginous material

INTRUSIVE ROCKS (Hercynian)

"Guarda Batholith", feldspar-phenocryst
menumio coarse-grain non-foliated granite +
border facies

MINOR INTRUSIVES (dikes + stocks)

Fine to medium - grain leucogranite,
occasionally two - mica granite

Pegmatites, of variable texture and composition

METAMORPHIC ROCKS (Cambrian)

THERMAL METAMORPHISM (produced by the "Guarda Batholith")

Calcsilicate - indurate schist sequence

Indurate mafic, biotitic schists

Indurate mafic schists with siliceous bands

THERMO - REGIONAL METAMORPHISM

Blue - gray banded calcarenites with schists

Fine - grain biotitic schists

Biotite schists with meta-greywackes

Quartzite bands in schist sequences

Biotite schists with meta-greywackes and
occasional meta-calcarenites

TECTONICS

Banding or bedding

Schistosity (first phase of deformation)

Plunge of fold axis (second phase of deformation)

Plunge of fold axis (third phase of deformation)

Fault

CONTACT METAMORPHISM

Approximate limit of calcisilicate formation and
induration of schist sequences (at surface)

Line of section

TOPOGRAPHY

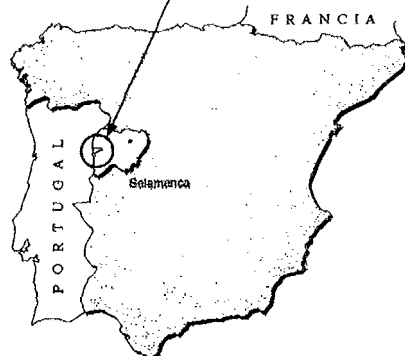
Drainage (generally dry)

Roads and tracks

Topographic contours

WORK FIELD SCALE 1:5,000

LOCATION CLAIM



GENERAL GEOLOGY

main tectonic structure "Sinclinal of Aldea del Obispo", located inside the study zone, was formed during this deformation phase.

Finally, and gently folding the previous structures, anew tectonic structure developed during the fourth Hercynian phase, with an axial plane striking N-S. No cleavage was developed during this deformation phase.

In the "Guarda Batholith", the preferred orientation of the felspar-phenocrystals leads to believe that the granitic rocks intruded while a compressive strength field was in motion (with a generally dominant N-S strike, which could correspond the fourth phase of deformation).

The mineralized band extends for some 1.5 km and appears to be approximately 35-40 m thick. For the most part, it strikes East-West and dips 20-30° S. The outcrop of the band terminates in both directions against the granite intrusion. To the West its orientation changes; striking at 125-1450 and dipping 30-50° SW, whilst to the East it strikes at 10-50° and dips 15-35°.

The mineralization occurs in a tough calcsilicate rock, which has occasional intercalations of biotite schists. Independently from banding present in the calcsilicate rock, the general mineralogical composition is as follows:

principal minerals: wollastonite, diopside, quartz, plagioclase and calcite
accessory minerals: idocrase, zoisite, titanite and epidote

Wollastonite is present as acicular crystals forming 80-90% of the rock, or as the principal component of the matrix, with quartz and diopside crystals. In this case, wollastonite has a typical fibrous-radiated texture, with considerable reduction in size.

Scarce calcite occurs in bands in which it forms the principal component with larger grain size than the others.

Bands barren of wollastonite are mainly composed of quartz, diopside or typical calcarenite composition.

From the information compiled in the geological and mineralogical studies, three different mineral assemblages can be defined in the mineralized band:

- a) (Wollastonite + Diopside + Plagioclase) + Schist
- b) (Wollastonite + Calcite + Diopside + Plagioclase) + Schist
- c) (Wollastonite + Diopside + Plagioclase + Quartz) + Schist

The formation of wollastonite at the edges of pressure and temperature of regional metamorphosism from pure carbonate mass is very difficult.

For the reaction to form wollastonite to take place in the conditions of regional metamorphosism in the study zone (1-2 kbars, 500-600°C), CO₂ must be diluted in the fluid phase. The only possibility of this occurring is for the partial pressure of CO₂ to be in the

region of 0.2, i.e. that H_2O be brought to the metamorphic process. This is feasible if the protolite is made up of thin layers of intercalated limestone and pelitic materials; in this way, the contribution of H_2O from the pelites can facilitate the dissolution of the CO_2 in the fluid phase up to a molar fraction of 0.2.

AREA 2

The main objective of the project was to evaluate the wollastonite occurrences in Greece and compare these concentrations with other similar deposits or occurrences mainly located in Northern Greece, such as the Kimmeria and Kalamou deposits in Xanthi area.

Panorama Area:

The geologic environment of the wollastonite occurrence is characterised by the small Panorama granitic intrusion, covering an area of approximately over 6 km². The granite in apical position, satellite to the larger Vrodou massif of 33 My age, intrudes the lower members of the Falakron carbonate Unit. Mineralogically, the granitic rock is consisting of quartz, K-feldspar (Or 75- Or 89), plagioclase, biotite and amphibole, as main components and apatite, ilmenite and zircon as accessories. It usually shows alteration patterns expressed as biotite chloritization, plagioclase sericitisation and development of some muscovite.

The marble at Panorama, is white to pale grey and it is mainly composed of calcite with minor (less than 1%) disseminated phlogopite with the rare forsterite, clinohumite, chondrodite and sometimes K-feldspars. Dolomite and tiny spinel crystals have been found once, in a bed of decimetric thickness.

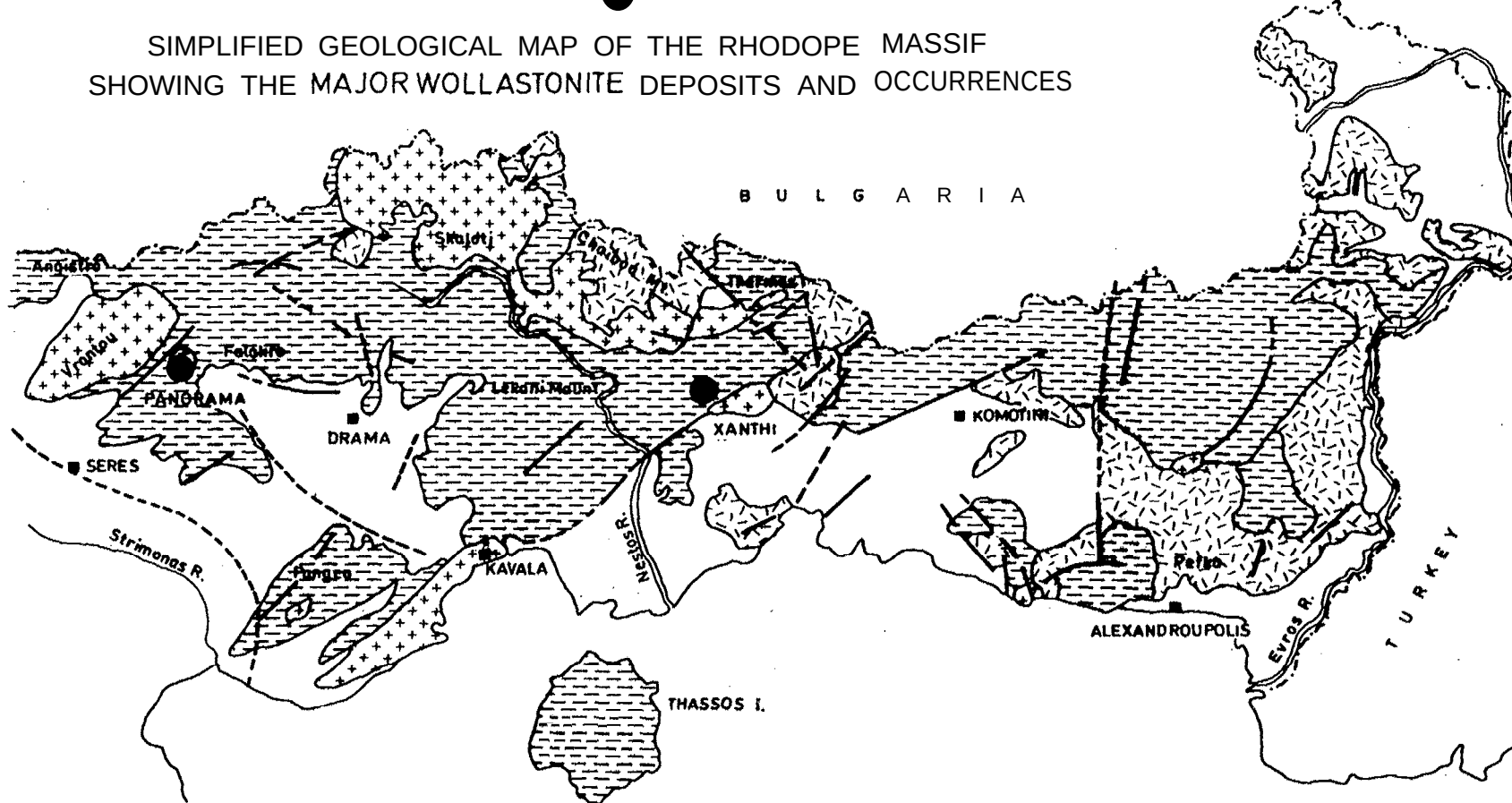
The skärns are developed at several places in the contact of marble-granite. They show two characteristic features: the unusual development of endoskärns, i.e. the metasomatic transformation of the granite observed on a few meters at the contact with the marble and the presence of wollastonite in both endoskärns (replacing the original qtz) and mainly in the exoskärns (replacing original calcite).

The wollastonite is developed within the skärn zone, mainly in the marble (exoskärn) at the contact with the granite which is transformed into endoskärns. The larger development of the wollastonite bearing skärn is shown in the Southern part of the map.

The wollastonite development of economic significance, belongs to one particular episode (only **economic stage**) in a series of successive hydrothermal phases which have followed the granite emplacement. Based on the above remarks, a later development of garnet - many times in the form of relatively large massive gametite bodies of andraditic composition - resulted in the replacement of wollastonite, therefore limited in several places the economic interest for wollastonite exploitation (exploration guides).

In the most interesting area the wollastonite bearing skärn is developed with breaks along the marble-granite contact in a length of 1.500 m approximately.

SIMPLIFIED GEOLOGICAL MAP OF THE RHODOPE MASSIF SHOWING THE MAJOR WOLLASTONITE DEPOSITS AND OCCURRENCES



-  Quaternary
-  Tertiary sedimentary and volcanic subvolcanic rocks
-  Plutonic rocks (granites-granodiorites)
-  Circum Rhodope belt rocks and Rhodope basement (Mafic-Ultramafic rocks Marble and Schist-gneiss amphibolite)

-  Major lineaments and fracture
-  Major wollastonite deposits and occurrences

0 5 10 15 20 25 km



Xanthi Area:

In the Xanthi area the wollastonite occurrences of **Kimmeria** and **Kalamou** are located.

The structure of the **Kimmeria skärn** in Xanthi is characterized by two major faults oriented E-W and NE-SW, separating three blocks which are in higher structural position in the South than in the North: the granite is deeply eroded in the southern block, the erosion is just at the level of its top in the middle one, and no granite outcrop is known in the northern one.

Two types of the wollastonite distribution have been identified:

The lithological nature of skärnified rocks, comparatively pure marble, which belongs to two groups (**Kalamou** and **Kimmeria** groups), of alternating amphibolitic/gneiss/marble levels of moderate individual thickness (up to 30 m) separated by a thick (800 m) gneiss series. At a local scale, individual beds appear more intensively wollastonised where they are thin (30 m to 10 m) and intercalated between well developed amphibolites. It has to be noted that the upper (geometrically) member of the **Kimmeria** group, a 200 m thick marble, is almost barren.

In the **Kalamou** area, the marble is wollastonised at the contact with the granite up to an horizontal distance of 100 m. Towards the granite, the wollastonite is limited by a garnet skärn as commonly observed in the Panorama area.

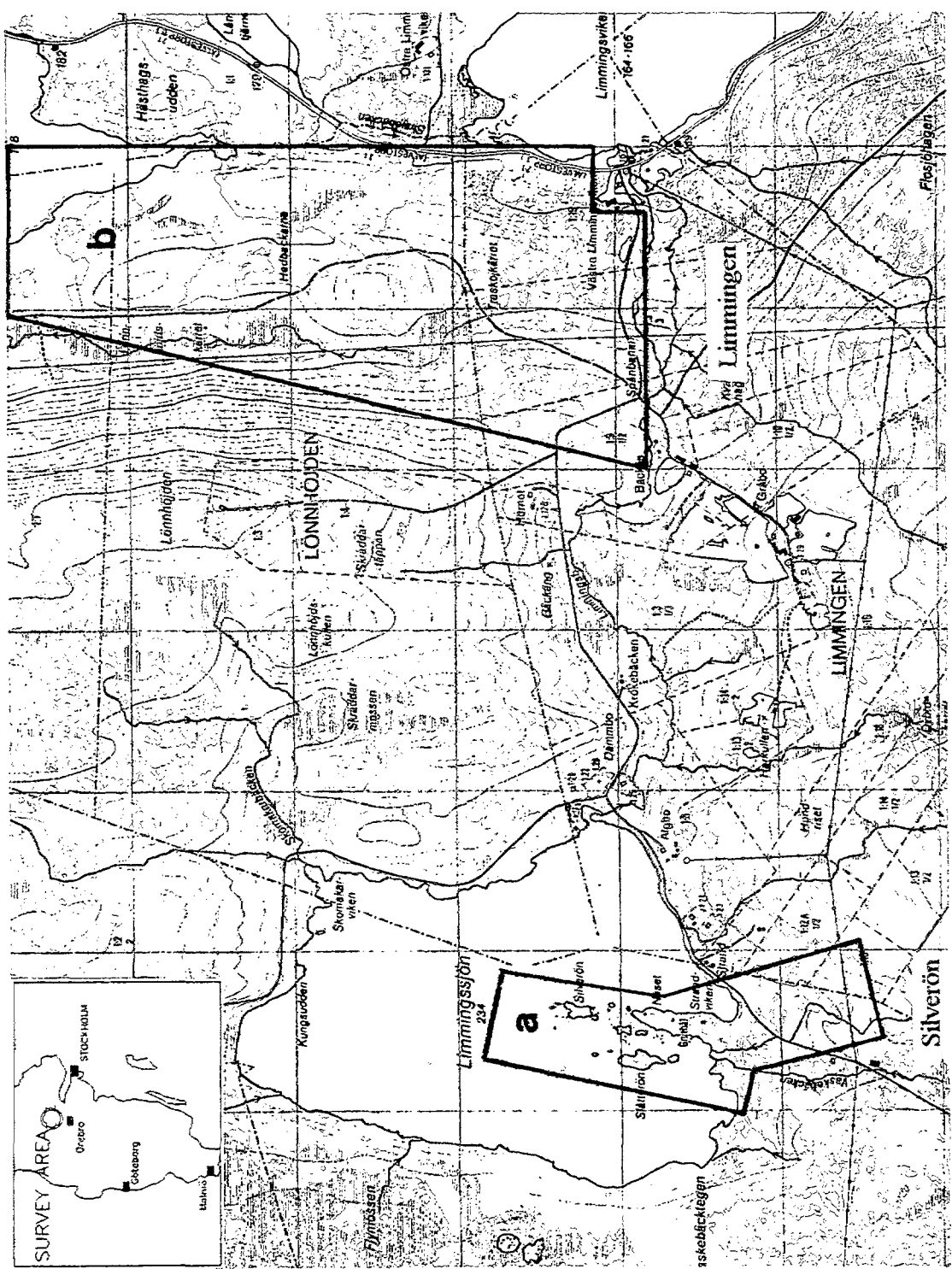
Wollastonite at **Kimmeria** of Xanthi area is especially developed in the northern block, in some marble beds of limited thickness only, showing that the fluid was channelled in some beds and not in others and that the presence of silicate rocks in the immediate vicinity is necessary as a source of silica for the replacement of calcite by wollastonite. In very conspicuous cases such occurrences may be described as “pipes” rather than as “beds”, since change into unskärnified marble is observed longitudinally at both ends of the outcrop.

AREA 3

These areas are made up of two groups of concessions of Albatross Minerals. A first group (**Silverön** and **Limmingen**) in the Bergslagen region of Central Sweden was studied by Euromin Srl with support from the University of Padua. The other group (**Hulta-Gruvor** and **Ullavi**) was investigated by Albatross Minerals themselves.

Silverön and **Limmingen** lie respectively 1,5 km west and 0,8 km north-east of **Limmingen** village in **Hällefors Kommun (Örebro Län)**, about 40 km west of the town of **Nora** (Fig.: **Silverön** (b) covers an area of about 50 ha, corresponding to the southern side of **Limmingssjön** lake. **Limmingen** (a) is a trapezoidal area, about 150 ha wide, localized between **Lonnhöjden** and the road to **Älvestorp**. Side of the geographic net: 500 m.

The inference of wollastonite in the **Limmingen** concession was based on a N-S trending marble horizon, crosscut the south by a major granite body, and the occurrence of several angular wollastonite bearing marble blocks. The results of exploration, carried out



Location of LIMMINGEN 1 (a) and LIMMINGEN 2 (b) claims.

during the first (1993) field season, were extremely disappointing: only one bedrock sample of 33 contained minor **wollastonite**. The N-S structure of the area, demonstrated by geological survey, geophysics, **photogeology** and exploration, essentially consists of fine grained marble lenses within **metavolcanis**, locally with minor **wollastonite**. On the basis of these results all activities in this claim area have been suspended, to **allow re-diversion** of financial resources to **Silverön** area, where exploration allowed the discovery of a significant deposit.

The **wollastonite-bearing skärns** of the **Silverön** peninsula and adjacent islets on **Limningssjön** south of Grythyttan belong to the Proterozoic Western **Bergslagen** province of Central **Sweden**. The deposit, occurs within the 1.9- 1.8 Ga **Bergslagen Supracrustal Sequence (BSS)**, a thick pile of felsic, mostly volcanic rocks (Baker et al. 1988). The BSS records the **polyphase** development of a subaqueous, continental rift zone. **Wollastonite** rock **protoliths** are limestone/ **dolostone** lenses interlayered within foliated and low-grade metamorphosed **volcaniclastics** of the initial rift phase (Middle **Leptite** Group) near the contact zone of the 1.74 Ga **Filipstad** granite (Oen et al. 1982, Van Meerten 1988).

The workable **wollastonite (clinopyroxene, garnet) skärn** body develops 200 x 500 m in a NNE direction, with possible extension to the SSW. The body comprises three **subparallel**, closely spaced zones (western, Central and Eastern alignments).

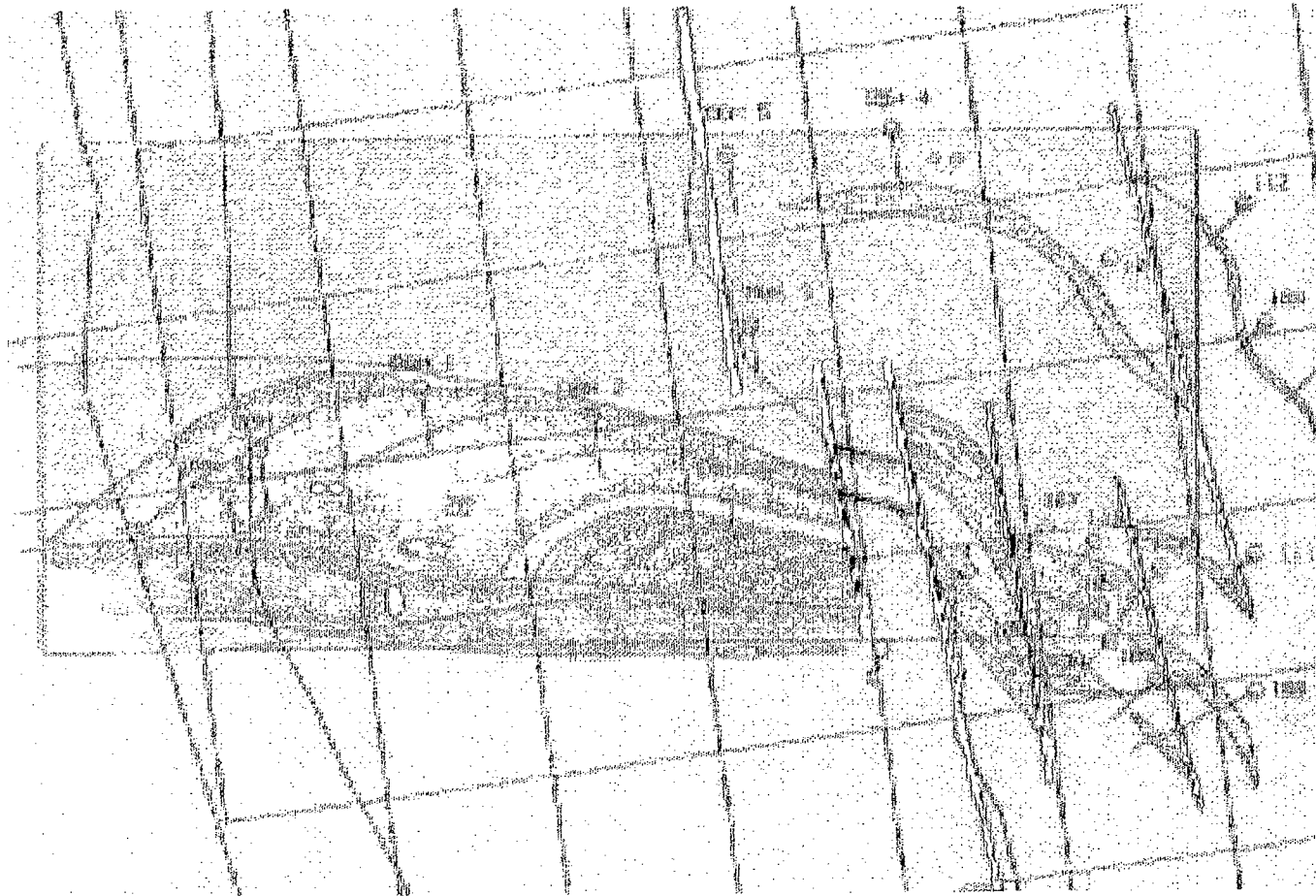
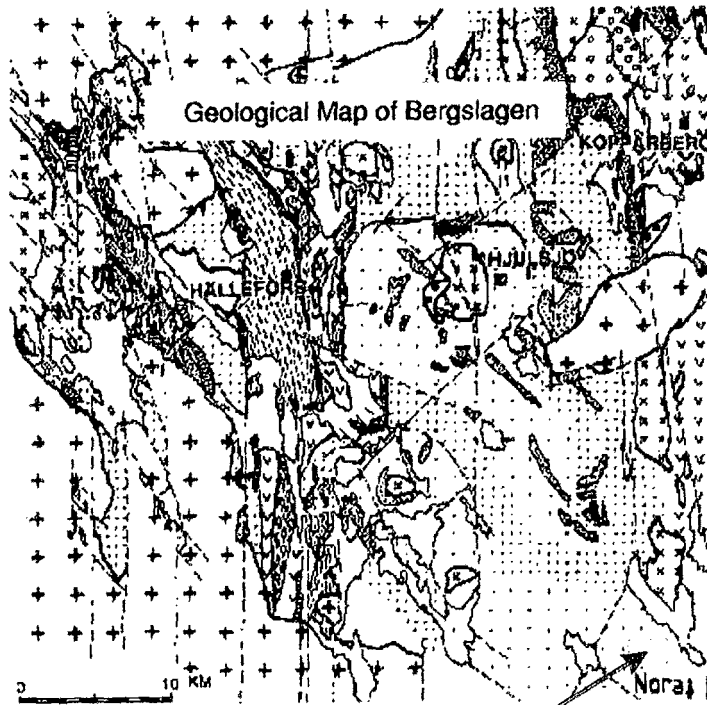
Prominent **skärn-associated lithologies** are sheared marble and serpentine marble with ubiquitous **Zn-Pb-Ag sulphide** disseminations. According to Oen et al. (1982) these features are typical for the Middle **Leptite** Group where **skärn-altered** marbles occur together with serpentine-rich "**sköls**" carrying **Zn-Pb-Ag sulphide** impregnations along sheared fracture zones. Meso- and microfabric evidence indicates a **syn-** to late tectonic formation of the **Silverön skärns**, via repeated and increasingly **H₂O-rich** fluid-assisted pulses accompanying NNE directed shearing and extension. Development of the **skärn assemblages** occurred in four main stages, (a) **clinopyroxene** stage, (b) **wollastonite** stage, (c) garnet (mostly **hydrogrossular**) stage and (d) late hydrothermal stage of **Zn-Pb(Ag) sulphide** deposition. Oen et al. (1982) suggest that the Middle **Leptite** Group **wollastonite-garnet skärns** are younger crosscutting occurrences formed in the contact zones of younger **Svecokarelian** granites.

Accounting for **wollastonite** distribution, concentration grades and mineral assemblage, eight zones grouped into three **NNE-trending** (western, central and eastern) alignments were recognized in the **Silverön** deposit.

AREA 4

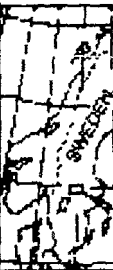
Initially Albatross started to investigate three or four **wollastonite** occurrences, but quickly discovered that only two of these, **Hulta** and **Ullavi**, had anything more than an academic potential, and started to concentrate on these ones. The results from **Ullavi** proved later to be disappointing, so it was decided that all resources should, for the time being, be directed towards **Hulta**.

The 1.8- 1.9 Ga **Bergslagen Supracrustal Sequence (3SS)** of western **Bergslagen** comprises a > 10 km thick pile of felsic, predominantly volcanic **supracrustal** rocks. In the



200 m

Sketch showing the Geological Map of the Hulta Claim Area in relationship to the regional setting of Bergslagen, Sweden



Hällefors-Hjulsjö-Nora area three lithostratigraphic groups of the BSS “are recognised; these show an upward transition from units produced by explosive volcanism, with thick ignimbrites and minor airfall deposits, to units formed by less explosive regimes marked by fewer pyroclastic flows and more tuffitic rocks, with ± 2 km of metasediments, including greywackes, shales and mass flow deposits forming the upper part of the sequence deposited in graben basins. Polymict conglomerates present in the upper units mark local unconformities, related to rift basin development.

The wollastonite occurrences of the Bergslagen Ore district, Central Sweden, are located in marble horizons, intercalated in thick sequences of volcanoclastic sediments of mid-Proterozoic age. Wollastonite development is here a product of 1) contact-metamorphism during intrusion of post-deformation, 1.74 Ga old, granitic plutons, and 2) contact-metasomatism by hypothermal F-Bi-W-Mo-bearing fluids. Since the marble horizons are also the host of many iron-manganese oxide and base metal sulphide mineralization, these horizons can often be traced by geophysical methods, even below considerable moraine cover. In fact, this cover reaches up to more than ten meters, which is the main reason why wollastonite occurrences were not recognized earlier as potentially economic occurrences.

The Hulta Gruvor prospect is located 7.5 km NW of the town of Nora, mapsheet 11E Filipstad SW, central Sweden. Three sub-horizontal to gently dipping marble horizons occur within a thick sequence of felsic metavolcanites, and are truncated by a nearly vertical, E-W trending dolerite dike on the southern end of the concession.

The wollastonite bearing marble is a flat lying to weakly dipping horizon which can be followed through drill cores from some small, abandoned iron ore mines in the east, 600 m to the west where it is exposed in four trenches. Wollastonite-bearing marble was intersected in core at depths between 4 and 70 m. The maximum thickness of uninterrupted wollastonite mineralization in drillcore is 7m. The country rock consists of garnet-pyroxene-scapolite-scheelite skärn, garnet-biotite-magnetite schists and marble-garnet-vesuvianite fels. Boulders with 90% wollastonite of a high quality have been found in the strike direction east of the wollastonite-marble horizons.

Two sub-parallel zones have been identified, intercalated in felsic metavolcanics, skärn and iron oxide units. The origin of the wollastonite is related to a hydrothermal - metasomatic event rather than contact metamorphism, as is generally assumed. The formation of a syn-volcanic iron formation and carbonate-chert horizon laid the chemical precursor to the wollastonite formation. Hydrothermal and metasomatic processes, possibly related to the presence of a major hidden granite, were responsible for the development of a scheelite - fluorite mineralization at Hulta and several other places, where the marble-chert horizons provided the chemical environment for interaction with the hydrothermal fluid. At the same time the wollastonite is thought to have developed in the Hulta marble-chert horizons with the other skärn minerals.

The mineralization is covered by moraine from 0-5 m thick. Wollastonite contents vary up to 80%, with an average grade estimated at 30%. The mineralogy varies from simple to complex, with parageneses including quartz, calcite, garnet, vesuvianite, pyroxene and feldspar. The wollastonite zones are usually sharply bounded by felsic volcanics or slightly calcareous metasediments, with no transitional zones. The wollastonite zones themselves

contain lenses or layers of **microcline chert**, with 95% potassium feldspar, **several** decimeters thick. While this poses problems for separation technologies, **the** feldspar is a saleable product, and **will** be recovered during mineral processing.

Several samples from the deposits in Central Sweden (one from **Silverön** and two from **Hulta-Gruvor**) were used by **CNR-ITM** to establish new methods for the processing of **wollastonite** ores with different mineral compositions: **wollastonite**, **K-Ca-Na-feldspars**, **vesuvianite**, **calcite** and **quartz**.

Currently-known dry and wet treatment processes usually involve run-of-mine with **wollastonite** contents greater than 60%. The first of these leads to a **wollastonite** concentrate that is obtained by dry crushing, grinding and sieving to reduce the untreated ore to a suitable size for subsequent treatment by magnetic separators where garnets and other magnetic material are removed. Subsequent air separation and micronization operations yield commercial **wollastonite** concentrates.

The wet process produces commercial concentrations of **wollastonite** by means of flotation techniques using anionic and **cationic** collectors, the technical details of which are an industrial secret.

The new technique developed at the Mineral Treatment Institute of the Italian **CNR** (National Research Council) involves an initial flotation step to remove **vesuvianite** and **calcite**, together with a large quantity of ferrous minerals in an alkaline circuit, followed by flotation of calcium-sodium-potassium **feldspars** in an alkaline circuit after acid conditioning, leaving a residue in the flotation cell consisting of **wollastonite**.

This method was worked up on a Swedish ore containing about 35% **vesuvianite** + **calcite**, 40% **feldspar** and 35% **wollastonite**. It was then applied to a **Silverön** ore containing about 60% **calcite**, 8% **feldspar** and 30% **wollastonite**.

The operating conditions to be adopted for the design of the best final circuit were then identified. The main operating variables covered were reagent quantities, and conditioning and flotation **pH** values. The influence of magnetic separation in various parts of the circuit to optimize results was also investigated.

Over the **three** years of the project a large amount of studies and work have been prepared on the occurrences **and** deposits briefly described here, in an attempt to solve **in** each case the methodological and technical problems which arose from the economic evaluation of the **deposits**.

There are many innovative aspects to the know-how developed by the work done on the project, though this has not led to any patents or registered rights (at least for the moment).

The most surprising of the initial difficulties consisted in the realization of the extreme difficulty in the precise quantification of the **wollastonite** content of any kind of sample. The

difficulties begin to be unmanageable when the number of samples is as high as is required for the industrial evaluation of a deposit, for the control of a *beneficiation* process, or for the contrasting of the quality of the products obtained with the *theoretical* specifications given for the products currently on the market.

These difficulties have been approached in different ways by the different members of the Consortium, by developing varied methodologies of analysis and adapting them to the *paragenetic* characteristics of each of the deposits being studied.

The scarce amount of practical information available in the technical literature which is accessible is evidence of how difficult it is to obtain this know-how. This is not the case with literature of a strictly scientific nature which is available to the same degree as with other industrial minerals. Above *all*, the high degree to which present producers and consumers of wollastonite protect their know-how, methodology and technology has become *clear*. Most of the members of the consortium have had negative experiences in this regard, and it has become clear that the development of specific products depends entirely on the collaboration of the consumers. Wollastonite is a perfect example in the industrial minerals market of “tailor-made” products to suit each customer.

The *secretism* which exists today amongst the main wollastonite-consuming sectors, apparently justified by strategic reasons, also *seriously* affects the possibility of calculating the size of the actual existing market.

6-7. RESULTS AND CONCLUSIONS

The following section consists of those results which each member of the consortium considers to be most relevant:

DRG - CINCOMINAS

The most outstanding result is the confirmation of a new model of world-class wollastonite deposit, with close to 70 Mt of classified reserves as follows: 4.5 Mt of proven reserves with an average grade of 35 % wollastonite, accessible by open pit exploitation and a waste/ore ratio of 0.46: 1; 25 Mt of probable reserves; 40 Mt of possible reserves.

The quality of the mineral meets market standards and can be beneficiated by the customary methods according to laboratory tests using the minimum specifications required by present markets. Results also indicate the possibility of obtaining products with a high added value.

Different ceramics-manufacturing firms belonging to the Portuguese association of companies known as CINCOMINAS, which includes nine companies from different industrial groups, have carried out tests on wollastonite from DRG's deposit. The best results were obtained in ceramic bodies by CERISOL (Vista Alegre group), who produce electroceramics. This company had not used wollastonite before the Brite-EuRam II project. They are currently developing new uses for wollastonite together with DRG.

IGME - CNRS

Skärn-type wollastonite reserves at Panorama are presently estimated at more than 700,000t.

The main guide for this type of deposit is the existence of contacts between pure marbles and silicate rocks (local source of silica) which could act as channels for fluids, at a distance of < 300m from the granite.

After pre-concentration and beneficiation, a saleable wollastonite concentrate fulfilling some general specifications was produced. A method for improving the whiteness of the above concentrate has also been developed. A garnet pre-concentrate was obtained as a by-product.

This wollastonite seems to be most suitable for powder-type products, either for filling or metallurgical purposes. However, other uses are not to be excluded, provided that its quality can be further improved (ie. reduction of Fe, grinding/classification).

EUROMIN - UNIVERSITÀ di PADOVA

Euromin activity was focused on the evaluation of a wollastonite deposit in the Western Bergslagen Proterozoic province of Central Sweden. Two areas, Limmingen and Silveron, were selected to this aim and claimed on the basis of few showings of ore but justified by the geological modelling. While Limmingen frustrated expectations, Silverön revealed as a potential economic deposit, very similar in its principal characteristics of geology and mineralogy to the Lappeenranta deposit in Finland. Wollastonite ore is related to a NNE-trending elongate marble body, and consists of three conformable, closely spaced zones. Main associated lithologies are clinopyroxene-garnet skarn, sheared marble and serpentine marble with disseminated Zn-Pb-Ag ore. Enclosing rocks are deformed and low-grade metamorphosed volcanoclastics of the 1.9-1.8 Ga Bergslagen Supracrustal Sequence, intruded by the 1.74 Ga Filipstad younger granite. Available exploration data allowed the

assessment, as **probable** reserves, to a depth of 30 m, of about 670,000 tons of wollastonite while **global** (probable and possible) reserves could be in excess of 1-1.5 Mtons.

ALBATROSS

2.5 Mt of exploitable reserves containing an average grade of 30% wollastonite have been established by sophisticated computer **modelling** based on the results obtained by three years of field work and associated mineralogical and **geochemical** studies. The **three** dimensional structure of the ore was obtained from diamond **drill** cores. **Beneficiation** test work demonstrated that the **wollastonite** could be separated from the host rock using magnetic separation and flotation. Pilot test work on a 40t sample has yielded a wollastonite concentrate for quality assessment and industrial testing, providing input for the final feasibility study, complementing extensive market research.

CNR - ITM

- An innovative wet circuit was found.
- A simple flow-sheet for treating different types of run-of-mine was developed.
- Wollasonite, feldspar and calcite concentrates were obtained in open circuits on three different runs-of-mine.
- The **wollastonite** concentrate obtained has a grade above 80% with a **recovery** calculated to be in excess of 70 %

The feldspar concentrate obtained has a grade of85% and the estimated recovery is **70%**

- The calcite concentrate grades above 90% with a recovery above 90%
- The design of an industrial circuit and the estimation of costs are possible only after the knowledge of commercial targets and the amount of run-of-mine to beprocessed.

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Aside from this individual results, the project has been prolific in significant common results due to cooperation between the different members of the consortium; both enterprises and scientific and technical researchcentres. This shared know-how covers different areas, which can be listed under the following headings :-

- Prospection methodology
- Beneficiation processes
- Information on markets

Of particular significance in the first case is the development of several new specific methods of analysis for the mineralogical and chemical characterization of wollastonite samples and concentrates, and the establishment of different models of deposit(some with important innovative aspects) and guidelines for their prospection.

There has also been substantial progress in the knowledge and definition of commercial products for different industrial sectors presently consuming wollastonite and the development of new “tailor-made” products, and know-how which is shared by the members of the consortium.

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Title : **DEVELOPMENT OF EXPLORATION AND INDUSTRIAL TECHNOLOGY TO EXPLOIT NEW SOURCES OF WOLLASTONITE IN EUROPE**

Contract N° **BRE2-CT92-0134**

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Lastly, this has been a complex project, with a large number of partners (8) from six different countries. That it has concluded without encountering any unsurmountable problems, has been due to a great degree to the Linguistic and communicative capacity of the Project Secretary, Mr Gordon COWELL, whose work is acknowledged by all partners.

9. REFERENCES

- 1982 OEN I. S., HELMER H., VERSCHURE R.H. & WICKLANDER U. "Ore deposition in a Proterozoic incipient rift zone environment: a tentative model for the Filipstad-Grythyttan-Hjulsjö region, Bergslagen, Sweden". *Geol. Rundsch.* 71(1):182-194.
- 1988 BAKER J. H., HELLINGWERF R.H. & OEN I.S. "Structure, stratigraphy and ore-forming processes in Bergslagen: implications for the development of the Svecofennian of the Baltic Shield". *Geologie en Mijnbouw* 67:121-138.
- 1988 VAN MEERTEN T.G. "Lithostratigraphic correlations in an asymmetrical rift-basin: the Grythyttan area, W. Bergslagen, Sweden". *Geologie en Mijnbouw* 67:203-212.
- 1995 INDUSTRIAL MINERALS. *Raw Materials for Pigments, Fillers & Extenders (Second Edition)*.