This paper presents the first specific study of the Th- and U-bearing minerals, which were recently found in the SE Mediterranean margin of Spain (El Hoyazo area, Almería province). These minerals are REE phosphates (mainly monazite) which occur as amoeboidal-to-elongate inclusions, from around 10 µm to 120 µm, hosted in single garnet crystals from dacite lavas and metamorphic rocks from the El Hoyazo Volcanic Complex. Th and U contents are higher than 1 wt%, with 3.04 to 5.62 wt % for ThO₂, and 0.7 to 1.75 wt% for UO₂. Both elements are also found in xenotime (ThO₂: 0.24, UO₂: 0.27 wt%). Given that the erosion of the volcanic source rocks has generated a "placer-type" deposit of monazite sands and that garnets (main carriers of monazite) are being commercialised, an environmental monitoring and management plan should be urgently executed in the area.

Introduction

It is well known that uranium and thorium are responsible for the majority of naturally occurring radioactive materials. Their decay produces radium, radon, and several isotopes of polonium, lead, and bismuth. Perhaps the best known is radon, which is a gas. The concentration of uranium in the Earth’s upper crust is about 3 ppm. Naturally occurring uranium nominally contains 99.28305% by weight 238U, 0.7110% 235U, and 0.0054% 234U. Studies show that the per-

Acknowledgements

Several works tackle the presence and concentration mecha-

Geological setting

The El Hoyazo Volcanic Complex (EHC) forms part of the Neogene volcanic province of the Mediterranean margin of Spain. This province is located to the east of the Betic Cordillera and extends from Cabo de Gata (Almería province) to Cartagena (Murcia province). The magmas generated in this region include the following rock series: calc-alkaline, K-rich calc-alkaline, shoshonitic, ultrapotassic and alkaline basaltic (López Ruiz and Rodriguez Badiola, 1980). Radiometric dating indicates two episodes of magmatic activity (Bellon, Bordet and Montenat, 1983). The first began in the Late-Burdigalian/Early-Langhian with the generation of CA rocks, continued with simultaneous extrusion of calc-alkaline, K-rich calc-alkaline and shoshonitic rocks, and ended in the Messinian with...
emplacement of ultratrapassic rocks. The second episode began 2 Ma later, with growth of the alkaline basalts. The K-rich calc-alkaline and shoshonitic rocks occur as domes, lacolites and dikes, and the main volcanic areas where they are found are: El Hoyazo and Vera (Almería province), and Mazarrón and Mar Menor (Murcia province). In general terms, the calc-alkaline and shoshonitic rocks are characterized by abundant metamorphic and igneous xenoliths as well as other inclusions of isolated crystals of garnet and cordierite. This richness of rock and mineral inclusions is more emphasised in El Hoyazo than elsewhere (Zeck, 1968).

The EHC is an extremely garnet-rich volcanic-subvolcanic dacite dome made up of K-andesite and dacite, which covers a circular area of approximately 0.7 km². It is situated between two sedimentary episodes and the central cone has been eroded. Although other garnet-rich zones exist in Spain (Sierra Nevada, Granada; El Cabril, Hornachuelos, Córdoba; Sierra Capelada, La Coruña, among others), El Hoyazo is unique being the only place where garnet can be found in such a large quantities and diversity. The garnet occurs (1) as isolated idiomorphous crystals (2 to 10 mm in size) in the volcanics; (2) as principal components of metamorphic xenoliths (crystals of up to 1.5 cm in size), and (3) as debris formed by the erosion of the volcanic dome. This is extremely important as garnet is the mineral where inclusions of monazite and xenotime occur. In addition, El Hoyazo is, following Zeck (1968), where the first described cordierite was found (this mineral occurs in clear association with the garnet). Detailed descriptions of the petrology and geochemistry of the volcanics from the EHC can be found in Zeck (1968, 1970), López Ruiz et al. (1977), Molin (1980), Munksgaard (1984, 1985), Zeck (1992), Benito (1993), Cesare et al. (1997), Benito et al. (1999), Lunar et al. (1999) and Muñoz-Espadas et al. (2000).

**U-Th-bearing monazite. Source rocks (metamorphic xenoliths) and main characteristics**

The REE phosphate, monazite, is an important mineral comprising three compositional varieties, Ce-monazite: (Ce,La,Nd,Th)PO₄ La-monazite: (La,Ce,Nd)PO₄, and Nd-monazite: (Nd, Ce, La, Pr, Sm, Gd)PO₄. Monazite has different mineralogical and geological applications: as a repository for rare earths (mainly Ce, La and Gd) and Th and U in the continental crust; for understanding of the processes involving fluid-rock interactions; for petrogenetic and geochemical studies concerning both the grade of metamorphic events and determination of crustal protolith composition; for U-Th-Pb geochronology, etc. In SE Spain, works about monazite are very scarce (Cesare et al., 2003), but they cover wide petrologic, geochemical, and geochronological aims in other areas of the Iberian Peninsula (mainly Central and NW Spain) (Bea et al. 1994, Casillas et al. 1995, Zalduegui et al. 1996, Bea, 1996).

The detection of U-Th bearing monazite in the EHC was the result of a detailed sampling of metamorphic rock and single crystal (garnet, cordierite and quartz) inclusions. As indicated above, monazite grains were only found as µm-sized inclusions hosted in both garnet crystals and the matrix of the metamorphic xenoliths in the volcanics (Figure 1). The highest quantity of inclusions was found in xenoliths from the north and south zones of the volcanic dome outcrop. These metamorphic xenoliths broadly represent 10–15 vol% of the EHC dacite, and are made up of both Al-rich restite xenoliths and monocrysts derived therefrom. The rock fragments consist of: 1) almandine-biotite-sillimanite-plagioclase (± cordierite) rock with a well-developed metamorphic foliation, and without quartz or K-feldspar; 2) spinel-cordierite hornfels, and 3) cordierite-quartz rock without plagioclase or K-feldspar. Approximately 1 vol% of the dacitic rock is made up of 2–10 mm ruby-red euhedral to subhedral garnet crystals. They do not present any reaction or precipitation products on the crystal edges, and closely resemble the crystals found in Al-rich restite xenoliths in habit, size, colour, inclusions (quartz, biotite, fibrolite), refringence and chemical composition and zoning. Other monocrystal restite xenoliths are corroded quartz (up to 10 cm; average size ~ 2 cm), anhedral cordierite (0.5–10 mm), graphite (up to 200 µm), anhedral andesine (100–300 µm), dark lilac or green spinel hercinite (50–300 µm) and usually anhedral zircon (around 50 µm).

Geochemically, the xenoliths display (Table 1) low content of SiO₂ (38.35–50.35%) but high Al₂O₃ (26.11–36.38%), Fe₂O₃, MgO +TiO₂ (Fe₂O₃+MgO+TiO₂: 9.06–21.28%). The geochemical composition of the other major elements varies according to the mineralogy. The compatible trace elements, Sc, V, Cr, Co and Ni, show higher geochemical values than those from their host volcanics. Some incompatible elements (i.e. Zr (226–474) and Nb (20–32) are also higher. The metamorphic xenoliths (source rocks of the U-Th bearing monazite) present almost identical contents of Rb (113–176), Ba (486–1264 ppm), La (43–58), Ce (84–122), and Pb (11–53 ppm). The concentrations of Sr (52–545) and Th (11–19) are slightly lower (Benito, 1993). Concerning the isotope composition, the xenoliths display ⁸⁷Sr/⁸⁶Sr ratios of between 0.7153 and 0.7303 and δ¹⁸O values ranging from +9.7 and +16.2‰, (Munksgaard, 1984, López Ruiz and Wasserman, 1991, Benito, 1993). Given that, as previously defined, the U-Th bearing monazite has only been found as inclusions in garnets and matrix from the metamorphic xenoliths, its existence could be important regarding the controversy about the origin of the EHC garnet crystals: either by direct crystallization from dacitic melts, or by derivation as restitic monocrysts from the metamorphic xenoliths (Zeck, 1968, 1970, López Ruiz et al. 1977, Molin, 1980; Munksgaard, 1985, Martinez-Frias et al. 1999).
Table 1 Chemical analyses of major d trace elements from selected samples of almandine-biotite-fibrolite-plagioclase xenoliths (El Hoyazo-garnet rich volcanic Complex).

|          | GAT-55 | GAT-38 | GAT-49 | GAT-53 |
|----------|--------|--------|--------|--------|
| Major elements, wt% |        |        |        |        |
| SiO₂     | 38.35  | 40.65  | 42.71  | 45.72  |
| TiO₂     | 1.80   | 1.33   | 1.71   | 1.48   |
| Al₂O₃    | 36.38  | 34.62  | 32.08  | 28.18  |
| Fe₂O₃    | 9.79   | 10.71  | 12.44  | 9.69   |
| MnO      | 0.02   | 0.15   | 0.07   | 0.07   |
| MgO      | 2.71   | 2.34   | 3.64   | 2.30   |
| CaO      | 0.94   | 0.78   | 0.45   | 1.34   |
| Na₂O     | 0.16   | 0.35   | 0.32   | 1.24   |
| K₂O      | 2.72   | 2.78   | 2.95   | 4.27   |
| P₂O₅     | 0.10   | 0.12   | 0.21   | 0.17   |
| L.O.I.   | 99.60  | 99.29  | 99.73  | 97.89  |
| Trace elements, ppm |        |        |        |        |
| Sc       | 20     | 29     | 18     | 19     |
| Rb       | 137    | 136    | 144    | 171    |
| Sr       | 134    | 129    | 52     | 545    |
| Y        | 26     | 71     | 39     | 27     |
| Zr       | 298    | 236    | 285    | 226    |
| Nb       | 32     | 20     | 27     | 27     |
| Ba       | 663    | 951    | 486    | 1264   |
| La       | 47     | 50     | 58     | 48     |
| Ce       | 90     | 93     | 122    | 86     |
| Pb       | 24     | 22     | 24     | 53     |

Textural and crystal-chemical characteristics

The U-Th bearing monazite was firstly cited by Muñoz-Espadas (2002) and Cesare et al. (2003). It is the most abundant REE mineral of El Hoyazo. It occurs as tiny, anhedral (mainly amoeboidal) to subhedral elongated inclusions (Figure 2) in both the garnet monocrystals and matrix of the metamorphic xenoliths, with a size ranging from around 10 µm to 120 µm. Monazite’s crystal-chemical characteristics were determined on the basis of a large data set of electron microprobe analyses (Jeol Superprobe JXA-8900M), bulk and channel-selected (TAP, PETJ, LIF, PETH) X-ray spectra search and identification routines, along with further SEM studies (JSM-100), including both semi-quantitative analyses and detailed textural observations. Selected electron microprobe analyses of monazite are shown in Table 2. In broad terms they indicate that the type of host crystals/grains, crystal size, degree of idiomorphism and other textural differences are not represented by significant chemical variations. No textural or chemical zoning was detected in different inclusions.

Table 2 Selected electron microprobe analyses of monazites from the metamorphic enclaves (El Hoyazo-garnet rich volcanic Complex). G43B2, G43B4, G10A2, G10A1, G10A9: monazite inclusions in garnet snygle crystals. M10A5 and M10A10: monazite inclusions disseminated in the intergranular matrix.

|          | GAT-55 | GAT-38 | GAT-49 | GAT-53 |
|----------|--------|--------|--------|--------|
| SiO₂     | 0.04   | 0.03   | 0.54   | 0.28   |
| CaO      | 0.14   | 0.13   | 0.11   | 0.16   |
| SrO      | 0.16   | 0.17   | 0.17   | 0.15   |
| P₂O₅     | 0.10   | 0.12   | 0.21   | 0.17   |
| K₂O      | 1.33   | 1.33   | 1.71   | 1.48   |
| Na₂O     | 0.16   | 0.35   | 0.32   | 1.24   |
| MgO      | 2.71   | 2.34   | 3.64   | 2.30   |
| CaO      | 0.94   | 0.78   | 0.45   | 1.34   |
| Na₂O     | 0.16   | 0.35   | 0.32   | 1.24   |
| K₂O      | 2.72   | 2.78   | 2.95   | 4.27   |
| P₂O₅     | 0.10   | 0.12   | 0.21   | 0.17   |

The major anion group P₂O₅ is around 30 wt % (29.03–30.41), and SiO₂ values are always below 0.6 wt %. Among LREE, Ce₂O₃ is the most abundant (up to 32.5 wt %), followed by La₂O₃ (13.02–14.12), Nd₂O₃ (11.17–11.96), Sm₂O₃ (1.80–2.27), and Pr₂O₃ (0.70–0.97). Among the HREE, Gd₂O₃ is the only one with more than 1 wt % (up to 1.86 wt %); Dy₂O₃ and Er₂O₃ show values of around 0.70–0.97 wt %, whilst the others display even less than this amount. Yttrium (similar in ionic radius as the HREE, between Dy and Ho) is between 0.9 and 2.32 wt % Y₂O₃. All monazite inclusions show a similar descendent trend, and a pronounced negative anomaly in Yb (Figure 3), which is similar to that found by Zhang and Nozaki (1998) related with seaweed samples. Other non-REE were also detected forming part of the monazite composition, although only Th and U display contents higher than 1 wt %. Th values range between 3.04 and 5.62 wt % of ThO₂ and U (UO₂) ranges from 0.7 to 1.75 wt %. Zr values are always below the detection limit (< 0.05 wt % of ZrO₂). A good positive correlation is observed between Th and U, Y and Er respectively.

To compare these contents with those obtained from the EHC volcanics and metamorphic xenoliths, it is important to take into account that the lavas show the following REE values: La: 52.1 ppm, Ce: 104 ppm, Nd: 45.9 ppm, Sm: 7.92, Eu ppm: 1.73, Tb ppm: 0.89, Yb: 1.78 ppm, Lu: 0.30 ppm. Y ranges between 24 and 41 ppm, and Th and U are always below 26 ppm and 8.82 ppm, respectively. Finally, the only existent analyses of these trace elements in the metamorphic xenoliths comprise Y (20–71 ppm), Zr (226–474 ppm), La (43–58 ppm), Ce (84–122 ppm) and Th (11–19 ppm).

Figure 2 Tiny irregular inclusion of monazite hosted in a garnet crystal from the metamorphic xenoliths.
Besides these chemical features, the Sm$_2$O$_3$ vs. La$_2$O$_3$ and Y$_2$O$_3$ vs. ∑HREE values obtained in the EHC monazites also reflect the high-grade metamorphism undergone by the metamorphic source rocks, which is corroborated by the petrological and geochemical characteristics of the xenoliths (Zeck, 1968).

Other REE (U, Th)-bearing minerals

Although monazite is the most widespread REE phase in the EHC, other accessory REE (U, Th)-bearing minerals were also found: zircon (Figure 4) which had already been identified by Zeck (1968) and recently was studied in detail by Zeck and Whitehouse (2002), and Cesare et al. (2003) even reaching a crystal size of up to 0.3 mm, and xenotime (Figure 5), cited here for the first time (although only one well-faced inclusion, of around 55 µm, was found in all the samples studied). The chemical analyses of these two minerals indicate they match the experimental formulas well. In the zircon, almost all the REE, U and Th are below the detection limit: 0.1 wt%; only Gd, Er and Yb display values which can reach 0.3 wt %. The analysis of the only xenotime found in the EHC (a more in-detail search for xenotime inclusions is currently in progress), gives the following chemical composition: SiO$_2$: 1.04, CaO: 0.05, P$_2$O$_5$: 35.36, Y$_2$O$_3$: 43.30, ThO$_2$: 0.24, UO$_2$: 0.27, Gd$_2$O$_3$: 5.34, Dy$_2$O$_3$: 5.89, Er$_2$O$_3$: 4.19, Yb$_2$O$_3$: 4.33. All other rare earths are below the detection limit (around 0.01 wt %).

Conclusion

This work presents the first study of the U, Th-bearing minerals (monazite, xenotime) in the SE Mediterranean margin of Spain (El Hoyazo, Almería province). Monazite has been found as tiny (10–120 µm), non-zoned, rounded and elongated inclusions, which are hosted in garnet crystals and matrix from metamorphic xenoliths disseminated in the volcanics. The detailed analysis of its chemical composition indicates Ce and Gd are the most significant LREE and HREE (up to 32.5 wt % Ce$_2$O$_3$ and 1 wt % Gd$_2$O$_3$, respectively). All monazite inclusions display similar descendent REE distribution pattern, and a pronounced negative anomaly in Yb. Sm$_2$O$_3$ vs. La$_2$O$_3$ and Y$_2$O$_3$ vs. ∑HREE diagrams verify the high-grade metamorphism of the host metamorphic xenoliths. This has already been deduced by other petrological and geochemical studies and appears to confirm the parallel genetic history of this environmentally significant REE mineral and its host xenoliths.

Although the small amounts in which these monazites occur mean their influence could be considered of little importance, it should be remembered that natural mechanisms have concentrated large masses of monazite rich sands: the “Rambla de las Granatillas placer-type deposit”. The Quaternary alluvial fan, that forms the placer deposit, covers an area of 1 km$^2$ and has a maximum thickness of 40 m. Garnets (main carriers of U, Th-monazite) are found loose in layers 5–50 cm thick and up to 50% in volume garnet-rich. At the beginning of the twentieth century, garnet exploitation reached an all-time high, peaking in 1933. From 1996 until very recently, a private company, Garnetkao, S. L., had recommenced the exploitation intermittently. The end product is an 80-mesh garnet-rich powder, and the average yield was estimated at 6t/day (Lunar, Martinez-Frias, Benito and Wolf, 1999).

Therefore, an environmental monitoring and management plan of the area is necessary, not only for the presence of uranium and thorium but also for radium, radon, and several isotopes of polonium, lead, and bismuth which are also related to the decay of both elements. This plan should be focussed on the source volcanic outcrops and the monazite sands, on the final industrial garnetiferous product and its exportation. In this sense, it is important to note that some international regulations (e.g. Regulation 11 of The Department of Industry, Science and Resources, Australia) include severe exportation restrictions for “Nuclear source material which comprises uranium and thorium (including thorium contained in monazite obtained from mineral sands) and special fissionable material includes plutonium".
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Hutchison "Young Scientist" Foundation

William Watt Hutchison, "Hutch" to his many friends around the world, was a Scots-born Canadian geologist who served Canada and the IUGS in myriad dynamic and creative ways. Most notably, he served as the IUGS Secretary General (1976–1980) at a pivotal time in its history, and as IUGS President (1984–1987). The same boundless energy, enthusiasm, skill in communications, and ability to foster teamwork that characterized his work with the IUGS also carried him to preeminent scientific administrative positions in the Canadian Government, where he served as Director General of the Geological Survey of Canada and as Assistant Deputy Minister of Earth Sciences. His distinguished career was terminated in 1987 by his untimely death at the age of 52, following a painful struggle with cancer.

One of Hutch's last wishes was to establish under IUGS auspices a memorial foundation intended to promote the professional growth of deserving, meritorious young scientists from around the world by supporting their participation in important IUGS-sponsored conferences. The first 3 beneficiaries of the Hutchison "Young Scientist" Foundation attended the 28th International Geological Congress (IGC) in Washington, D.C., in 1989.

Initially, earned interest on the funds available to the Hutchison Foundation were insufficient to sustain comparable grants every four years without seriously eroding the principal. For that reason, the IUGS made no grants from the Foundation for the 30th IGC (1996), preferring instead to strengthen the fund by allowing it to earn interest for a longer period of time and by appealing for donations from the international geologic community. Grants from the Foundation again supported deserving young scientists beginning with the 31st IGC (2000), and should continue for future Congresses. The IUGS would like to expand the resources of the Foundation to make it possible also to offer support to deserving young scientists to attend other important IUGS-sponsored scientific meetings.

The Hutchison "Young Scientist" Foundation is a worthy cause that honors a fine, caring man and a distinguished, public-spirited scientist and administrator. The foundation also celebrates and promotes those things that gave Hutch the most professional satisfaction: geology, international scientific collaboration, and stimulating young minds.

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