Applied Earth Science

Transactions of the Institutions of Mining and Metallurgy: Section B

ISSN: 0371-7453 (Print) 1743-2758 (Online) Journal homepage: http://www.tandfonline.com/loi/yaes20

$^{40}Ar/^{39}Ar$ dating of mesothermal, orogenic mineralization in a low-angle reverse shear zone in the Lower Palaeozoic of the Anglo-Brabant fold belt, Belgium

S. Dewaele, A. Boven & Ph. Muchez

$^{40}Ar/^{39}Ar$ dating of mesothermal, orogenic mineralization in a low-angle reverse shear zone in the Lower Palaeozoic of the Anglo-Brabant fold belt, Belgium

S. Dewaele, A. Boven and Ph. Muchez

Lower Palaeozoic mesothermal gold mineralization formed during the Caledonian orogeny has been identified in Wales[3,26,34] Scotland[15,22,25] and Ireland[28,37,43] (Fig. 1). The mineralization is hosted preferentially in structural elements produced during the accretion of the Laurentia, Baltica and Gondwana terranes. Other turbidite-hosted gold deposits have been found within the Cambrian–Ordovician Meguma Province of eastern Canada[23] and the Baie Verte Peninsula of Newfoundland[6] (Fig. 1).

The origin and genesis of mesothermal deposits are variously attributed to metamorphic, plutonic and lithospheric processes. Absolute timing of the mineralizing events is crucial to understanding of the ore-forming processes within the orogenic belts as temporal constraints help to determine the possible relationship between mineralization and magmatic, metamorphic or tectonic events at a regional scale. Unfortunately, direct measurement of the age of ore minerals is often very difficult or even impossible owing to the absence of datable minerals and overprinting by several mineralization stages. However, once the mineral paragenesis of the deposits is fully described, reliable timing of vein formation can be obtained through $^{40}Ar/^{39}Ar$ dating of such minerals as muscovite, biotite and amphibole, for which the hydrothermal origin has been well established.[24,29,42]

Application of the $^{40}Ar/^{39}Ar$ technique in the dating of mineralizing events is not, however, always straightforward. The often cryptocrystalline texture of the minerals may be a reason for ^{39}Ar recoil. The occurrence of different generations of hydrothermal minerals of compositionally and microstructurally heterogeneous grain populations can yield different $^{40}Ar/^{39}Ar$ ages. Ar loss resulting from deformation[35] or thermal overprinting because of subsequent magmatic or hydrothermal activity[4,21] has been reported from various deposits, as has excess argon.[17]

Recently, borehole data in the Marcq area (Figs. 1 and 2) led to identification of mesothermal, orogenic polysulphide mineralization along a low-angle reverse shear zone[32] present in turbidites of Ordovician age. The mineralization consists of pyrite, pyrrhotite, marcasite, arsenopyrite, galena, chalcopyrite, sphalerite and stibnite. The shear zone shows intense alteration, characterized by sericite, chlorite and quartz.

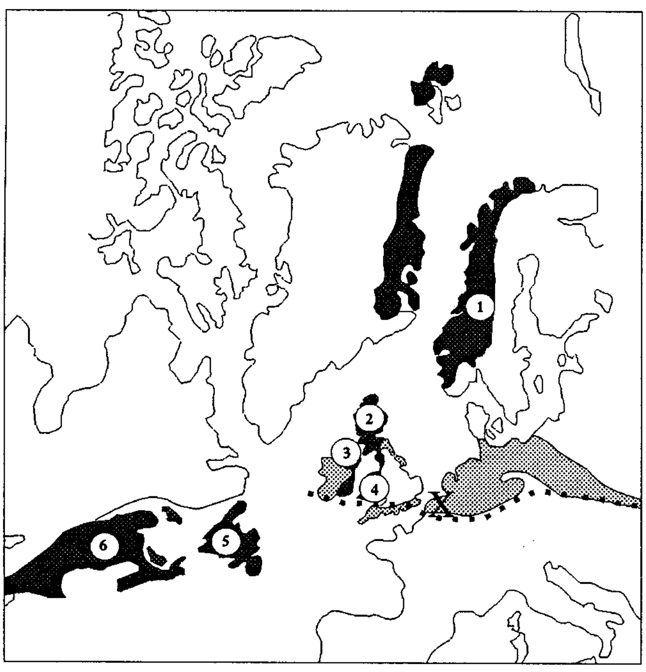

Fig. 1 Occurrence of Lower Palaeozoic deformation belts, differentiating those with (*dark grey*) and without (*light grey*) known Au occurrences.[6] Known gold occurrences: (1) Scandinavia (Graddis); (2) Scotland (Glendinning); (3) Ireland (Clontibret, Cavanacaw and Curraghinalt); (4) Wales (Dolaucothi and Dolgellau); (5) Newfoundland (Baie Verte); and (6) Nova Scotia (Meguma Terrane). Mesothermal, orogenic polysulphide deposit in Anglo-Brabant fold belt in Belgium indicated by X. The Variscan front is indicated by the dotted line and no Lower Palaeozoic deformation belts are indicated in the figure south of this

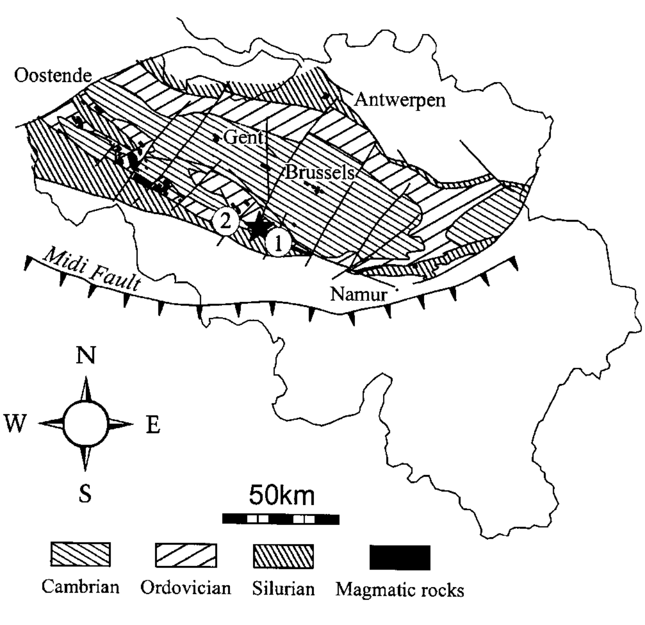

Fig. 2 Sub-outcrop map of Anglo-Brabant fold belt in Belgium.[13] Study area indicated by star. Magmatic bodies at Quenast (1) and Lessines (2) also shown

Manuscript received by the Institution of Mining and Metallurgy on 30 October, 2002. Technical note published in *Trans. Instn Min. Metall.* (*Sect. B: Appl. earth sci.*), **111**/*Proc. Australas. Inst. Min. Metall.*, **307**, September–December 2002.

Detailed microscopical investigations demonstrated that the emplacement of the polysulphide mineralization was contemporaneous with the formation of the shear zone and with alteration.[32] On the basis of the general geological setting the shear zone is interpreted to have formed during the Early to early Middle Devonian deformation event recognized in the Anglo-Brabant fold belt.[1,39] This deformation phase has been attributed to the Lower Palaeozoic orogeny, locally called the Brabantian phase in reference to the Anglo-Brabant fold belt in Belgium.[40]

The $^{40}Ar/^{39}Ar$ dating technique was applied to sericites closely associated with the mineralization in the Marcq area to provide better temporal constraints. The characteristics of the mesothermal polysulphide mineralization in the Marcq area are compared here with those of mesothermal, orogenic gold deposits from other parts of the world and especially gold deposits situated in the Caledonian orogeny in northern Europe. Although the mineralization in the Marcq area has been identified as being mesothermal orogenic mineralization, gold has been detected only at levels 0.1 ppm.

Geological setting

The Lower Palaeozoic in Belgium forms the southeastern part of the Anglo-Brabant fold belt.[30] This Lower Palaeozoic Caledonian slate belt is moulded around the Cadomian Midlands Microcraton forming the core of the East Avalonia microcontinent.[7] The oldest sediments of the Anglo-Brabant fold belt identified in Belgium are of Early Cambrian age; they occur in the central part of the fold belt. Younger sediments up to Silurian age flank this Cambrian core to the north and south (Fig. 2).

Several volcanic and intrusive rocks of different ages are distinguished. These volcanic rocks are present at the southern border of the fold belt and are characterized by strong alteration. Hertogen and Verhaeren[20] interpreted these rocks to have formed as subaerial and submarine ignimbrites. Their composition and distribution indicate them to be related to near-surface intrusive bodies. The Rb–Sr whole-rock age for the sill of Lessines and the U–Pb age for zircons from the neck of Quenast obtained by André and Deutsch[2] are 419 $\pm$13 m.y. and 433$\pm$10 m.y., respectively. Rb–Sr whole-rock ages of 376$\pm$24 and 404$\pm$19 m.y. from an andesitic breccia and 384$\pm$20 m.y. from ignimbrites[1] are interpreted to reflect low-grade metamorphic Sr-isotopic resetting during the Givetian. These volcanic–magmatic rocks are related to the subduction of a small oceanic basin north of the Anglo-Brabant fold belt.[41]

The Lower Palaeozoic basement is discordantly concealed by younger deposits of Givetian age (late Middle Devonian), which do not show any sign of regional cleavage development or metamorphism. Therefore, metamorphism, folding and cleavage predate the Givetian and postdate the Gorstian (Ludlovian)—the youngest sediments affected. At present, there is only evidence for one major tectonometamorphic deformation in the Anglo-Brabant fold belt in Belgium, which occurred during the Late Silurian to early Middle Devonian.[12] The deformation can be considered as the result of a post-accretionary intracontinental accommodation within the East Avalonia microcontinent due to the closure of the Rheic Ocean.[9,31,33] On the basis of the cumulative thickness curve of Verniers *et al.*[41] and the subsidence curve of Van Grootel *et al.*[39] Debacker[12] demonstrated that progressive deformation and foreland basin development in the Anglo-Brabant fold belt in Belgium started at the Llandovery–Wenlock transition.

The southwestern margin of the Lower Palaeozoic Brabant Massif, where the study area is located, has a complex, distinctive deformation history caused by the inferred presence of a rigid granitoid basement block at depth.[16,36] The low-angle reverse shear zone identified in the Marcq area by Debacker[11] can be considered as the result of south-vergent overthrusting on top of this presumed granitoid basement block.

Brittle–ductile origin of the shear zone in the Marcq area

The mineralized shear zone is characterized by an envelope of intense sericitization, chloritization and silicification. Microscopic investigations demonstrate that mineralization and alteration were synkinematic with the formation of the shear zone.[32] The same minerals as characterize the alteration (sericite and chlorite) can be observed in pressure shadows of pyrite crystals present in the mineralized veins. Sericite and chlorite show the same geochemical evolution whether they are found in the pressure shadows or in the alteration zone.[32] The orientation of the mineralized veins parallel to the cleavage and the subsequent deformation of these veins indicate that mineralization took place during a protracted, simple shear deformation in which cleavage planes were reactivated as shear planes. The compositional changes of the alteration minerals along these reactivated cleavage planes show a similar trend in sericite–chlorite pattern to the surrounding altered host rocks.[32] Therefore, mineralization, alteration and deformation occurred largely during the same progressive deformation event, slightly postdating the development of the cleavage fabric.

Microthermometric and Raman spectroscopic analysis of fluid inclusions in quartz indicates that the mineralizing fluid had the composition H_2O–CO_2–CH_4–NaCl–(KCl) and minimum temperatures between 250 and 320°C.[14] On a ^{18}O– D plot the values of the mineralizing fluid cluster in the field typical for metamorphic fluids and partly overlap that for primary magmatic fluids.[32] The ^{34}S values of sulphides present in the mineralization, however, fall outside the interval typical for I-type magmas. The microthermometric data combined with chlorite geothermometry indicate a formation temperature between 300 and 400°C and a pressure of 100–200 MPa for the mineralizing fluids.[14] This is in agreement with formation within the ductile–brittle region at a depth of *ca* 8 km.

$^{40}Ar/^{39}Ar$ dating

$^{40}Ar/^{39}Ar$ dating was carried out on sericite samples taken at different depths from three boreholes (B6, B7, B8) in the Marcq area. Six samples were selected from borehole levels that show different degrees of alteration (Fig. 3). The sample numbers consist of the sampling depth in the borehole in centimetres followed by the number of the borehole (e.g. 19110B7 corresponds to a sample taken at 191.10 m depth in borehole B7).

The sericite separates comprised millimetre-size flakes. The sericite was identified by petrographical and X-ray diffraction (XRD) analysis as very pure, fine-grained muscovite. This muscovite crystallized from the hydrothermal fluids and occurs either adjacent to some minute mineralized veinlets or along cleavage planes, which can also contain ore minerals. Muscovite is most abundant within the alteration envelope surrounding the mineralized veins. Only pure, hand-picked sericite flakes were retained for the present study. These samples, together with aliquots of the LP-6 biotite standard, CaF_2 and K-glass monitors, were irradiated under Cd shielding for three days in channel E30 in the DG5 carrier of the BR2-reactor of the Belgian Nuclear Research Centre at Mol.

Ages were calculated by use of a J-factor determined from interpolation between three J-factors obtained on aliquots of LP-6 biotite, for which an age of 128.1$\pm$0.2 m.y.[5] was used.

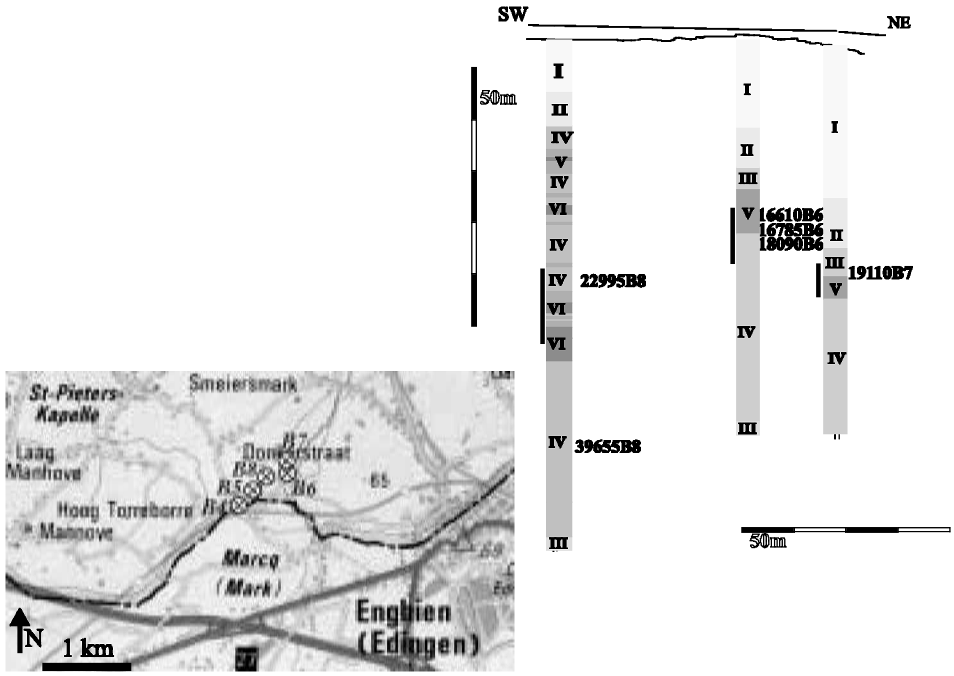

Fig. 3 Position of sericite samples in boreholes B6, B7 and B8 dated by $^{40}Ar/^{39}Ar$ method. Numbers I–VI indicate increase in sericitization and silicification. Dark band on logs indicates position of shear zone. Increase in alteration measured by macroscopic, geochemical and XRD investigation[32]

All errors for the ages are given at the 2 level, thereby accounting for the analytical errors, which included the variability of the neutron flux as determined by dosimetry measurements on an Fe wire. The analytical details were as described by Boven *et al.*[8] The uncertainty in the J-factor is ±1%, but excludes errors on the K and Ca correction factors. Step-wise heating experiments with numerous steps at very small temperature intervals were carried out in a high-vacuum resistance oven and argon measurements were taken with a MAP 216 mass spectrometer operated in static mode. Most samples yielded consistent, plateau-shaped age spectra and fairly stable Ca/K spectra. Both plateau and total ages, based on use of the percentage of released ^{39}Ar as a weight factor, were calculated (Fig. 4).

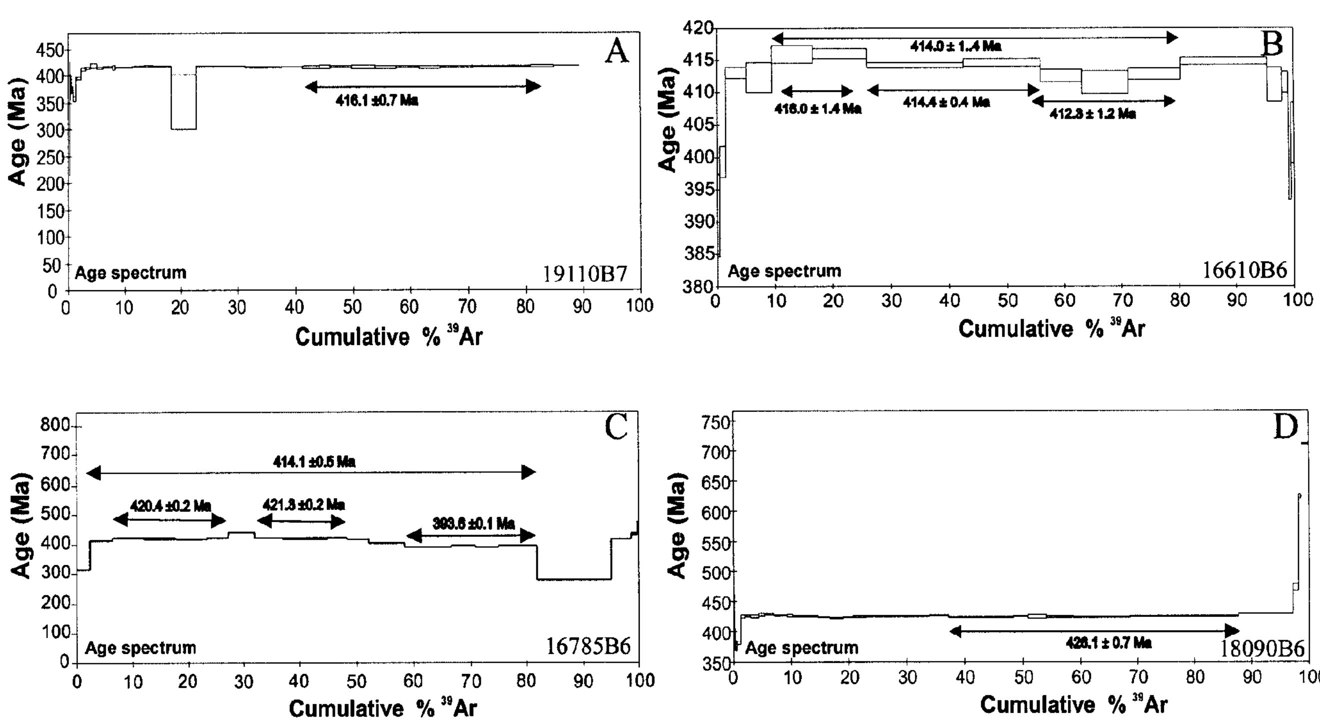

Fig. 4 $^{40}Ar/^{39}Ar$ age spectra of sericite (muscovite) from boreholes in Marcq area: (*a*) sample 19110B7, (*b*) 16610B6, (*c*) 16785B6 and (*d*) 18090B6

Sample 19110B7 yielded an excellent plateau age of 416.1 ±0.7 m.y., which accounted for 90% of the released ^{39}Ar (Fig. 4(*a*)). Within error limits this is equivalent to the plateau age of 417.0±1.8 m.y. for sample 39655B8.

Sample 22995B8 yielded a less regular age spectrum with a stepped pattern of increase for the first 20% of released ^{39}Ar; this can be attributed to a loss of $^{40}Ar^*$. The highest step age was 414.9±3 m.y.—similar, within the range of error, to the age of the two previous samples.

Sample 16610B6 showed a more disturbed, saddle-shaped spectrum (Fig. 4(*b*)). Two consecutive steps yielded a highest apparent age of 416.0 ±1.4 m.y., again similar to previous results. The base of the saddle yielded an apparent age of 412.3±1.2 m.y. on two consecutive steps. A total fusion age of 414±1.4 m.y. is considered for further interpretation since this corresponds to *ca* 80% of ^{39}Ar released.

The age spectrum for sample 16785B6, from the most altered part of B6, had a peculiar shape (Fig. 4(*c*)) and fluctuations were observed in the Ca/K spectrum. This may be attributed to phase changes that occur during the step-heating experiment. A total fusion age of 414.1 ±0.5 m.y. was derived for this sample. The heterogeneity observed in the shape of the individual age spectra could be due to microstructural heterogeneity at the level of the grains, as mentioned by Sletten and Onstott,[35] which is characteristic of shearing activity.

Sample 18090B6 produced a plateau spectrum with a distinctively higher apparent age of 426.1±0.7 m.y. (Fig. 4(*d*)). Some excess argon was present in the high-temperature steps, but this sample had a very homogeneous Ca/K spectrum. Since no excess Ar is considered for this sample, circulation of fluids could have started about 12 m.y. before the main alteration and mineralization (around 417–414 m.y.) This earlier period of circulation could have been obliterated in most samples during subsequent fluid migration. These ages are in agreement with the model of a prolonged period of deformation, as proposed by Debacker.[12] The onset of fluid circulation (426 m.y.) possibly coincided with the start of the foreland basin development during the Llandovery–Wenlockian transition; this is also illustrated by the cumulative thickness curve of Verniers *et al.*[40] and the subsidence curves of Van Grootel *et al.*[39] and Debacker.[12]

Discussion

Mesothermal orogenic deposits in slate belts are widely distributed throughout the world, occurring in rocks from Archaean to Tertiary.[18] Phanerozoic orogenic gold deposits are associated with convergent plate margins in close proximity to major translithospheric structures or transpressional–transtensional shear zones.[6] Although the Caledonian orogeny in northern Europe (Fig. 1) is characterized by long-lived margins and arc-trench systems, orogenic gold deposits are relatively rare. Some gold has been produced from deposits in the Scandinavian Caledonides and a little from deposits in Wales,[3,26,34] Scotland[15,22,25] and Ireland.[28,37,43] K–Ar dating of wallrock micas in the Dolgellau gold belt, Wales, yielded ages from 410±13 to 390±12 m.y.[26] Similar ages are generally accepted for the other deposits in Wales, Scotland and Ireland.[6] The formation of these deposits is closely associated with the closure of the Iapetus Ocean and the accretion of different continental fragments during the early Palaeozoic.

These ages are similar to those determined in the mineralization in the Anglo-Brabant fold belt. The $^{40}Ar/^{39}Ar$ results from five of the six hydrothermal sericite samples show very consistent plateau ages within a time interval between 417 and 414 m.y. One sample yielded an age of 426 m.y.

Mesothermal orogenic gold deposits are almost entirely structurally controlled and are often hosted in thick, marine sedimentary rock sequences.[6] The deposits are characterized by quartz-dominated vein systems with 3–5% sulphide minerals (mainly Fe sulphides) and 5–15% carbonate minerals associated with a strong alteration, especially sericitization and silicification.[19] The ore fluids were CO_2-rich metamorphic or magmatic fluids with variable amounts of CH_4. Deposits were formed between 250° and 400°C and between 1 and 3 kbar. The most typical examples are found at or above the brittle–ductile transition in greenschist-grade terranes. The polysulphide mineralization and alteration of the wallrock in the Marcq area were identified as contemporaneous with the formation of the shear zone. Structural, geochemical and microthermometric data indicate that the mesothermal orogenic polysulphide mineralization in the Marcq area was formed at a depth of *ca* 8 km and at elevated temperatures and pressures (300–400°C and 100–200 MPa) in the ductile–brittle transitional regime, most probably by the circulation of metamorphic fluids.

Similar formation parameters have been obtained for Lower Palaeozoic, mesothermal, orogenic gold mineralization identified in Wales,[3,26,34] Scotland[15,22,25] and Ireland.[28,37,43] Often, however, the mineralizing fluids proposed for these deposits have been either magmatic or a mixture of metamorphic and magmatic. There is a small overlap between the ages of the magmatic intrusions and the ages obtained by Ar–Ar dating of the alteration associated with the Marcq mineralization, which means that it is not possible to exclude a magmatic–volcanic origin for the mineralizing fluid. Even so, geochemical and microthermometric data clearly favour a metamorphic origin.[32] Comparably, the gold deposits in the Cambro-Ordovician Meguma province of eastern Canada[23] and the Devonian Cobar deposit in central New South Wales[38] were formed from CO_2-metamorphic fluids, with a temperature generally between 200 and 350°C and at a pressure between 2 and 3 kbar.

Like the Marcq mineralization, some of the Cobar deposits are dominated by polysulphides with only minor gold content. These deposits are also present along a low-angle shear zone, whereas the majority of gold deposits are associated with high-angle fault zones. Several reasons can be proposed for the lack of economic quantities of gold in the Anglo-Brabant fold belt. One is an absence of host rocks suitable for the leaching of gold and sulphur, but this is unlikely since the metasedimentary and volcanic rocks in the southern margin of the Anglo-Brabant fold belt are similar to those in other fold belts with gold-bearing veins. Another could be that the low angle of the shear zone impeded upward flow of deep fluids, but this is also unlikely since gold mineralization is associated with low-angle shear zones at Hyde-Macreas in New Zealand[10] and the Revenge gold mine in Western Australia,[27] for example.

A third explanation is that the Anglo-Brabant fold belt was not an important collisional belt with significant tectonic disturbances of the temperature profile.[12] This is indicated by the low degrees of metamorphism, the deformation style, the gradual rate of inversion and the inferred overall geometry of the fold belt and the surrounding crustal basement blocks.[12] Indeed, Goldfarb and co-workers[18] showed that major gold mineralization in orogenic belts closely follows the peak of metamorphism and is associated with the uplift and unroofing of the orogenic belt and lithospheric delamination. These add extra heat to the lower crust by mantle upwelling and the higher temperature results in a mobilization of gold in the lower crust. The lack of these special characteristics is the likely reason for the low gold content in the Anglo-Brabant fold belt in Belgium.

Conclusion

Mesothermal polysulphide mineralization has been identified along a low-angle shear zone in the Marcq area at the southern rim of the Lower Palaeozoic Anglo-Brabant fold belt in Belgium. Structural, petrographical, geochemical and microthermometric investigations indicate that this mineralization formed synorogenically under ductile–brittle conditions at a depth of *ca* 8 km as a result of the migration of metamorphic fluids.

The ages obtained by Ar–Ar dating of sericites present in the alteration surrounding the mineralization show a homogeneous time interval between 417 and 414 m.y. One sample, however, yields a distinctly older age of 426 m.y. Since no excess Ar is considered for this sample, circulation of fluids could have taken place episodically over a time-span of about 12 m.y. The ages obtained are in agreement with the model of a prolonged period of deformation. The period measured for the Marcq mineralization is comparable with that for the emplacement of mesothermal gold mineralization during the Caledonian orogeny of Wales, Scotland and Ireland.

The geochemical and microthermometric data of the polysulphide mineralization in the Marcq area in Belgium also show similar characteristics to the mesothermal, orogenic gold deposits in the Caledonian fold belt in Europe and fold belts throughout the world (Nova Scotia, New South Wales, New Zealand, etc.). In this case, however, the minimal gold enrichment found in the Anglo-Brabant fold belt probably reflects the lack of sufficient heat to mobilize gold in the lower crust.

Acknowledgement

Funding was provided by the Fund of Scientific Research of Flanders (F.W.O.-Vlaanderen, Belgium), project G.0274.99. The cores studied are the property of the company Terex and the Flemish community; the authors are grateful to both for permission to publish the results. Herman Nijs carefully prepared thin sections and the doubly polished wafers.

References

1. André L., Deutsch S. and Michot J. Données géochronologiques concernant le développement tectono-métamorphique du segment Calédonien Brabançon. *Annales de la Societé géologique de Belgique*, **104**, 1981, 241–53.
2. André L. and Deutsch S. Les porphyres de Quenast et de Lessines: géochronologie, géochimie isotopique et contribution au problème de líage du socle précambrien du Massif du Brabant (Belgique). *Bull. Societé belge de Géologie*, **93**, 1984, 375–84.
3. Annels A. E. and Roberts D. E. Turbidite-hosted gold mineralization at the Dolaucothi gold mines, Dyfed, Wales, United Kingdom. *Econ. Geol.*, **84**, 1989, 1293–314.
4. Arehart G. B. *et al.* $^{40}Ar/^{39}Ar$, K/Ar and fission track geochronology of sediment-hosted disseminated gold deposits at Post-Betze, Carlin Trend, northeastern Nevada. *Econ. Geol.*, **88**, 1993, 622–46.
5. Baksi A. K, Archibald D. A. and Farrar E. Intercalibration of $^{40}Ar/^{39}Ar$ dating standards. *Chem. Geol.*, **129**, 1996, 307–24.
6. Bierlein F. P. and Crowe D. E. Phanerozoic orogenic lode gold deposits. *Reviews in Econ. Geol.*, **13**, 2000, 103–39.
7. Blundell D. J., Freeman R. and Mueller S. *A continent revealed, the European geotraverse* (Cambridge: Cambridge University Press, 1992).
8. Boven A. *et al.* $^{40}Ar/^{39}Ar$ study of plagioclases from the Rogaland anorthosite complex (southwest Norway): an attempt to understand argon ages in plutonic plagioclase. *Chem. Geol.*, **176**, 2001, 105–35.
9. Cocks L., McKerrow W. and Van Staal C. The margins of Avalonia. *Geol. Mag.*, **134**, 1997, 627–36.
10. Craw D., Windle S. J. and Angus P. V. Gold mineralization without quartz veins in a ductile–brittle shear zone, Macraes mine, Otago Schist, New Zealand. *Mineral. Deposita*, **34**, 1999, 382–94.
11. Debacker T. N. Folds trending at various angles to the transport direction in the Marcq area, Brabant Massif, Belgium. *Geologica Belgica*, **2**, 1999, 159–72.
12. Debacker T. N. Palaeozoic deformation of the Brabant massif within eastern Avalonia: how, when & why? Ph.D. thesis, R.U. Gent, 2001.
13. De Vos W. *et al.* A new geological map of the Brabant Massif, Belgium. *Geol. Mag.*, **130**, 1993, 605–11.
14. Dewaele S. *et al.* *P-T-X* variation along a polysulphide mineralized low-angle shear zone in the Lower Palaeozoic Anglo-Brabant fold belt (Belgium). In *Mineral deposits at the beginning of the 21st century* (Rotterdam: Balkema, 2001), 727–31.
15. Duller P. R. *et al.* Gledinning deposit—an example of turbidite-hosted arsenic–antimony–gold mineralization in the Southern Uplands, Scotland. *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)*, **106**, 1997, B119–34.
16. Everaerts M. *et al.* Integrated geophysical/geological modelling of the western Brabant Massif and structural implications. *Bull. Societé belge de Géologie*, **105**, 1997, 41–59.
17. Gilbert L. A. and Foland K. A. The Mount Saint Hilaire plutonic complex: an occurrence of excess ^{40}Ar and short intrusion history. *Can. J. Earth Sci.*, **23**, 1987, 948–58.
18. Goldfarb R. J., Groves D. I. and Gardoll S. Orogenic gold and geologic time: a global synthesis. *Ore Geol. Rev.*, **18**, 2001, 1–75.
19. Groves D. I. *et al.* Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types. *Ore Geol. Rev.*, **13**, 1998, 7–27.
20. Hertogen J. and Verhaeren M. Studie van het magmatisme in het Massief van Brabant. Unpublished report ANRE VLA96-3.5.4, K.U. Leuven, Belgium, 1999, 24 p.
21. Ilchik R. P. $^{40}Ar/^{39}Ar$, K/Ar and fission track geochronology of sediment-hosted disseminated gold deposits at Post-Betze, Carlin Trend, northeastern Nevada—a discussion. *Econ. Geol.*, **90**, 1995, 208–10.
22. Ixer R. A. F., Pattrick R. A. D. and Stanley C. J. Geology, mineralogy and genesis of gold mineralization at the Calliachar–Urlar Burn, Scotland. *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)*, **106**, 1997, B99–108.
23. Kontak D. J. *et al.* Integrated model for the Meguma Group lode gold deposits, Nova Scotia, Canada. *Geology*, **18**, 1990, 238–42.
24. Kontak D. J., Smith P. K. and Reynolds P. H. Geology and $^{40}Ar/^{39}Ar$ geochronolgy of the Beaver Dam gold deposit, Meguma Terrane, Nova Scotia, Canada: evidence for mineralization at 370 Ma. *Econ. Geol.*, **88**, 1993, 139–70.
25. Lowry D. *et al.* Sources of sulphur, metals and fluids in granitoid-related mineralization of the Southern Uplands, Scotland. *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)*, **106**, 1997, B157–68.
26. Mason J. S., Fitches W. R. and Bevins R. E. Evidence of a pre-tectonic origin for the auriferous vein-type mineralization of the Dolgellau gold belt, north Wales. *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)*, **108**, 1999, B45–52.
27. Nguyen P. T. *et al.* Fault-valve behaviour in optimally orientated shear zones; an example at the Revenge gold mine, Kambalda, Western Australia. *J. struct. Geol.*, **20**, 1998, 1625–40.
28. O'Connor P. J. and Gallagher V. Gold prospectivity in the Caledonides of southeast Ireland: application of the upper-crustal reservoir model. *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)*, **103**, 1994, B175–87.
29. Pettke T., Diamond L. W. and Villa I. M. Mesothermal gold veins and metamorphic devolatilization in the nortwestern Alps: the temporal link. *Geology*, **27**, 1999, 641–4.
30. Pharaoh T. C., England R. and Lee M. K. The concealed Caledonide basement of eastern England and the southern North Sea—a review. *Studia Geophysica Geodaetica*, **39**, 1995, 330–46.
31. Pickering K. T. and Smith A. G. Arcs and backarc basins in the early Palaeozoic Iapetus Ocean. *The Island Arc*, **4**, 1995, 1–67.
32. Piessens K. *et al.* Fluid flow, alteration, and polysulphide mineralization associated with a low-angle reverse shear zone in the Lower Palaeozoic of the Anglo-Brabant fold belt, Belgium. *Tectonophys.*, **348**, 2002, 73–92.
33. Rey P., Burg J.-P. and Casey M. The Scandinavian Caledonides and their relationship to the Variscan belt. In Burg J.-P. and Ford M. eds *Orogeny through time* (London: Geological Society, 1997), 179–200. *Spec. Publ. geol. Soc. Lond.* 121
34. Shepherd T. J., Bottrell S. H. and Miller M. F. Fluid inclusion volatiles as an exploration guide to balck shale-hosted gold deposits, Dolgellau gold belt, north Wales, UK. *J. geochem. Explor.*, **42**, 1991, 5–24.
35. Sletten V. W. and Onstott T. C. The effect of the instability of muscovite during *in vacuo* heating on $^{40}Ar/^{39}Ar$ step-heating spectra. *Geochim. Cosmochim. Acta*, **62**, 1998, 123–41.
36. Sintubin M. Arcuate fold and cleavage patterns in the south-eastern part of the Anglo-Brabant fold belt (Belgium): tectonic implications. *Tectonophys.*, **309**, 1999, 81–97.
37. Steed G. M. and Morris J. H. Isotopic evidence for the origins of a Caledonian gold–arsenopyrite–pyrite deposit at Clontibret, Ireland. *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)*, **106**, 1997, 109–18.

38. Stegman C. L. Cobar deposits: still defying classification! *SEG Newsletter*, **44**, 2000, 1,15–26.
39. Van Grootel G. *et al.* Timing of magmatism, foreland basin development, metamorphism and inversion in the Anglo-Brabant fold belt. *Geol. Mag.*, **134**, 1997, 607–16.
40. Verniers J. *et al.* The Cambrian to mid Devonian basin development and deformation history of eastern Avalonia, east of the Midlands Microcraton: new data and a review. In Winchester J., Verniers J. and Pharaoh T. eds *Palaeozoic amalgamation of central Europe. Spec. Publ. geol. Soc. Lond.*, **201**, 2002, 47–93.
41. Verniers J. *et al.* Cambrian–Ordovician–Silurian lithostratigraphical units (Belgium). In Bultynck P. and Dejonghe L. eds Guide to a revised stratigraphical scale of Belgium. *Geologica Belgica*, **4**, 2001, 5–39.
42. Werner O. and Lippolt H. White mica $^{40}Ar/^{39}Ar$ ages of Erzgebirge metamorphic rocks: simulating the chronological results by a model of Variscan crustal imbrication. In Franke W. *et al.* eds *Orogenic processes: quantification and modelling in the Variscan Belt* (London: Geological Society, 2000), 323–36. *Spec. Publ. geol. Soc. Lond.* 179
43. Wilkinson J. J. *et al.* Gold remobilization by low-temperature brines: evidence from the Curraghinalt gold deposit, Northern Ireland. *Econ. Geol.*, **94**, 1999, 289–96.

Authors

S. Dewaele is a Ph.D. student at the Katholieke Universiteit Leuven, Belgium, and is working on mineralization in the Anglo-Brabant fold belt in Belgium. His main interest is the evolution of the physico-chemical conditions during its formation.

Address: Fysico-chemische Geologie, Katholieke Universiteit Leuven, Celestijnenlaan 200C, 3001 Leuven, Belgium; e-mail stijn.dewaele@geo.kuleuven.ac.be

A Boven is a F.W.O. researcher and is responsible for the dating facilities at the department of geochronology at the Vrije Universiteit Brussel.

Ph. Muchez is a professor at the Katholieke Universiteit Leuven and head of the Ore Geology and Geofluids research unit.