EUG XI

Symposium FMF5

The Timing and Location of Major Ore Deposits in an Evolving Orogen

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Wednesday PM Session

FMF5 : WEpm25 : F4

Geodynamic Control of Late-Stage Orogenic Mineralisation in Young Orogenic Belts: The Alpine-Carpathian-Balkan-Dinaride Mountain Belt

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The study of young orogenic belts is the key for understanding of the geodynamic control on location and timing of major ore deposits in ancient mountain belts. The Alpine-Balkan-Carpathian-Dinaride orogen (ABCD) shows that late-stage orogenic mineralisation events are always within short periods (< 10 Ma) and linked to major brittle structures which allowed magma/fluid/metal transfer from deep to shallow structural levels.

The ABCD belt includes over large sectors the superposition of Tertiary collision structures on early to late Cretaceous ones. The Cretaceous belt formed due to consumption of Vardar-Meliata-Severin oceanic tracts and subsequent late Cretaceous collision of Austroalpine-Danubian blocks with Tisia/Southalpine blocks forming the future promontory of the Adriatic microplate. Reconstruction of Cretaceous collision structures, magmatic features and mineralisation reveal significant variations along strike which include: (1) The Alpine-West Carpathian sector is characterised by strong metamorphic overprint (eclogite facies: ca. 20 kbar) in Alpine areas due to subduction of Austroalpine continental crust and subsequent exhumation during post-orogenic collapse (ca. 80 Ma). This sector comprises deposits of metamorphogenic minerals (talc, magnesite, siderite), and vein-type (Pb-As-Au) and shear zone (Cu-Au-Sb) mineralisation related to exhumation of metamorphic core complexes. (2) In contrast, the Apuseni Mountains to Balkan sector comprises late Cretaceous banatite magmatism (ca. 80-75 Ma) associated with Cu-Au-Fe deposits. Magmatism is interpreted to represent either (1) andinotype magmatism due to northward subduction of oceanic crust or (2) post-collision I-type magmatism due to break-off of the subducted lithosphere. The missing magmatism in the Alpine-West Carpathian sectors can be explained by continuous southward subduction and cooling of the overlying mantle wedge due to ongoing subduction of the Penninic ocean tract. Cretaceous slab break-off has probably not affected western ABCD sectors.

The Cretaceous terrane collage was heavily modified by Tertiary collisional, extrusional and oroclinal processes due to oblique collision and indentation of the Adriatic and Moesian microplates and subsequent invasion of Alpine units into the Carpathian arc. Different types of mineralisation were also formed within the Alpine-Carpathian belt during Late Oligocene to Neogene collisional processes. The Western and Eastern Alps are dominated by mineralisation events which are linked to the formation of metamorphic core complexes (e. g. mesothermal Au-quartz veins, replacement As-Ag-Cu ore bodies, mineralised low angle normal faults), the Carpathians and Apuseni mountains by subduction- and/or collision volcanism and associated Pb-Zn-Sb-Au mineralisation along major wrench zones. Principal structures in volcanic edifices are steep mineralised tension parallel to the motion direction of crustal blocks, and along Riedel shears in wrench corridors separating blocks.

The Drina-Rhodope Pb-Zn province is a further, Oligocene to early Miocene, belt which is also largely related to calcalkaline volcanism. This belt is probably related to ca. northward subduction beneath the Hellenic arc and initial stages of extension due to south-westward slab retreat.

FMF5 : WEpm26 : F4

A Comparison of the ^{187}Re-^{187}Os and $^{40}Ar/^{39}Ar$ Chronometers in the Ore-Forming Environment

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Recently the ^{187}Re-^{187}Os chronometer, the only means to directly date sulphides and oxides, has been successfully applied in a variety of ore-forming environments. Prior to this, indirect estimates of the timing of mineralisation have been based on dating gangue and alteration minerals, or bracketing ore-forming events by dating pre-ore and post-ore units. The Re-Os chronometer is preferred for dating any magmatic-related mineralisation (e.g., porphyry-related deposits) or any other mineralisation that may have been overprinted by multiple magmatic/hydrothermal or metamorphic pulses. Using $^{40}Ar/^{39}Ar$ may yield analytically precise, but geologically inaccurate ages that are slightly to significantly younger than the true time of ore deposition. The Re-Os chronometer is unsurpassed, particularly in the single mineral dating of molybdenite (Stein et al., 1997, 1998; Selby and Creaser, 2000).

Chemical behaviour of parent-daughter pairs: Argon does not naturally reside in the lattice of silicate minerals, and it is therefore subject to erratic and unpredictable loss with heating. Hornblende has the added complication of potential excess argon. Re and Os, on the other hand, are chalcophile-siderophile elements structurally bound in sulphide minerals. Isolated sulphide phases are undoubtedly robust, as they cannot communicate with other sulphides and Re and Os will not choose to relocate in a silicate or aqueous phase. In a sulphide-bearing hydrothermal environment, it has been shown experimentally that Re and Os remain fixed in sulphide. Only under highly oxidising conditions are they slightly soluble in an aqueous phase, probably as chloride species, with Re 100 to 1000 times more soluble than Os (Wood and Xiong, 2000).

Locking the chronometers: A datable mineralising event is one with a clear beginning and ending, plus a discernible temporal separation from previous and ensuing events. Even though the analytical uncertainty in an argon lab may be very good, that beginning and ending can only be defined after the local geologic environment passes below (and stays below) the blocking temperature for a particular mineral. The closure temperature for ore-associated minerals commonly dated by the $^{40}Ar/^{39}Ar$ method (e.g., biotite, muscovite) is well below the near magmatic temperatures at which the Re-Os chronometer for molybdenites becomes locked. Subsequent high-temperature overprints do not unlock the Re-Os chronometer in molybdenite, but do disturb the argon chronometer (e.g., Watanabe and Stein, 2000). In fact it has been demonstrated that the Re-Os chronometer in molybdenite can survive temperatures associated with high-grade metamorphism (Raith and Stein, 2000). Sharp closure for an argon-based chronometer is unlikely in environments with fluctuating or sustained high temperatures, such as polymetamorphic terranes and complex magmatic systems. The high locking temperature for Re-Os in molybdenite permits the temporal discrimination of individual mineralising pulses during closely spaced magmatic events, whereas the $^{40}Ar/^{39}Ar$ ages will drift youngward until the last intrusion has cooled.

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FMF5 : WEpm27 : F4

Timing the Mineralization in an Evolving Orogen. The Relativity of Absolute Age Information

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The research that focuses on the timing and location of ore deposits is demanding an increase in the amount of available age information. In theory the sensitivity of modern age analyses should help us to pinpoint any remarkable happening in the evolution of an orogen within a resolution of a few million years. In practice the timing of a combined physical and chemical anomaly like an ore deposit is difficult to establish. To fully appreciate the produced age information it is very important to familiarise with the limits of the dating techniques to lower the potential obscuring effect of misidentified absolute ages. This contribution investigates the complex assignment of age information to mineralisation. Examples from the Balkan region, presenting published and new information, show us that parallel to our analytical challenge we have to solve a three-fold timing question; i) what is the timing of a specific mineralisation, ii) what is the duration of a mineralising event and iii) do we identify different stages of mineralisation. The sources of information that contribute to the answer of the above individual questions may not be completely identical. The integration of several observations is essential to understand the geological significance of our age information and to relate identified stages of mineralisation to controlling geodynamic processes. Ideally all temporal (and spatial) information has to be critically examined and incorporated in the genetic model of the mineralisation. Evidently this includes information of the mineralisation (timing of mineralisation, timing of host rock deposition, duration of the mineralising event, duration of associated volcanism, duration of associated hydrothermal activity) but also involves information associated with the regional tectonics (e.g. timing of deformation in surrounding basement rocks, timing of basement denudation, timing of basin formation and sedimentation).

FMF5 : WEpm28 : F4

Dating of Formation of Mesothermal Quartz-Gold Veins within the Tauern Window, Eastern Alps (Austria): Constraints from $^{40}Ar/^{39}Ar$ Ages of White Mica and Adularia

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Formation of open, crystal-filled extension veins within the Tauern Window of the Eastern Alps (Austria) has been dated using adularia and white mica. In general, formation of these minerals coincides with, or post-dates, mineralisation in mesothermal Au-quartz veins. $^{40}Ar/^{39}Ar$ dating has been carried out on 10 samples of white mica (Ms) and adularia (Kfs), which have been separated from up to cm-large free crystals post-dating mineralisation. We also separated (the K-free mineral) chlorite and hoped to be able to date intergrowths of white mica, thus dating formation of the chlorite. Unfortunately, dating has not been successful because of the low Ar-content of the sample. Although age spectra and $^{36}Ar/^{40}Ar$ vs. $^{40}Ar/^{39}Ar$ isotopic correlation plots indicate variable contributions of extraneous ^{40}Ar-components to the isotopic system of Ms and Kfs, results indicate two different pulses of vein formation, probably caused by two independent fluid pulses. We do not observe any correlation between the dated minerals (e.g. Ms or Kfs) and the obtained ages, nor with the amount of incorporated extraneous ^{40}Ar components. The ages obtained are significantly different, and indicate: (a) a first pulse at c. 19 Ma (1 Ms, 3 Kfs analyses), (b) followed by an event at c. 15 Ma (2 Ms, 3 Kfs analyses), and (c) one well defined analysis of a Kfs reports an age of c. 13 Ma. Because temperatures for vein formation were similar or lower than closure temperatures for the Ar-isotopic system in white mica (c. 400˚C), and K-feldspar (c. 200˚C), these ages are interpreted as crystallisation ages, and to directly date the formation of the veins. Samples yielding an age of ca. 19 Ma have been collected from within an area where quartz-Au veins are most widespread. We interpret this age to closely date ore formation during c. ESE-WNW extension in accomodation zones along the a strike-slip zone that separates distinct culminations of the Tauern metamorphic dome. The second age group, at ca. 15 Ma, is related to barren veins at upper margins of the Tauern window. This age group is interpreted to represent a distinct thermal pulse which coincides in age with a weak thermal pulse also found in mylonites. The third age, at c. 13 Ma, is found in the western part of the Tauern Window and coincides in age with regional cooling found by zircon fission track dating. In summary, $^{40}Ar/^{39}Ar$ dating of vein adularia and white mica seem to have a great potential for dating low-temperature vein formation, and thus extension and related epigenetic ore deposits.

FMF5 : WEpm29 : F4
Re-Os Ages for Molybdenites from the Felbertal Tungsten Deposit, Tauern Window, Austria

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The Felbertal scheelite deposit, one of the largest operating tungsten mines in the world, is hosted by a Cambro-Ordovician volcanic arc sequence (metabasalts, metagabbros, orthogneisses derived from felsic I-type granitoids) and Variscan granitoids. The latter belong to the Early Carboniferous episode (ca. 340 Ma) of a multi-stage Variscan magmatic activity (Eichhorn et al., 2000).

Both syngenetic and epigenetic models have been discussed for the Felbertal scheelite deposit. Epigenetic granite-related models presently replace previous concepts favouring sedimentary-exhalative processes for tungsten enrichment (Eichhorn et al., 1999). However, it is still unclear if ore formation is exclusively linked to highly-evolved Variscan intrusions of Early Carboniferous age ("K1-K3 gneiss", 336 ± 19 Ma) or if there exists an additional earlier mineralisation stage at ca. 520 Ma, a possibility expressed by Eichhorn et al. (1999) and Höll and Eichhorn (2000). The main goal of this project is to directly date, using the Re-Os method, established and paragenetically distinct stages of ore formation using co-existing pairs of molybdenite and scheelite. We present here the first Re-Os results on molybdenite, which clearly demonstrate the importance of direct dating of ore relative to U-Pb dating of some ore-hosting units (e.g. 520 Ma orthogneisses).

A molybdenite sample from the western ore field, collected from a mineralised quartz cupola above an Early Variscan granitic gneiss body ("K1" ore body, underground level 1152) yielded an age of 346.0 ± 1.3 Ma. A massive banded scheelite-quartz ore ("K2" ore body, underground level 1164) containing minor molybdenite and sulphides aligned along the penetrative foliation yielded an age of 340.8 ± 1.3 Ma. A third molybdenite sample from the outcropping eastern ore field (1920 m level) is from the scheelite-quartz stringer zone within Cambrian orthogneisses and underlying the (now completely mined out) quartzitic scheelite ore, and its age is 343.7 ± 1.4 Ma. Hence molybdenites of the K2 ore body and of this stringer zone are also Early Carboniferous.

Two mineral separates of fine-grained molybdenite from a well-foliated retrogressed amphibolite in the eastern ore field yielded Re-Os ages of 414.3 ± 1.6 and 418.4 ± 1.6 Ma, and are nearly within their 2-sigma error. These ages are significantly older than the Early Carboniferous ages for mineralisation, and they may represent an event previously unrecognised at Felbertal but reported from other basement rocks in the Tauern area (Von Quadt et al., 1997).

Re-Os dating of molybdenites from the Felbertal tungsten deposit indicates a main ore-forming event at 340-345 Ma and the molybdenites are not affected by Variscan and Alpine regional metamorphism. The robustness of the chronometer has been recognised (e.g. Stein et al., 1998), and this study again demonstrates that the Re-Os dating of molybdenite produces credible results in complex geologic and hydrothermal environments.

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FMF5 : WEpm32 : F4
Hydrothermal Activity Related to the Precious/Polymetallic Mineralization in the Baia Mare District, Romania

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The Baia Mare district (Romania) represents a complex segment of the Neogene/Quaternary, subduction related, volcanic chain of the Carpathians. In this province, the calc-alkaline volcanism and associated mineralisation are closely related to a major strike-slip fault and an underlying pluton. The ore-deposits of the entire district have many features typical of low-sulphidation epithermal systems. The combination of fluid-inclusion microthermometry, Raman spectroscopy, bulk crush-leach analysis, LA-OES of individual fluid inclusions and stable isotope data have been used to characterise the hydrothermal activity related to the precious/polymetallic mineralisation. Ore-fluids of Baia Sprie, Cavnic and Sasar deposits have temperatures of 320 to 150°C and salinities in the range 0–21 wt.% NaCl equiv. During phreatomagmatic activity, fracturing and periods of vein dilation, the pressure may have decreased, causing boiling. The hydrothermal fluids were Na-K-Ca chloride solutions with lesser amounts of Li, SO_4 and F. The Na/K ratio and the stable isotope composition are consistent with equilibration of the fluids with country rocks at a low water-rock ratio and at progressively lower temperatures. The halogen ratios, together with sulphur isotopic systematics are consistent with a magmatic origin. The ore-fluids sampled have a complex composition reflecting the combined effects of an initial magmatic input and extensive fluid-rock interaction, together with boiling, dilution and mixing.

FMF5 : WEpm33 : F4
The Elatsite Porphyry Copper Metal Deposit of the Panagyurishte Corridor, Srednogorie Zone, Bulgaria: U-Pb Zircon and Isotopic Investigations for Timing and Ore Genesis

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This big Cu-Au porphyry deposit is located 7.5 km to the south of Etropole at the contact between greenschist-facies metamorphites of the Berkovitsa Group (Early Paleozoic?) and the Vezen granodioric intrusion (Late Palaeozoic?). Late Cretaceous subvolcanic bodies and dykes (Petrunov et al., 1992; Lilov and Chipchakova, 1999, etc.) intruded into these two main geological units. Field evidence demonstrates that the Cu-Au-PGE mineralisation is coeval with at least some of the Cretaceous magmatites. One main goal of this work is the precise geochronological study of timing of different intrusion episodes and the isotopic-petrological-geochemical characterisation of the volcanites and their genetic relations to the mineralisation of the Elatsite deposit. The subvolcanic rocks of the Elatsite deposit and its region are presented by pre-, syn- and 'post-ore' forming dyke systems. The oldest dyke type may be of metagabbroic composition and is observed as xenoliths in the largest subvolcanic dyke (4 x 0.1 to 0.45 km), which is of monzodiorite composition. Further, there are K-feldspar-, plagioclase-, amphibole-bearing dykes for which some age relationships could not be established from field evidence. There are some observations that the plagioclase-bearing dykes are cut by the amphibole-bearing system (Fanger et al., 2001, this volume). Single grain U-Pb analyses on zircon suggest an intrusion age of 92.3 ± 1.4 Ma for the monzodiorite porphyry. The idiomorphic zircon grains are clear and no visible cores are recognised. The calculation of the U-Pb data display some old lead components of 503 Ma. This age information may imply that components of the Berkovitsa group were involved in the Cretaceous intrusion process. These U-Pb data coincide with the K-Ar whole rock data of Lilov and Chipchakova, 1999. Preliminary data of $^{87}Sr/^{86}Sr$ ratio of 0.706728 as well as the 0.702356 (92 Ma) prefer an input of mantle material. On the other hand, an [epsilon]e-Nd value (T-92Ma, ‹7.0) indicates a participation of crust material. Further isotope-geochemical investigations on mineral assemblages as well as on the timing of the alteration and mineralisation processes, together with the ongoing studies of the syn- and post-ore dykes, will provide additional constraints on the sources of magmas and the associated porphyry copper deposit of Elatsite and help to unravel their genesis.

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FMF5 : WEpm34 : F4
Temporal and Thermal Evolution of Hydrothermal Vein Deposits in the Madan Extensional Core Complex (Bulgaria)

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Large lead–zinc mineralised vein swarms are associated with the Madan Dome in the Central Rhodopes, which is interpreted as a large metamorphic core complex. We are investigating the timing of extensional detachment motion, core complex uplift, local acid magmatism, and hydrothermal ore formation, using high-precision geochronology to determine the geodynamic and thermal controls of fluid flow and ore formation. In conjunction with isotopic tracer and fluid inclusion data, we then hope to identify the sources of ore-forming components and the mechanism of hydrothermal metal transport and precipitation. The Madan Dome has been interpreted as a (> 40 km diameter) metamorphic core complex that resulted from orogenic collapse after the Alpine collision between the Eurasian and African plates north of the Agean sea (Burg et al., 1990). An upper plate and a lower core of the dome are separated by a continuously mapped, outward-dipping fault zone, which is considered to be a major extensional detachment. Fault blocks of crystalline rocks represent the basement of the upper plate above the detachment. They comprise amphibolite-facies metapelite and metacarbonate in the upper parts and ortho- and paragneisses in the lower parts of the upper plate. Amphibolite facies metamorphism in the upper-plate crystalline rocks is currently not well dated. The lower plate of the inferred core complex consists of gneisses, micaschists, amphibolites and marbles. Migmatisation and local anatexis are common. The youngest available leucosome age is ca. 36 Ma (U/Pb zircon; Arkadaksky et al., 2000). The detachment is locally cut by rhyolite dykes, and shallow rhyolitic intrusives grading upward into volcanoclastics covering the central part of the exposed dome. These relations indicate that volcanism postdated not only extensional movement on the detachment, but also at least part of the uplift and denudation of the high-grade metamorphics in the lower plate of the core complex. First U/Pb dating of zircons indicates that the rhyolites intruded about 30 Ma ago. The main Pb-Zn deposits are metasomatic replacement bodies formed at the intersection of steep vein swarms with marble horizons in the upper and lower plate. The feeder veins crosscut the detachment faults, and associated carbonate–sericite alteration associated with the veins also overprint the rhyolite dykes. These observations show that mineralisation postdated extensional movement of the dome and occurred during or after uplift and magmatism. Current work is focused on radiogenic dating of the uplift history of the metamorphic rocks of the dome, refinement of the dating of rhyolitic magmatism, and precise geochronology of the vein-forming events in the four main ore fields. Such data should help us to decide whether ore formation is genetically associated with magmatism, or rather with fluid circulation driven by the thermal energy associated with metamorphic core uplift.

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FMF5 : WEpm35 : F4
Kinematics of Successive Eocene to Miocene Low-Angle Detachment Systems (Rhodope Zone, N Greece)

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Crust-scale detachment systems are important transport systems for fluids associated with formation of ore deposits. In the Rhodope several generations of crust-scale low angle detachment are linked to four successive exhumation pulses: The first pulse at about 65->48 Ma exhumed the uppermost Kimi Complex. The Kimi complex is characterised by Lower Cretaceous high P-/high-T metamorphism (>22 Kbar), cooling during decompression, and an overall slow exhumation lasting c. 50 Ma. The second pulse at >42-30 Ma exhumed the Sidironero Kardamos and Kechros Complexes W, underlying the Kimi Complex in the central and E Rhodope, respectively. These Complexes are characterised by probably Early Tertiary high-P metamorphism, isothermal decompression and probably rapid exhumation. Maximum pressures are highest in the Upper Sidironero Complex reaching >19 kbar at 700˚C. Exhumation tectonics between >42 and 39 Ma involves deep level thrusting of hot above cool HP-rocks synchronous with higher level extension. Between 38-30 Ma, this was followed by post-thrusting extension along the Xanthi low angle detachment system. Lutetian (c. 48-43 Ma) to Oligocene marine basins transgressed atop the Kimi Complex representing the upper plate of all detachment generations. The Xanthi detachment shows an overall ESE-dip with a ramp and flat geometry cutting across the earlier thrust structures. This detachment extends over a distance of 100 km, from its break up zone above the Sidironero Complex (Central Rhodope) into the E Rhodope and is interpreted to be responsible for a decrease in recent crustal thickness of about 20 km from the central to the E Rhodope. A Miocene exhumation pulse between 26 to 12 Ma, exhumed the Thasos/Pangeon metamorphic core complexes representing the structurally lowermost tectonic units of the Rhodope domain. Miocene extension occurred by displacements on Strymon and Thasos detachment systems representing the early stages of Aegean back arc extension. Metamorphic complexes exhumed during the 42-12 Ma episodes are considered to represent windows of the Apulian plate beneath material (Kimi Complex) that accreted earlier (Cretaceous) onto the composite European continent. In sum, detachment systems excise, several tens of km of material within the crustal profile.

We focus on the timing and kinematics of mass movements that successively dominated exhumation of high-P rocks in the long lasting time interval from the Lower Cretaceous to the Late Tertiary.

FMF5 : WEpm36 : F4
A Little Rain Falls but Faulting is Essential for the Origin of Zn-Pb Deposits in Western Europe

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Numerous studies carried out during the last two decades, especially on the American continent, suggest that Mississippi Valley-type (MVT) lead-zinc deposits are the result of a basin-wide groundwater movement. Numerical modelling of the temperature field associated with the MVT deposits indicates that a gravity-driven system was responsible for the Pb-Zn mineralisation. However, the question, at least in western Europe, remains whether the gravity-driven system exerted the major control on the deposits. Based on structural and geochemical data and time relationships, it can be demonstrated that in most deposits in western Europe, extensional tectonism played the most essential role and not the gravity-driven fluid flow system. Especially the structural setting during the Jurassic was favourable for Pb-Zn mineralisation in western Europe.

First, a gravity-driven system is related to a topographic relief, which formed during tectonic deformation. In Ireland, at least part of the Pb-Zn mineralisation precipitated during the Tournaisian and early Viséan, preceding the Variscan deformation by 20 to 40 Ma. Geological and geochronoligical data indicate that the MVT deposits in Belgium and western Germany formed during the Jurassic, more than 100 Ma after the Variscan orogeny. During the Jurassic, a large part of the orogen has been eroded and is certainly not the period during which the topographic relief was most pronounced. Secondly, the Pb-Zn deposits are often located along nearly vertical faults. Even the Maubach-Mechernich deposits, which are characterised by the mineralisation of permeable sandstones, show a transition from disseminated sandstone-hosted ore into vertical veins at deeper levels. The faults played a crucial role as channels for the near surface venting of the hot, saline fluids. Thirdly, recent investigations on the geochemistry of the fluid inclusions in synsedimentary Devonian barytes and in gangue minerals associated with a post-Variscan Zn-Pb deposit in Belgium, indicate that the mineralising fluids originated from evaporation of seawater during the Palaeozoic. These brines underwent an intense water-rock interaction with the sedimentary rocks and the basement. This implies a downward movement of the fluids up to a depth of at least 5 km and an upward expulsion along extensional faults during the Mesozoic.

Numerous Pb-Zn mineral deposits in western Europe formed during the early to middle Jurassic period. This period is also characterised by increasing diagenesis which has been related to a thermal and likely hydrothermal event. The Jurassic corresponds to the time of the breakdown of the western European craton and the formation of the Atlantic Ocean. This extensional phase is regarded not only as the cause for the thermal event but also for the widespread expulsion of fluids along faults, causing multiple diagenetic processes and mineralisation (e.g. Mitchell and Halliday, 1976).

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FMF5 : WEpm37 : F4
Timing of PGE Deposition during the Generation of Successive MORB to Boninitic-Type Ophiolites

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Magmatic PGE anomalies within ophiolites may be associated with disseminated base-metal sulphides or with chromitites. In both cases they form in low-S deposits. Six major types of PGE deposits can be defined. In all of them, the PGE pattern reflects the nature of the PGE carrier. These carriers may be dominated by alloys, sulphides, sulpharsenides or arsenides depending on local sulphur, oxygen and/or arsenic fugacities. A model will be presented which discusses the type of deposits and the timing of PGE deposition in the framework of multi-stage magma generation processes. These processes are related to the evolution of ophiolitic basins from opening to closure, bordered by passive or active margins.

Early S saturation of silicate magmas parental to MORB would produce immiscible sulphide melt. These would gather PGE, leading to the deposition of Pt- and Pd- rich sulphide-bearing ultramafic rocks along channels where $Ti0_2$-rich silicate magmas ascend to the surface (type 1). This mineralisation occurs in the Corsica and Lizard ophiolites which strongly resemble Mid-Oceanic Ridge products. The associated chromian spinel is generally Al-rich. This type of mineralisation is also found in the less depleted mantle portions of ophiolites formed from island-arc tholeiite (IAT) magmatism (Cyprus, New Caledonia). There, fractionation of a Cu- and S-poor sulphide-liquid generated from second-stage silicate melts, would lead locally to Ni- and Pd -rich residual liquids parental to Pd-rich pentlandite-bearing dunite, known in Albania and Philippines (type 2). As the degree of mantle depletion increases from early to late-stage ophiolites, silicate liquids produced become poorer in Ti and S, and chromitites could precipitate before S-saturation is reached. In such chromitites, commonly found in ophiolites (with variable Cr/Al ratio), only the more compatible IPGE precipitate, either as alloys or sulphides which are trapped during the growth of chromite (type 3). Pt- and Pd-rich chromitites, with interstitial sulphides, are deposited later after some fractionation of the silicate magma has occurred (type 4). Liquids parental to the latest ophiolites are very poor in Ti and S, but PGE-rich. These boninitic liquids are parental to the chromitites richest in Cr. Deposition of Pt, (with minor Pd) and its mineralogical expression, seems to be controlled by aAs and aS_2. When aAs is high compared to aS_2, Pt precipitates early together with IPGE, forming an arsenide type of mineralisation (type 5). At lower aAs, Pt precipitates later as Pt-Fe alloys, once IPGE-bearing chromitites have been formed, resulting in an alloy-type of PGE mineralisation (type 6). The high Fe^{3+} content of these Cr- and Pt-rich chromitites reflects deposition of PGE under lower aS_2 but higher fO_2 conditions than those of the previously formed chromitites.

FMF5 : WEpm38 : F4
Pre-Metamorphic Fluorine in Orthoamphibole Dominated Pb-Zn-Cu Deposits

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Magmatic volatiles are essential components in magmatic-hydrothermal ore formation. In order to evaluate the potential of fluids in transporting and concentrating elements in different types of ore deposits, it is critical to constrain their composition and source. Many volcanogenic massive sulphide (VMS) deposits occur in fluorine-bearing hydrothermal systems, which usually are more voluminous than ore deposits and therefore more easily recognisable (Lavery, 1985). Available studies on the behaviour and distribution of fluorine in natural rocks and fluids suggest that (i) fluorine is strongly partitioned into the solid phases during fluid-rock interaction (Willner et al., 1990); (ii) fluorine stabilises relict biotite and amphiboles during high-grade metamorphism and partial melting. Hence, it seems that fluorine geochemistry is relatively undisturbed by high-grade metamorphism, allowing one to “see through” the various metamorphic events and investigate the role of fluorine in the mineralising fluids during earlier hydrothermal processes.

Cordierite-orthoamphibole (Crd-Oam) rocks are rare, but characteristic, rock types commonly associated with sulphide ore deposits (Zaleski & Peterson, 1995), making them suitable pathfinder assemblages. At higher P and T, they may show a different mineralogy, and phases such as orthopyroxene (Schreurs & Westra, 1985) and garnet + sapphirine (Kriegsman et al., 2001) may become part of the assemblage. High fluorine contents of Oam-bearing rocks from the Oonagalabi (central Australia) and OrijSrvi (southern Finland) Pb-Zn-Cu deposits have been documented by whole-rock geochemical and microprobe analyses (orthoamphiboles, phlogopite, chondrodite) and by the presence of fluorite.

The observed order of decreasing F content in hydrous minerals is consistent in samples from the two areas. Combining all data, the order is: fluorite >> chondrodite > biotite (phlogopite) > gedrite >> anthophyllite. The OrijSrvi samples contain mainly anthophyllite, whereas gedrite is very common in Oonagalabi. This reflects the different peak temperatures: relatively low (550-650 ˚C) at OrijSrvi, much higher (750-800 ˚C) at Oonagalabi. Our data show that anthophyllite has a much lower F content than gedrite and therefore much less fluorine can be accommodated in orthoamphiboles at OrijSrvi than at Oonagalabi. Phlogopite is the main F-bearing mineral in the OrijSrvi Crd-Oam rocks, but fluorite in most other rock types. By contrast, orthoamphibole is the dominant F-bearing mineral at Oonagalabi.

Our data confirm that the timing of sulphide mineralisation is pre-metamorphic in both areas. Host rocks generally become more F-rich with proximity to sulphide-rich zones in agreement with earlier work (Lavery, 1985). Our preliminary data suggests that source rocks for Cu + Pb + Zn show negative correlations between these elements and fluorine. Hence, Cu + Pb + Zn were leached out of the source rocks by highly corrosive, F-rich fluids, leaving behind the highly lithophile fluorine as testimony.

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Wednesday PO Session

FMF5 : WEpo01 : PO
GIS Andes: Mining Districts

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Mining Districts is one of the 13 layers of GIS ANDES. The 162 metal mining districts correspond to polygons of very varied size (from several tens to 1000 km^2) contained within the borders of the seven countries concerned: Venezuela (5 districts), Colombia (12 districts), Ecuador (8 districts), Peru (54 districts), Bolivia (19 districts), Chile (34 districts) and Argentina (30 districts).

Fifteen Belts, divided into 30 Sub-Belts independent of political frontiers, which take into account the temporal and spatial metallogenic evolution along the entire Andes Cordillera, are denoted either by commonly used geographic or structural names (e.g.. Eastern Cordillera, Intra-Andean Graben), or by major metallogenic families (e.g. Andean Neogene-Quaternary volcanics, porphyry-epithermal belt), or by a combination of the two (e.g. S-Peru/N-Chile Cretaceous-Paleocene porphyry/epithermal belt).

The mining districts cover one or more mining centres, mineral showings and/or prospects and, more rarely, zones with no known major deposit or showing but with a true potential for a certain type of mineralisation (e.g. Machu-Picchu District with a Sn-W-Au potential). The district name is that of its major deposit qualified by the metallogenic type or sub-type (e.g. R'o Blanco-Los Bronces: porphyry-epithermal Cu-[Mo]).

The metallogenic lexicon used in the deposit database includes:
• 10 main families characterising the most common geological environments so as to enable syntheses at small scales (>1,500,000): e.g. C: Ore deposits in an acid and alkaline plutonic context
• 54 major classic deposit types to enable a rapid classification and the construction of small-scale (<1,500,000) predictive maps: e.g. C5: Porphyry and porphyry-related ore deposits: Cu, Au, Mo, Sn, Ag, (W, Pb, Zn..)
• 143 sub-types defined over the past 20 years and taking into account the latest metallogenic models for the correct orientation of modern exploration. e.g. C55: Porphyry wolfram deposit: W

The district identification sheet includes:
• An index comprising the country code and a sequence number.
• The name of the Belt and possibly the Sub Belt (cf. lexicon) and that of the District.
• A list of the deposits, showings and/or prospects (cf. lexicon) contained in the district.
• The main (max. 3) and secondary (max. 4) substances (cf. lexicon) with the geological reserves (in tonnes) calculated automatically from the deposit data of the district.
• The metallogenic family, metallogenic type(s) and possibly sub-type(s).
• The name, lithological code and structural control of the host formation.
• The age of the mineralisation and host formation.
• The description of the District.
•The major references.

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FMF5 : WEpo02 : PO
Predictive Mapping with GIS Andes Datasets

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GIS Andes, a homogeneous information system of the entire Andes Cordillera, covers an area of 3.83 million km^2 and extends for some 8500 km from northern Colombia to Tierra del Fuego. Conceived as a tool both for the mining sector as an aid to mineral exploration and development and for the academic sector as an aid to developing new metallogenic models, GIS Andes is based on original syntheses and compilations (Cassard, 1999a,b).

Considering metallogeny at continental scale requires knowledge of the parameter combinations controlling the spatial-temporal distribution of the ore deposits. The resultant "data association model" derives from: 1. existing metallogenic base models (e.g. BRGM's SignateX base for mineral deposits); 2. the search for pertinent relational criteria within existing databases through statistical analysis (e.g. factor analysis of correspondences [FAC]) and Data Mining (extraction of information). Multicriteria processing (SynArc®) of these data associations, using functions of similarity, classification, user-defined weighting from constructed multicriteria matrices, and probabilistic weighting (= weight of evidence modelling), allows one to test metallogenic hypotheses and generate predictive maps.

As an illustration of point 2, location maps of main deposits show that their distribution is not haphazard (e.g. Bolivian tin belt, Chilean/Peruvian copper belt, etc.). The distribution of Neogene gold deposits (porphyry, high- and low-sulphidation epithermal) is not so evident: the major Au districts fall along shallow-dipping segments of the Wadati-Benioff plane to either side of the Bolivian Orocline. Moreover, plotting the deposits on a detailed topographic map of the Wadati-Benioff plane compiled from seismic data shows that recent gold mineralisation is preferentially associated with the flattest areas (slope <15˚) within these segments. Although comparison with the present morphology of the Benioff plane is valid for the youngest mineralisation (~5Ma), it is only hypothetical for older mineralisation (~20 Ma).

Preliminary predictive maps capable of outlining major areas of interest can be obtained through combining (i) gold-potential scoring for intrusive and volcanic rocks and linear structures (determined through remote sensing, mapping, geophysics, etc.) using buffer zones, (ii) fertility calculation of lithological contacts using highly mineralised training areas, and (iii) Benioff plane depth and slope. Such processing, which does not directly involve the mineralisation, will locate 80% of known mineral occurrences and delimit potentially favourable areas for the presence of this type of mineralisation.

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FMF5 : WEpo03 : PO
Crustal-Scale Fracture Zones Controlling Ore-Forming Processes: A Case Study from Central Mexico

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Crustal-scale fracture zones have been recognised to play a major role in the localisation of ore deposits. In particular, fracture zones that traverse magmatic arcs are known to be favourable sites for ore-forming processes. For some regions of the Cordilleran arc of North and South America it has been demonstrated that the centres of magmatic and hydrothermal activity are strongly related to transversal crustal-scale fracture zones that intersect arc-parallel structural features such as suture zones and terrane boundaries. These fracture zones favour the emplacement of magmatic bodies, which may act as sources for heat, fluids and metals and thus may be responsible for the formation of ore deposits. Most precious metal- and base metal-bearing deposits in Mexico are associated with the magmatic activity of the subduction-related Mesozoic-Cenozoic Laramide orogeny and (or) subsequent stages of extension. The characteristics of the deposits reflect their tectonic position within the arc system and are also indicative of the arc migration, which headed towards the east during the Laramide orogeny and retreated towards the west in the Oligocene and Miocene. Due to this arc-parallel alignment of deposits with similar mineralisation styles, element distributions, and mineralogical characteristics, several metallogenic belts have been defined. An interesting and yet unexplained structural feature of the Sierra Madre Oriental is the Monterrey-Torreon orocline, which is related to Laramide contractional deformation. This orocline marks a strong structural inhomogeneity as well as a velocity discontinuity between the northern segment and the central segment of the Mexican fold-thrust belt. This feature is exceptional and could be an important indication for a deep-seated arc-transversal fracture zone, enhancing the formation of secondary porosity and permeability as the primary controls of the formation of magmatic and hydrothermal centres.

FMF5 : WEpo04 : PO

The Mississippi Valley-Type Zn-Pb Deposit of San Vicente, Central Peru: A Syntectonic Deposit during the Andean Orogeny

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The Mississippi Valley-type Zn-Pb deposit of San Vicente is located 300 km east of Lima in the subandean tectonic zone of central Peru, and is hosted by Upper Triassic-Lower Jurassic carbonate rocks of the Pucará Group along the western margin of the Brazilian shield. In the San Vicente district, the Pucará Group overlies magmatic and continental clastic sedimentary rocks of the Late Permian to Early Triassic Mitu Group. The host carbonate sequence consists mainly of a succession of low permeability and relatively high permeability porous horizons. Several superposed ore bodies occur in dolomite units as lens-shaped bodies sub-parallel to stratification. A significant part of the mineralisation, sphalerite and galena cemented by hydrothermal dolomite, occurs as zebra texture and, subordinate, cement of breccias with angular clasts. During one of the last phases (Quechua 3) of the Andean orogeny, a Permian granodiorite overthrust the Pucará Group in the San Vicente district from west to east.

This study investigates the relationships between Zn-Pb mineralisation and the tectonic evolution of the host rock. Orientations of the different structural elements of the San Vicente mine, including normal, reverse and en-echelon faults, extension veins, breccia pipes, breccia elements, zebra textures, bedding and thrust zones have been measured and analysed. The preliminary results show a good correlation between the orientation of the structural elements and the direction of the regional overthrust, indicating an east-west compression. In this model the mineralised breccias are interpreted as tectonically controlled hydraulic breccias. They are considered as large scale tensile fractures due to a regional subhorizontal shearing. The zebra fabrics are now interpreted as self organisation textures originating largely in tensional structures which can locally favour the fluid flux responsible for mineralisation. Most dolomitised veins are also interpreted as T, P or R fractures in a simple shear-zone model. The main mineralised ore bodies are also cut by the major overthrust faults which, in turn, precede a normal faulting phase. These new data indicate that the Zn-Pb Mississippi Valley-type San Vicente mine is a Miocene-Pliocene syntectonic ore deposit formed during the Andean orogeny.

FMF5 : WEpo05 : PO

Lead and Sulfur Isotopic Characteristics of the Neoproterozoic Araes Gold Deposits, Mato Grosso State, Brazil

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Lead and sulphur isotopic analysis were carried out in sulphides from Araés mesothermal gold deposit (Mato Grosso State, Brazil) with the purpose of constraining their ages and the source(s) of the mineralising hydrothermal fluids. The ore bodies have 46 ton of gold (3.47 g/ton) and are hosted by metamorphic mafic and ultramafic volcanic rocks whose origin and deformation are correlated to the Paraguai Belt evolution. The origin of this fold belt is correlated to the Neoproterozoic collage (Amazonian Craton and Rio Apa block) which originated Western Gondwana during the Brasilian-Panafrican event (ca. 600-500 Ma). The Neoproterozoic Paraguai Belt and its corresponding cratonic cover were formed on the southern margin of the Amazonian Craton where the Cuiabá, Corumbá, Boqui and Alto Paraguai Groups were deposited and subsequently metamorphosed in greenchist facies conditions.

Lead isotope compositions in galenas showed $^{206}Pb/^{204}Pb$ ratios ranging from 17.967 to 17.987, $^{207}Pb/^{204}Pb$ ratios ranging from 15.646 to 15.651, and $^{208}Pb/^{204}Pb$ ratio of 38.028, yielding Pb model ages in the time interval of 592 Ma to 567 Ma. Lead isotopes in pyrites yielded $^{206}Pb/^{204}Pb$ ratios in the interval from 18.020 to 18.066, $^{207}Pb/^{204}Pb$ ratios ranging from 15.704 to 15.791, and $^{208}Pb/^{204}Pb$ values ranging from 38.187 to 38.519, suggesting a slightly more radiogenic Pb source. Most of the Pb isotopic variations may be explained in terms of mixing of a less radiogenic lead isotopic component probably from mafic and ultramafic-host basement rocks (Cuiabá Group volcanic units) and a more radiogenic lead component derived from the metasedimentary rocks (Alto Paraguai Group).

Sulphur stable isotope results of Araés deposit show homogeneous $\delta^{34}S$ values ranging from 1.1‰ to 0.9‰ (galenas) and 0.7‰ to 0.9‰ (pyrites). These values suggest a homogeneous source which is quite comparable to mantle-derived igneous rocks sulphur stable isotope signature and similar (~0‰) to Canyon Diablo Troylite $\delta^{34}S$ composition. The small variation in $\delta^{34}S$ values in sulphides from Araés gold mineralised veins suggest that the gold deposition occured in an environment which had a small variation of fO_2 and fH_2S. The hydrothermal fluids could have originated from a homegeneous source probably correlated to the host rocks comprised by the mafic and ultramafic volcanic units.

These data support a model in which the mineralisation is epigenetic, and it is not linked with the main metamorphic regional event. Instead the mineralising fluids have filled extensional faults parallel to the host-rocks foliation. The Araés gold deposit yielded ages correlated to late stages of the Brasiliano/Panafrican event, and it was probably formed during an extensional tectonic period, which may characterise an important metallogenic epoch in the region.

FMF5 : WEpo06 : PO

Structural Control of Ag-Sn Vein-Type Mineralisation at the Pirquitas Mine (Prov. Jujuy, NW-Argentina) – Ore Precipitation during Fold and Thrust Belt Evolution

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The Ag-Sn deposit of Minas Pirquitas is situated at the boundary zone of the Central Andes high plateau and the Eastern Cordillera, at the NW-Argentinean Province of Jujuy. The deposit is hosted by an Ordovician flyschoid succession. The mineralisation is polyphase and shows "telescoping" with an early stockwork type generation and a later generation of subvertical NW- to WSW-trending veins and veinlets. Remarkable similarities to south Bolivian Ag-Sn-deposits related to Middle Miocene rhyodacitic to dacitic stocks and domes led to the conclusion that Minas Pirquitas is the southernmost member of the "Bolivian Tin-Belt". Hostrock bedding at the mineralised area is deformed by two anticlines with subhorizontal NNE-trending foldaxis. The eastern anticline (Cerro San Pedro Anticline, CSP) is strongly asymmetric and verging to the west. Mineralised veins are restricted to the hinge zone and the eastern limb of the CSP. The western anticline (Quebrada Medano Anticline, QMA) is more or less symmetric and, on its western limb, truncated by a NNE-trending, steeply inclined thrust (Quebrada Medano Thrust, QMT). Further to the west a more complex feature of folding, westward thrusting and minor eastward backthrusting is established. Slickenside striations on the QMT imply oblique thrusting overprinted by sinistral strike-slip movements, both controlled by NW-SE compression. Folding is accompanied by the development of a brittle axial plane foliation and multiple joint sets. Early conjugate joints show intersections either parallel or perpendicular to bedding. Conjugate joints, implying bedding parallel contraction, are restricted to the eastern limb of the CSP and the area to the west of the QMT. The QMA and the hinge zone of the CSP are characterized by conjugate joints which imply contraction perpendicular to bedding. These are suggested to result from ramp related stress deflection during early fault-bend folding. Backrotation of these joints provide the possibility to reconstruct the ramp geometry, leading to a model of two WSW-dipping frontal ramps with an eastern ramp causing the formation of the CSP, and a western ramp responsible for evolution of the QMA. Both frontal ramps are connected by a NNE-dipping lateral ramp where the terminations of the two anticlines are overlapping. Ongoing contraction led to the formation of the QMT. Oblique thrusting and strike-slip movements along the QMT caused fold-approximation and -tightening, accompanied by further jointing and formation of mineralised veins at the CSP. Vein distribution and orientation is controlled by ramp geometry and stress deflection at active thrust-/ fault-planes. This investigation is financially supported by the Austrian Research Council through grants P11987 and 13974 to WHP, which is gratefully acknowledged.

FMF5 : WEpo07 : PO

Re-Os Dating of Orogenic Gold Deposits, Yilgarn, Western Australia

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The Archean Yilgarn block of western Australia contains some of the best-studied orogenic Au deposits in the world. Because a number of these deposits contain small quantities of Au-associated sulphides, including molybdenite, they provide an excellent opportunity to use the Re-Os chronometer in molybdenite as a means to directly date Au mineralisation. The direct dating of Au, a platinum metal, concentrator of Os, and containing negligible Re, does not permit the isochron age resolution possible with Re-Os dating of molybdenite. The U-Pb dating of zircon from spatially associated intrusives may bracket the timing of Au mineralisation, but does not directly address its age. The same is true for $^{40}Ar/^{39}Ar$ and U-Pb dating of accessory phases associated with regional or local alteration.

Orogenic Au deposits constitute an important and unique class of epigenetic deposits that form over a large crustal-depth range (2-20 km) in collisional or accretionary terranes of Archean to Phanerozoic age (Groves et al., 1998). They may occur in the same orogens as Au-rich porphyry-style and epithermal vein-deposits (Groves et al., 2000). In contrast to porphyry-style deposits, where Os isotopes indicate a primitive mantle-like component in the ore-forming process (Watanabe et al., 1999; McInnes et al., 1999; Stein et al., 1998), the source of Au in orogenic deposits continues to be debated as deep crustal or mantle. Orogenic Au deposits produced by related processes over a continuum of depths may also span a range of ages within the lifespan of an accreting margin. The array of ages revealed depends on exposure levels across the orogen.

For many Yilgarn deposits, Au veining postdates regional metamorphism, plutonism, and early orogenic deformation in the immediate host rocks. A late timing for Au mineralisation within the tectonic evolution of the host terrane can be documented through Re-Os dating, and age results agree very well with previous indirect dating estimates.

Using molybdenite from four major Au deposits in the Yilgarn (Chalice = 2621 ± 10 Ma, Bucci et al., 2000; Edna May = 2640 ± 9 Ma; Big Bell = 2635 ± 10 Ma; Mount Gibson = 2628 ± 9 Ma), we present a Re-Os Model 1 isochron age of 2631 ± 24 Ma (2-sigma, initial $^{187}Os = 0 \pm 1$, MSWD = 19), that we believe is an estimate for a cratonic scale event related to Au mineralisation. Demonstration of timing is vital to exploration, as many of the significant Au deposits in the Yilgarn appear to have formed near the end of major orogenic events.

Acknowledgments: This work was funded through Placer Dome Exploration (Greg Hall), Normandy Poseidon Group (John Hammond), and the National Science Foundation (EAR-9706185). Samples were provided by Alex Bevan (Edna May), Louis Bucci (Chalice), Andreas Mueller (Big Bell), and Chris Yeats (Mount Gibson).

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FMF5 : WEpo08 : PO
Age and Structural Control of the Ifri Copper Mineralization (Western High-Atlas, Morocco)

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The Ifri copper mineralisation occurs within the Palaeozoic western High Atlas (Morocco). The lithological succession is marked by alternating schists and limestones. The studied zone is affected by four regional-scale deformational events and three distinct hydrothermal events have been recognized. First, stratoid massive pyrite was emplaced during the sedimentation. Secondly, white dolomite developed by replacement of the grey one and finally, a stockwork formed within the more competent lithologies. Mineralogically, earlier sulphide levels are composed of massive pyrite (I) and very scarce chalcopyrite whereas the stockwork contains the main copper mineralisation with, by order or abundance: chalcopyrite, pyrite (II), quartz, ankerite, siderite, galena, sphalerite, gersdorffite, ulmannite, arsenopyrite, brannerite, pyrrhotite, bismuth, bismuthinite, stannite, sheelite and hessite. Within the black schist and dolomitic levels, an additional Décollement-type tectonics, characterized by top-to-the-NNW shear criteria, looks to be developed even if the stretching lineation responsible for this event remains barely observable, most certainly because it has been obliterated by the late extension. Its place within the regional structural evolution remains questionable. We demonstrate that the concentration of the copper mineralisation was syntectonic and that the mineralised stockwork formed in response of the above described top-to-the NNW shearing event. This ductile shearing appears well developed within the black schist levels and is accommodated within the more competent grey and white dolomite by the formation of tension-gashes assimilated to the stockwork. They are oriented N50˚E to N90˚E and represent the orebodies. This tectonic event is assumed to develop at the end of the structural evolution of the studied area under NW–SE shortening. This event could be reasonably correlated with the late-Hercynian tectonics responsible, in the same area, for the Tichka granite emplacement at ca. 291 ±- 5 Ma also under the control of NW–SE shortening. Indeed, the Tichka granite represents a good candidate to explain the origin of the mineralised fluid. Such a hypothesis is confirmed by the Permo-Triassic ages given by the $^{40}Ar/^{39}Ar$ dates obtained on white micas related to the stockwork formation. Ages bracketed between 270 and 275 Ma were obtained.

FMF5 : WEpo09 : PO
Constraints on Age Variation of Different Ore Forming Processes due to Orogen Development Duration

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Isotope dating is the main way of timing ore genesis processes which occur in the evolution of an orogen. To investigate their age differences, it is very useful to estimate the order of these differences. The aim of this work was to carry out such a study as well as to compare the results obtained with the duration of real ore deposit formation.

To meet the aim, time intervals corresponding to the development duration of 78 orogen cycles (Condie, 1994) were statistically generalised for the last 3.5 Ga. An interval between the age of eruption of earlier volcanic melts and the collision age was regarded as a measure of an orogen cycle duration. Geodynamically united orogen associations corresponding to megacycles of tectono-magmatic activity were treated as separate samples. The histograms obtained on Çorogen evolution duration against distribution frequencyÈ enable the following conclusions to be drawn: (1) An orogen cycle duration is not constant varying from 5 to 300 Ma. (2) In Early and Middle Precambrian (megacycles with culmination stages 3.6, 2.7 and 1.9 Ga) the most frequent orogen cycle duration varies from 10 Ma to 60 Ma; in the Late Precambrian from 10 Ma to 100 Ma, and in the Phanerozoic from 10 Ma to 120 Ma. Therefore, age variations in ore deposits of different styles can be as wide: (a) as 250-300 Ma for long-living orogens of the Phanerozoic and Late Precambrian; (b) as 50-60 Ma for orogens of most frequent longevity in the Precambrian (c) as 120 Ma for orogens of most frequent longevity in the Phanerozoic. As for short living orogens of any age, the difference in the age of ore deposits associated with them cannot exceed 10 Ma. Another constraint on isotope dating application to timing ore deposits of different mineralisation styles is the relation between the duration of the orogen evolution and that of the ore deposit formation. The duration of some superlarge ore deposits formation in the Phanerozoic of Russia and former USSR (Sukhoi Log, Pravourmyiiskoe, Voznesenskoe, Muruntau etc.) can be as long as 50 Ma. It is comparable with the time of orogen evolution. However, the age and isotope characteristics of the main ore forming stage (which makes the ore deposit be regarded as a superlarge one) show that the time of ore genesis is at least an order shorter.

To sum up, the most favourable conditions for isotope data application to timing major ore deposits in evolving orogen are found in Late Precambrian and Phanerozoic orogens, such as the areas of current tectonic activity.

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FMF5 : WEpo10 : PO
Discrimination Criteria for Affiliation of Ore Deposits Located in the Dinaridic Triassic-Paleozoic Formations to the Variscan or Alpine Metallogeny

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The important Dinaridic ore deposits are located in the Triassic (T)-Paleozoic (Pz) magmatic-metallogenic formations. Spatially, the ore deposits connected with Triassic rocks are genetically related to the Triassic gabbro-diorite-granosyenite suite in intrusive level and basalt-andesite-dacite at extrusive level. Among many Pz terranes only Mid-Bosnian Mts. incorporate Upper Pz rhyolites, metamorphosed into metarhyolites. Within Pz formations the following types of ore deposits occur: *type A* polymetallic deposits formed in a broad pneumatolitic to epithermal interval; *type B* stratabound carboniferous siderite±ankerite deposits with chalcopyrite; *type C* Mid-Bosnian Mts. barite and barite-siderite deposits with Au-Hg-tetrahedrite; type D monomineral barite occurrences with accessory sulphides.

There is a dispute whether the ore deposits located in Paleozoic formations (PzODs) originated either during the Variscan or Alpine (TODs) orogeny. The following discriminative criteria can be used for their affiliation:

1) *Mode of occurrence* PzODs located into Pz rocks are dominantly veiny or metasomatic in forms, except siderite deposits which are stratabound; TODs are dominantly stratabound or stratiform, spatially connected with T magmatic rocks;

2) *Parageneses* of PzODs are very simple and represented by predominant Au-pyrite, Au-Hg-tetrahedrite, $CuFeS_2$, Ag-Sb-Pb sulphosalts; TODs are more complex and characterised by HgS, Ag-ZnS-PbS and FeS_2; among Fe and Mn minerals, PzODs contain siderite and ankerite, whereas TODs contain siderite, magnetite, hematite, ferrodolomite and Mn-oxides;

3) *Precious and trace elements* PzODs contain Au, Ag, Sn, W, Mo, F, B; TODs only Ag;

4) *Isotopic composition of sulphur* $\delta^{34}S$ *%* PzODs barite +10,79 (n=117), anhydrite +11,02 (n=61); TODs barite +21,69 (n=56), anhydrite +25,08 (n=21);

5) *Content of* $SrSO_4$ *in barites;* PzODs 3,40% (n=156); TODs 2,36% (n=54);

6) *Fluid inclusions* PzDOs include three different age fluid systems. The oldest is NaCl-KCl-H_2O system characteristic for ore deposits types A and B. Slightly younger is NaCl-H_2O system but both of them belong to Early Variscan phase. The second system is NaCl-$CaCl_2$-(±$MgCl_2$)-H_2O, especially characteristic for C and D types belonging to Late Variscan. Some of PzODs are overprinted by Tertiary NaCl-H_2O-CO_2 (CH_4, N_2) fluid system. TODs include only $CaCl_2$-NaCl-H_2O system (Palinkas et al., 2001);

7) *Iodine and Bromine ratio* in fluids of PzODs corresponds to the contemporaneous sea water (Palinkas et al., 2000).

Palinkas AL, Herlec U & Strmic S, *J. Conf. Abs, Strasbourg*, (2001).
Palinkas AL, Balogh K, Siftar D, Prochaska W & Strmic S, *An. Inst. Geol. Rom, Special Issue, Bucuresti*, **72**, 65, (2000).

FMF5 : WEpo11 : PO
Timing and Compositional Evolution of Magmatism and Mineralization in a Large (Borovitsa) and a Small (Madjarovo) Paleogene Volcanic Center of the Rhodope Massif, Bulgaria

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Clear spatial relationships between magmatic and hydrothermal events make the Rhodope Massif in Bulgaria and Greece favourable to genetic studies (Singer & Marchev, 2000). Borovitsa and Madjarovo are contemporaneous early Oligocene volcanic centres of mainly shoshonitic composition in the Eastern Rhodopes situated about 30 km apart. The most important contrasts are in size and duration of the magmatic activity. $^{40}Ar/^{39}Ar$ laser-fusion ages indicate that volcanism covering >1000 km^2 at Borovitsa began ca. 34 Ma and terminated with caldera collapse at 31.8 Ma. Magmatism at Madjarovo (~120 km^2 occurred over a period of not more than 300 ky. between 32.5 Ma and 32.2 Ma. At both centres, magmas evolved progressively from intermediate-basic to high-silica varieties accompanied by emplacement of monzonitic intrusions and associated porphyry to high-sulphidation style of alteration/mineralisation. The earlier stages at both volcanoes ended ca. 32.1 with low-sulphidation epithermal systems that postdate rhyolite dykes at Borovitsa and trachytic dykes at Madjarovo by less than 100 ky. At Borovitsa, low-sulphidation mineralisation was followed at 31.8 Ma by formation of two nested calderas: Borovitsa

(30x15 km) and Murga (7x7 km) and a later basaltic-rhyolitic cycle of post-caldera volcanism. In both volcanic centres the epithermal mineralisation is younger than porphyry deposits; at Borovitsa it is younger by 500 ky, whereas at Madjarovo the difference in age is not resolveable given the ± 200 ky. uncertainties of our $^{40}Ar/^{39}Ar$. Formation of calderas partly destroyed the epithermal system at Borovitsa and probably buried a large part of it in the vicinity of the caldera-ring fracture. These results from Madjarovo and Borovitsa demonstrate that the porphyry minerlisation is linked to the early subvolcanic stages of evolution in these systems. Epithermal mineralisation tends to occur in close spatial and temporal relation with silicic magmatism at the end of magmatic activity of the smaller systems, but could have occurred earlier in the larger system. The source of rapidly emplaced rhyolites and trachytes at Borovitsa and Madjarovo and the low-sulphidation mineralisation resided in deeper silicic magma chambers at depths >3 to 5 km. Thus, the general evolution of the magmatism and styles of ore mineralisation in large and small centres are similar but the timing of processes strongly depends on the size of the individual magmatic centres.

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FMF5 : WEpo12 : PO
Exhumation of the Central Rhodopian Core Complex and Related Magmatism– Isotope and Geochronologic Studies of the Madan Dome (Bulgaria)

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The Rhodopian massif (Bulgaria) is an element of the Alpine Metamorphic Belt, consisting of collisional nappes of metasedimentary and meta-igneous rocks (Ivanov, in press). The late Alpine extensional evolution of the massif is marked by a detachment system connected with exhumation of the granites and migmatites in the core part of different core swells (Madan dome, Biala reka, Kesebir and West Rila Rhodope domes). The post-collisional extension was followed by graben depressions filled with sediments of Eocene-Oligocene age and active volcanism and ore mineralisation (Zn-Pb and Cu-Pb-Zn ore deposits). Ore deposits in the Central Rhodopes typically occur in the vicinity of silicic dyke swarms. Since some of the porphyry dykes show crosscutting relationships with the main detachment and ore veins the absolute and relative timing of deformation, magmatism and mineralisation can be used to constrain the metal and fluid sources. During extensional tectonic conditions a gently dipping main detachment was developing, which caused a separation of the Madan dome into an upper and lower plate. The available geochronological data (U-Pb zircons and Rb-Sr ‹ W.R.) for the lower plate indicate Hercynian protoliths ages (about 300 Ma) and an Eocene age of migmatisation and granite melt generation (36-37Ma, Arnaudov et al., 1990; Arkadakskiy et al., 2000; Peycheva et al., 2000). A Rb-Sr mineral isochron give evidence for a closing age of 34.5±0.34 Ma (Peycheva et al., 2000). New Ar-Ar data on biotite from gneisses of the upper plate (eastern part of the Madan dome) yield an age of 34.9±0.6 Ma. The same age is reflected by an Rb-Sr isochron (W.R., Bt and Ap) ‹ 35.22±0.35 Ma. Connected with the most intensively 'stretched' sections of the extensional system is the formation of rhyolite dykes at 30.3±3.5 Ma, based on U-Pb analysis on single zircons. The Rb-Sr W.R. analysis of the same rhyolites yields an $^{87}Sr/^{86}Sr$ ratio of 0.7065 (T-30Ma) that could be explained with input of mantle material or young crust as well. The [epsilon]e-Nd value (T-30, ‹5.3) indicates a crustal source of magma generation. It is in compliance with the suggestion that the high-grade core of the dome contains intrusions that could be feeders of the volcanism and also possible sources of magmatic-hydrothermal fluid contributions to the Pb-Zn veins (Arnaudov et al., 1990). The available data for the timing of the high-grade metamorphism event (36 Ma, >600°C), cooling (34 Ma, 300°C) of the core complex and volcanic flows (30 Ma) confirms the idea of a rapid exhumation during the extensional unroofing (Liati & Gebauer, 1999; Peycheva et al., 2000). Petrological data on rapid Alpine exhumation lead to similar conclusion for the North-Western Rila Mt. (Cherneva & Arnaudova, 1998).

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Peycheva I, Salnikova E, Kostitsyn Y, Ovtcharova M & Sarov S, *ABCD-GEODE Workshop, Borovets*, **1**, 67, (2000).

FMF5 : WEpo13 : PO
Elatsite Copper Porphyry- Relative Age Relations between Host Rocks, Structures, Ore Mineralisation, and Alteration

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The Elatsite copper porphyry ore deposit is located on the main chain of the Balkan on the northern boundary of the Banat-Sredno-Gore Zone and the Panagyurishte ore district in Bulgaria. The deposit is connected to multiphase intrusion of late Cretaceous (92.3 ±1.4 Ma; Von Quadt & Peycheva, 2001, this volume) porphyric dykes close to the contact of a Cambrian to Precambrian greenshist-metamorphic so-called diabase-phyllitoid from the Berkovitsa Group and the middle Paleozoic granodioritic Vezhen intrusion. The deposit is famous for its relatively high platinum and palladium content. In this work it was tried to unravel the relative age relations between host rock lithologies, structures, ore mineralisation, and alteration from field observations and various laboratory techniques. Field evidence clearly shows at least four distinguishable types of dykes. In terms of mass, a plagioclase-porphyry is the most important. It probably belongs to the first dyke generation followed by multiple phases of amphibole-porphyry, which intruded into the host rock as well as into the plagioclase-porphyry. Simultaneously, dykes consisting almost exclusively of potassium feldspar intruded. Some of them cut amphibole-porphyries and in turn some are cut by amphibole-porphyries. The fourth type is a dark, fine-crystalline dyke, for which no direct cross-cutting relationships with other types could be observed. Since it is mineralised and shows some potassic alteration similar to the other dyke types, we can assume that it intruded at the same time. The mineralisation and the alteration respectively started with magnetite veining connected with a potassic alteration. The magnetite stage possibly took place before dyke intrusion because it is absent in the dykes. The potassic alteration accompanies also the following – chalkopyrite+magnetite+bornite paragenesis, which is the carrier of the platinoids and partly of the gold. At this stage a part of the dykes already intruded as some of these shows this parageneses. While the typical stock work porphyry veining took place, the intensity of potassic alteration decreased and chalcopyrite, pyrite and molybdenite were precipitated. The last dykes were intruded during this stage as evidenced by a reduced degree of potassic alteration and quartz vein density. Subsequently, veins of massive chalkopyrite-pyrite were formed and later the deposit was overprinted by a feldspar destructive alteration (mainly sericite), which is also seen in the outer region, along thick (1-30 cm) massive Quartz-Pyrite veins. Late subvertical, WNW-ESE striking faults cut and displaced all the lithologies and caused remobilisation of ore at least along the two major faults and some smaller ones.

Petrunov R, Dragov P, Neykov H, Ignatov G, Illiev Ts, Vassilieva N. Tsatsov V, Djunakov S & Doncheva K, *Compt. rend. Acad. Bulg. Sci.*,, **45, 4**, 37-40, (1992).
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FMF5 : WEpo14 : PO
Geochemistry of Upper Cretaceous High-K Calc-Alkaline Post-Collisional Intrusions from the Banat Province (Western South Carpathians, Romania)

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The Carpathians are part of the European Alpine Belt and result from the collision between the Eurasian and African plates which itself caused the closure of the Tethys ocean. The uppermost nappes (Getic/Supragetic) of the South Carpathians were stacked by Mid-Cretaceous and later crosscut by Upper Cretaceous volcanic and plutonic rocks (the Banatitic Magmatic and Metallogenetic Belt; von Cotta, 1864 ; Berza et al., 1998). This belt is made up of volcano-plutonic complexes emplaced in an extensional setting and of shallow intrusions generating numerous mineral deposits (porphyry copper, base-metal massive sulphides and skarn deposits) in Romania, Eastern Serbia (Timok) and Bulgaria (Srednogorie). The origin of the banatitic magmas was either ascribed to subduction of several paleo-oceans (Vardar, Transylvanian, Severin) or to extensional structures such as rifts and grabens. We present here geochemical data acquired on 24 samples from 7 intrusions disposed on a NNE-SSW lineament of 100 km (Tincova, Bocsa, Ocna de Fier–Dognecea, Oravita, Ciclova, Sasca and Moldova Noua) of South-East Banat (Romania). These samples range in composition from gabbros to granites (SiO_2 : 48 to 67%) and define, in major and trace elements variation diagrams, a single high-K calc-alkaline trend due to a fractional crystallisation process. They are characterised by similar patterns in REE and spider diagrams: they display enrichments in LILE and LREE as well as depletion in Nb-Ta-Zr as usually observed in magmas associated with subduction zones.

Sr_i and ε_{Nd} range between 0.7042 to 0.7058 and +3.9 to -0.2, respectively. Variable Sr_i and ε_{Nd} with SiO_2 point to a minor AFC process during differentiation and also suggest that the intrusions belong to several magma batches. Moreover the generally positive $[epsilon]_{Nd}$ together with moderate Sr_i indicate that the parent magma of the banatitic suite results from the partial melting of a Rb-enriched and LREE-depleted source, either the upper mantle or a mafic crust derived from it. The selective Rb enrichment of the upper mantle could have occurred during a previous subduction event (the well-documented Cretaceous one or an hypothetical older one at about 600 My as suggested by Nd model ages) which metasomatised the overlying mantle wedge. The collected data also show that after a stay in at least one intermediate magma chamber, magmas emplaced astride a poorly outcropping fault system in successive batches as evidenced by the occurrence of rounded mafic microgranular enclaves. These intrusions of South-East Banat are geochemically similar to Tertiary post-collisional plutons from the Western and Central Alps, but isotopic data show that crustal contamination processes played a much more subordinate role in the South Carpathians.

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FMF5 : WEpo15 : PO
Hydrothermal Alteration Associated with Bolcana Porphyry Cu-Au Ore Deposit (Metaliferi Mts., Romania)

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The Bolcana porphyry Cu-Au deposit is located in Metaliferi Mountains (western Romania). It is an intrusion-related mineralised hydrothermal system associated with a subvolcanic body (Bolcana microdiorite) of Sarmatian age, which intruded mainly Miocene volcanic rocks (Hondol-Faerag andesite) (Bostinescu, 1984).

The alteration minerals were identified by optical microscopy, electron microprobe analyses, scanning electron microscopy and X-ray diffractometry. Major and trace elements of sampled rocks were analysed by ICP method and Au by atomic absorption spectrophotometry.

The distribution of copper mineralisation and hydrothermal alteration show a close spatial relationship to the Bolcana porphyry. Four alteration types (potassic, phyllic, argillic and propylitic) were separated (Milu, 1999). The potassic alteration is developed in the deepest and innermost part of the intrusive body: it grades upward either to phyllic and then to argillic alteration or directly to argillic alteration. The phyllic alteration is developed at a low level and the characteristic minerals both crystallised in veinlets and replaced the pre-existing minerals in wall rocks. The argillic alteration (intermediate argillic type) affected the upper part of the Bolcana system. Fissures bearing alteration minerals characteristic of phyllic and argillic alteration crosscut even the deeper part of the porphyritic intrusion. The propylitic alteration occurs like a broad halo of the other alteration types and as relict islands to the margins of the argillic alteration zone. The large development of sulphidation (anhydrite often replaced by gypsum) and carbonatation (calcite) is a particularity of Bolcana hydrothermal system.

Using mineral chemistry of some alteration minerals, their crystallisation temperatures were estimated applying different geothermometers. Taking into consideration the values obtained and also the alteration zones and the stability domains of specific minerals, the alteration pattern at Bolcana is the result of an overprinting of the alteration process. Propylitisation seems to be nearly simultaneous with, but peripheral to, potassic alteration. Phyllic alteration post-dates the potassic alteration and it is supposed would have formed a reduced halo around the Bolcana intrusion. Argillic alteration overprints the other alteration types.

The results of paragenetic studies also indicate an evolution of the system from an early period of porphyry copper mineralisation (mainly chalcopyrite, pyrite, magnetite, hematite, bornite, molybdenite, with subordinate native gold) to a late period of low-sulphidation mineralisation (pyrite, sphalerite, galena, chalcopyrite, tetrahedrite, marcasite, bournonite, arsenopyrite, pyrrothite and native gold). The epithermal mineralisation consists of polymetallic veins in gangue of carbonates and auriferous veins in gangue of quartz (Udubasa et al., 1978, 1981 - GIR internal reports). The potassic alteration and porphyry copper mineralisation are spatially related and are thought to be formed almost at the same stage with the likelihood that the mineralisation process continued during later alteration process.

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FMF5 : WEpo16 : PO
A Review of Fluid Inclusion Typology in Barren and Productive Subvolcanic Structures from the Alpine Carpathian Chain (Romania)

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Fluid inclusion study of magmatic-hydrothermal systems is obviously used to reconstruct the ore fluid phase evolution that is sometimes responsible for ore deposit formation. In this respect, fluid inclusion typology includes natural occurrence, distribution and PVTX - properties of silicate glass, polyphase, CO_2-rich and aqueous inclusions in rock forming minerals and hydrothermal deposits, i e. epithermal products from veins, breccia, stockworks and disseminated ores.

In this review, fluid inclusions were described as vitreous, polyphase, aqueous and vapour rich inclusions in quartz, pargasite, apatite from productive and barren Alpine volcanic structures from the Apuseni Mountains and subvolcanic area of north-eastern Carpathians. During the magmatic-hydrothermal transition the main part of the ore elements were collected as chloride complexes and deposited in a protore from the inner zone of the crystallising shallow bodies. This kind of internal structure is composed of numerous small fractures filled with quartz + feldspar + metallic minerals and is the first sign of a possible productive magmatic-hydrothermal system. The second important observation is due to the internal zoned quartz texture as a result of physical and chemical changes during magma emplacement. Consequently, it is possible in certain cases to reconstruct the entire fluid phase evolution associated with porphyry copper and related epithermal ore deposit genesis. The third useful set of data is related to the fluid inclusion evidence for fluid immiscibility, mainly in the common productive magmatic-hydrothermal systems (e.g. Rosia Poieni, Valea Morii, Rosia Montana, Tibles etc). The simultaneous trapping of silicate melt, fused salt and a low density aqueous phase in the same microcavities or as contemporaneous pairs in the same zone of the host mineral is the best evidence that the main ore metal content was exolved directly from crystallizing magma. Several successive boiling episodes could be also distinguished by vapour and salt rich inclusions. Fourthly, the presence of CO_2-rich inclusions associated with silicate glass, polyphase and aqueous fluid inclusions seems to be a distinctive feature in barren subvolcanic structures in the Gutai Mountains and Vladeasa massif.

FMF5 : WEpo17 : PO
The Volcanic Rocks Petrology and K-Ar Ages for Widen Zone Bor Ore Deposit as the Part of the Timok Magmatic Complex (East Serbia)

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Representing the biggest volcanic area in East Serbia, Timok magmatic complex (TMC), is the part of composite Carpathian-Balkan Terrain and within it the part of Kucaj Terrain (Karamata & Krstic, 1996; Krstic et al., 1996). East parts of TMC are well known as Bor ore zone with cooper mineralization deposits known worldwide. The petrologic investigations of volcanic rocks were conducted southwestwards from Bor. The SiO_2 content in these rocks varies from 51,47% to 60,48%. In the SiO_2:Na_2O+K_2O diagram the analyzed rocks belongs to the field of sub-alkali petrochemical grade. Due to FeO(t)/MgO:FeO(t) ratio and Ti:Zr:Y and Ti:Zr ratio, the calc-alkaline tendency of magmatic differentiation is confirmed in all samples. On the SiO_2:Na_2O+K_2O diagram for classification of volcanic rocks analyzed rocks corespond to basalt and andesite. On the Ng/Y:Zr/TiO diagram are gathered in the basaltic andesite field.

The elucidated calc-alkaline character, litological characteristics typical for stratovulcanic complexes as well as the content and ratio of macro and trace elements, as shown in the discrimination diagrams and spider diagrams of normalised content of microelements to the content in the primitive mantle, represent elements of subductive affinity of magmas.

Previous data for radiometric K-Ar ages volcanic and subvolcanic rocks from Bor area were 91-88 Ma, plutonian rocks 76 Ma, (Jankovic et al., 1981; Jankovic, 1990) and extrusive and intrusive rocks of Coka Marin 85-63 Ma (Zivkovic et al., 1996). In my study new data for volcanic rocks of the widen Bor zone were received: 1. Bor ore deposit zone - 89,7 ±3,6 Ma (monomineralic fractions (horblende) separated from hornblende andesite). 2. Widen Bor zone (SW from Bor) - 76,7 ±3,0 Ma (whole rock of pyroxene basaltic andesite).

From these data it is evident that TMC magmatism is of Turonian to Maastrichtian age (Paleogene?) so, further investigations should provide more precise data about the age of hydrothermal fluids and mineralisation.

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FMF5 : WEpo18 : PO
Petrology of the Paleozoic Metamorphic Rocks in the Area between Mlava and Pek Rivers (Eastern Serbia)

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The subject of investigation of this work are low-grade metamorphic rocks in the area between Mlava and Pek rivers. They are the composite part of Ranovac-Vlasina-Osogovo Terran (Karamata & Krstic, 1996) which correspond to the upper complex of Serbo-Macedonian massif.

Investigated area is situated northwestwards from Kucevo in Eastern Serbia. It is divided in to four units (going from east to west) as following: Kaona, Turija, Sena and Obreski potok unit. In these units different types of metamorphic rocks occur, such as: metaspilites, actinolite and actinolite-epidote-zoizite schists, metakeratophyres, metaquarzkeratophyres, metadiabases, albite-chlorite and albite-chlorite-epidote schists, metasandstones, philites and metaalevrolites. The age of those rocks is determined as Silurian-Devonian and Devonian.

Orto metamorphic rocks were generated from spilites, basaltic and andesitbasaltic rocks, keratophyres and quarzkeratophyres, and their voulcanoclastites. They occur in the form of sills and shapeless magmatic bodies in metasediments, and flows, and have massive and slightly shistos structure. Those rocks usually have very well preserved primary magmatic textures as ophitic, intersertal and porphirytic. They are usually consisted of actinolite, plagioclase (predominantly albite), epidote, zoizite, chlorite, etc.

Para metamorphic rocks were generated from conglomerates, sandstones and clay sediments. Primary bedding as well as sedimentary textures are well preserved.

Regional dinamometamorphism had isochemical character (excluding spilites). The rocks were metamorphosed under the low grade conditions up to the lowest parts of greenschist facies (T=350°, P around 3 kbar, Fray et al., 1991).

According to results of chemical analysis of orto metamorphic rocks the protolites were determined as basic, transitional and acidic magmatic rocks. On the basis of trace element data, but regarding to other geological parameters, author concluded that investigated orto metamorphic rocks (their protolites) derived from one genetic type of magma which corresponds to with-in plate basaltes (WPB).

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FMF5 : WEpo19 : PO
Are there Genetic Links between a Granite Dome and Gold Mineralisation in the Variscan Belt? A Case Study of the South Limousin (French Massif Central)

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In the western French Massif Central, the South Limousin region shows two structural zones spatially associated with Au-As hydrothermal palaeofields: the Meuzac antiform containing deposits of the St-Yrieix district (second French gold field) and the Argentat fault. So, this region appears as a key area in the study of late-Variscan palaeofields. New geological (mapping, structural and petro-structural analysis) and geophysical data (gravimetry and two seismic lines) have been acquired as part of GeoFrance3D programme. From these data, we present and discuss the relationships between Au-As hydrothermal palaeofields and a crustal-scale structure, in particular in the St-Yrieix gold field.

The discovery of a granitic dome at mid-crustal level, according to geological, gravimetric and seismic modelling, gives new constraints on the tectonic evolution of the Variscan belt, considering the revealed widespread extensional structures. The origin of this granitic dome and its relationships with the hydrothermal palaeofield are discussed. The spatial link between the St Yrieix gold field and the 10 km deep granitic dome can of course be accidental, i.e. a geometric coincidence, without any genetic link. However, the crustal-scale of such anhydrothermal palaeofield requires a discussion of the possible sources, the channelling and the trapping of Au-As mineralised fluids at 310–305 Ma in connection with this dome. Three hypotheses are discussed.

Ar/Ar ages and geometric constraints suggest that the 10 km deep dome is disconnected from the gold-bearing hydrothermal event. It can be interpreted as a granite formed at mid-crustal level, similar to the one of Millevaches (340-330 Ma), with a general trend parallel to the elongation of the belt. It then acted as a passive dome and provided geometrical and rheological controls for the development or reactivation of extensional faults, used as channelling faults for later gold bearing fluids at 310–305 Ma.

Thursday AM Session

FMF5 : THam01 : F4
Tectonics, Geodynamics, and Metallogeny of the Eastern Margin of the North Asia Craton

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The North Asia craton is a crustal block including the Siberian platform and marginal fold-and-thrust belts. On the eastern margin of the North Asia craton there is the Verkhoyansk fold-and-thrust belt extending for 2000 km from the Laptev sea in the north to the sea of Okhotsk in the south. It is 200 km wide. A system of frontal thrusts separate the belt from the platform structures. The belt is subdivided into sectors and segments of different structure. The frontal part of the belt is made mainly of Carboniferous and Permian terrigenous rocks of paleodeltas and submarine fans which grade eastward into Triassic and Jurassic sediments of the continental slope. The belt contains extensive (150-200 km) linear concentric folds. The front of the belt is characterized by thrusting and strike-slip faulting with large horizontal displacements (Parfenov et al, 1995). The largest anticlinoria at the front of the belt have a duplex structure (Prokopiev, 2000). Formation of the major ore deposits (gold, tin, antimony) and fold and fault structures, as well as igneous activity in the region is thought to be related to the collision of the North Asia craton with the Kolyma-Omolon superterrane and the Okhotsk terrane in the Late Jurassic-Neocomican (Fridovsky, 2000) . The collision occurred in two stages: the early Neocomian frontal collision and the Late Neocomian oblique collision (Prokopiev, 2000).

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FMF5 : THam02 : F4
Archean Orogenic Gold Mineralization in India (Hutti, Ajjanahalli): Implications for Ancient Tectonics

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Globally, orogenic gold mineralisation occurred at four distinct times in Earth history: the late Archean, the Paleoproterozoic, the lower Paleozoic and the Mesozoic. Each of these times corresponds to major orogenic processes. The geodynamic setting is characterised by transpressive accretion of terranes, typified by Cordilleran tectonics. Recently, two models have been discussed for the tectonic evolution of the Dharwar Craton in southern India. Chadwick et al. (2000) suggest a lateral accretion model for the formation of the granite-greenstone succession of the Dharwar Craton similar to arc-normal and arc-parallel displacements during oblique convergence in Mesozoic-Cenozoic settings. This is mainly based on the observation of strong N–S alignment of batholiths and greenstone belts divided by steep transpressional strike-slip faults and the intra-arc characteristics of the greenstones. In contrast, Jayananda et al. (2000) proposed a mantle plume model to explain the evolution of the Dharwar Craton based on radiogenic isotope geochemistry and dating of granitoids. The mantle plume forms the heat source for the widespread granitoid intrusions and the inverse diapirism (sagduction) of the greenstones. In this paper we present new data for two Archean orogenic gold deposits situated in the Dharwar Craton: (1) the Ajjanahalli Mine and (2) the Hutti Gold Mine. The Ajjanahalli Mine is situated in the Chitradurga greenstone belt about 5 km west of a major structural break. The latter is characterised by a sinistral strike-slip shear zone. Gold mineralisation is structually controlled by a BIF sequence deformed by flexural-slip folding. Hence, deformation and mineralisation occurred in a transpressional environment during NW-SE compression. The Hutti Mine is located in the Hutti-Maski greenstone belt within a high angle strike-slip shear zone system. Ductile-brittle deformation mechanisms have led to the formation of laminated quartz-carbonate veins which contain the gold-sulphide mineralisation. Detailed structural studies indicate a polyphase deformation history of folding and shearing in a transpressional environment. Whereas a mantle-plume and associated granitoid plutonism can very well form a heat and fluid source of hydrothermal gold mineralisation, the structural framework of the gold deposits studied can not be explained by such a model. Additionally, in the Ajjanahalli area no intrusion can be observed and at Hutti gold mineralisation is only spatially associated with a granitic intrusion. In contrast, orogenic gold mineralisation in a transpressional environment is very well in agreement with lateral amalgamation of terranes and late orogenic arc-parallel displacements as proposed by Chadwick et al. (2000) for the tectonic evolution of the Dharwar Craton.

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FMF5 : THam03 : F4
Tectonic Controls on Gold Mineralisation in Southeast Asian Magmatic Arcs

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The Cenozoic magmatic arcs that surround the Pacific Ocean are richly endowed with magmatic-hydrothermal gold deposits such as high- and low-sulphidation epithermal Au deposits, porphyry Cu-Au deposits and skarn Cu-Au deposits. Although a spatial and temporal link between these types of metal deposit and subduction-related magmatism has been recognised for some time, the deposits are most abundant within specific arc sectors and during specific periods. This strongly suggests that large-scale tectonic factors are important to the formation and localisation of magmatic-hydrothermal gold deposits in magmatic arcs. Examination of the spatial and temporal distribution of gold deposits relative to the regional tectonic model of Hall (1996) shows that all principal deposits formed after 25 Ma with the majority from the Late Miocene to Pleistocene. Most gold deposits formed during major tectonic reorganisations. The first of these followed the entry of the Australian craton into the Sunda-Banda subduction zone at around 25 Ma. This was followed by a Middle Miocene period of mineralisation that followed the maximum rotation or extrusion of Indochina, cessation of spreading in the South China Sea and collision of the Ontong-Java Plateau with the Solomons arc at around 17 Ma. However, the majority of deposits formed in a broad belt from Taiwan through the Philippine arc, Irian Jaya and Papua New Guinea, to the Solomons arc following a major change in relative plate motion between the Pacific and adjacent plates at ~5 Ma. This change in relative plate motion was coincident with the ~5 Ma collision of the Philippine arc with the Eurasian plate in Taiwan and the change from transtension to transpression along the Alpine Fault in New Zealand.

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FMF5 : THam04 : F4
Resolving Miocene Magmatic and Mineralizing Events in the Pb-Zn-Ag-Cu Domo de Yauli District (Peru) by High-Precision Geochronology

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The Domo de Yauli is located 100 km east of Lima in the Western Cordillera of Peru. It is one of the major Zn-Pb mining districts of Peru, with subsidiary Cu and Ag production. The northwest-trending Domo de Yauli is mainly composed of Paleozoic phyllites, Permo-Triassic volcaniclastic rocks, Triassic-Jurassic limestones, and Cretaceous sedimentary rocks. Miocene magmatic activity is more important in the northern part of the Domo de Yauli , where numerous small stocks of monzogranite, e.g. Toromocho porphyry, intrude the large Anticona diorite. In the south there are multiple small apophyses of the very altered Chumpe intrusion. The northern monzogranite stocks are related to four different ore deposit types: Cu±Mo±Au porphyries, Zn-Pb skarns, Zn-Pb±Ag carbonate replacement deposit (mantos), and veins. In the south, the Chumpe intrusion is associated with Zn-Pb mantos and W-Cu-Pb-Zn veins with no porphyry style mineralisation.

This study is aimed at understanding the relationship between Miocene magmatic activity and ore formation in the Domo de Yauli area. U-Pb, Re-Os and $^{40}Ar/^{39}Ar$ dating will allow the definition of a sequence of magmatic and mineralising events and the duration of mineralisation in the Domo de Yauli area.

Sulphides from different ore deposit types have similar Pb isotopic compositions, which overlap with the ones of whole rock residual fractions of Miocene intrusions from Domo de Yauli. This indicates a predominant input of magmatic lead in each ore deposit. Preliminary U-Pb dating on zircon from the northern intrusions gives concordant ages of 14.11± 0.04 Ma for the Anticona diorite and 9.11 ± 0.30 Ma for the Toromocho porphyry. Analyses on zircons from the southern Chumpe intrusion result in discordant points defining a lower intercept age of about 6.6 (+1.0/-3.6) Ma. Analyses on Toromocho and Chumpe zircons indicate multiple inheritances of 0.06, 0.26 and 1.8 Ga, the oldest inheritance probably originating from the 1950 Ma old Proterozoic craton. Preliminary Re-Os ages on ToromochoÕs molybdenite are around 8 Ma and are in good agreement with U-Pb data. U-Pb age determinations reveal the existence of three distinct magmatic events at 14.1, 9.1 and 6.6 Ma, the two latter ones related to a phase of mineralisation. We therefore conclude that the particularly large abundance of economic ore bodies at the Domo de Yauli is the result of different hydrothermal and tectonic systems.

Initial Hf isotopic compositions of the dated zircons were found to scatter around an epsilon Hf of zero; they thus suggest a hybrid melt source of mantle plus crust origin, which remained virtually identical throughout 8 million years of magmatism. The contribution of partial melts from the underlying Proterozoic basement in the generation of the Miocene magmatism of the Domo de Yauli is documented by Hf depleted mantle model ages of around 1.0 Ga.

FMF5 : THam05 : F4

Paleomagnetic Signatures of Orogenic Events and Mn/Fe Mineralizations in the Northern Cape Province, South Africa

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Palaeomagnetism can help elucidate the nature and timing of ore-forming events, especially within the forelands of orogenic belts where strains and metamorphic effects are low but not entirely absent. We conducted paleomagnetic analyses on excellently preserved Fe and Mn orebodies and related rocks in the foreland of the Kheis (1700-1800 Ma) and Namaqua (1000-1250 Ma) provinces in the Northern Cape, South Africa. Paleomagnetic field tests and comparisons with previous well dated results from southern Africa allow dating of the various magnetic signatures. From the Kalahari manganese field (KMF), three magnetic components are present. Aside from an early diagenetic remanence in microcrystalline hematite, two overprint directions appear to be tectonically derived. The first, corresponding to low-grade levels of the KMF, results from 1800-1900-Ma fluids driven by either extensional magmatism or the ensuing Kheis shortening. The second KMF overprint, corresponding to high-grade Mn ore, most likely dates from the late Mesoproterozoic Namaqua orogenesis. From the Sishen and Beekshoek iron mines, we identified a hematitic remanence within ore-forming paleolaterite developed upon Superior-type iron-formation. Fold and conglomerate tests demonstrate a that the remanence dates from the lateritisation event (2060-2200 Ma). In addition, a synfolding hematitic partial overprint bears the Namaqua-related direction as found in the KMF, although this hematitisation did not further upgrade the iron ores. Tectonic events are thus responsible for Mn but not Fe enrichment in the Northern Cape region.

FMF5 : THam08 : F4

Do Paleozoic Altaids-Tethysides Reveal Metallogenic Zoning Similar to Mesozoic-Cenozoic Circum-Pacific and Neo-Tethys Belts?

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The Altaids are considered as an embayment of Panthalassa between Siberian, East European, North Chinese and Tarim cratons. In the 1990s, it was shown that the Altaids consist of Mugodzhar island arc in the Urals and two oroclinally deformed Kipchak and Tuva-Mongol island arcs, whose Precambrian crustal pediments were rifted off Baltica-Siberia. I suggest that Tuva-Mongol arc separates accretionary complexes of Central Mongolia and Circum Pacific belt from accretionary complexes inside the Altaids everywhere between the Siberian and North Chinese cratons, whereas a tectonic 'corridor' between North Chinese and Tarim cratons unites the Altaids and Tethysides.

These latter accretionary complexes do not extend outside the Altaids and Tethys belt. Paleozoic magmatic arcs of Western Europe, East Eropean, Tarim and Siberian cratons, Tuva-Mongolia, Northern China, Yangtze and Indochina represent a former northern active margin of the Tethys ocean, whereas the Kimmerian continent rifted off Gondwana and now found inside the Tethys belt form its southern active margin. Its Adrian and Corsican-Sardinian fragments might continue into Castilian-Saxo-Thuringian arc, thus limiting former ocean in the west, whereas Sinoburmania and Indochina were its natural limits in the east. The ophiolites within this large ocean-facing accretionary complex are Late Proterozoic to Early Cretaceous. Mesozoic ophiolites to the south of the Kimmerian continent represent another oceanic basin of Neo-Tethys, whose connection with Circum-Pacific belt has no obstacles. Plate tectonic reconstructions for the Paleozoic Tethys-Altaids and Mesozoic-Cenozoic Pacific ocean suggest that their geodynamic pattern was similar.

This provides a basis for comparative analysis of the metallogeny in the Mesozoic-Cenozoic Neo-Tethys-Pacific ocean and Late Proterozoic-Paleozoic Altaids-Tethysides, both hosting world-class Au, Cu-Mo, Pb-Zn, U, Mn and other deposits. For instance, Paleozoic diamondiferous East European craton is similar to Mesozoic-Cenozoic diamondiferous Eurasia, whereas Palaeozoic Cu-, Mo-, and Sn-porphyries on the western flank of the Siberian craton, in the Tuva-Mongol arc, and on the landlocked flanks of the North China and Yangtze correlate with Mesozoic-Cenozoic Cu-Mo-porphyry and Sn belts of North America - Mexican-Carribean arcs ‹ South America. VHMS and Pt deposits in the Mugodzhar arc of the Urals and Cu-, Au-porphyries of the Kipchak arc would find its equivalens in the multiple arcs of Kolyma-Alaska. Palaeozoic Kyzylkum mesothermal gold province of Central Asia correlates in its passive margin setting with the Kolyma goldfields in NE Russia. Paleozoic Sn-, W-bearing arcs striking from Europe to Caucasus-Northern Iran-Tadjikistan would correlate with Neo-Tethys structures of SE Asia-Malaysia. Palaeozoic Pb-Zn deposits extending from Ireland via Poland to Kazakhstan and mesothermal Au deposits on the western and southern flanks of the Siberian craton may find respective equivalents in E Asia and North American Cordillera.

FMF5 : THam09 : F4

Re-Os Dating and a Possible Metamorphic Origin for the Langvatn Cu-Mo Sulfide Deposits, Setesdalsheiene, Southern Norway

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The Cu-Mo deposit at Langvatn and the smaller Cu deposit at Kobbernuten are located in a synclinal sequence of supracrustal rocks (Proterozoic Telemark Suite) in southern Norway. Mafic metavolcanics with metagabbro as concordant lenses, but locally intrusive to the supracrustals, dominate the sequence (Vokes et al., 1975; Prestvik and Vokes, 1975). About 4 km northwest, several granite bodies cut the supracrustals. There are no age data available for intrusive units, but zircon from an underlying rhyolite yields a U-Pb age of 1264 ± 4 Ma.

Using Re-Os dating of molybdenite, we have determined the time of sulphide formation at Langvatn and Kobbernuten. Ore veins and lenses at Langvatn, locally deformed and sheared, consist of chalcopyrite and molybdenite with lesser bornite, magnetite, pyrite, and extremely coarse-grained calcite and quartz. The ore zone indicates a close temporal relationship between sulphide deposition, ongoing deformation, and a developing steeply dipping shear zone in the host metagabbro. Skarn-like features, including garnet-epidote and actinolite-bearing assemblages in the vicinity of mineralisation indicate synchronous mineral reaction and metal concentration, contemporaneous with syn-metamorphic shear pumping. Three different molybdenite samples from Langvatn yield Re-Os ages of 1030 ± 4, 1032 ± 4, and 1033 ± 4 Ma. The Kobbernuten deposit, 2.3 km southwest, is associated with a near vertical fault-fracture cutting a well-developed foliation in fine-grained metabasalt. Sulphides are limited and dominated by bornite pods and blebs within massive metabasalt. Randomly-oriented, delicate mm-size needles of molybdenite are associated with bornite but occur in the metabasalt, and clearly cut local foliation. Three different molybdenite-bearing samples from Kobbernuten yield consistently younger Re-Os ages of 1026 ± 4, 1025 ± 4, and 1015 ± 4 Ma. Regionally, there are no granites known in the 1035-1015 Ma age range.

Based on Re-Os ages and hosting structures for the two deposits, we suggest that Kobbernuten may be a structurally higher level expression (brittle vs. ductile) of Langvatn-type mineralisation. As an alternative to a model invoking granite-derived fluids at depth (Vokes et al., 1975), the Cu-Mo metal component for Langvatn and Kobbernuten mineralisation could be accounted for by leaching of basalt and gabbro during metamorphism. Regional metasomatism and widespread epidotisation and alkali-enrichment of metabasalts has been shown to provide a source for Cu, Ca, and silica, leading to the formation of metamorphic vein deposits (e.g., Kish and Stein, 1989). While neither deposit appears to hold any significant economic potential, Re-Os dating of lesser ore deposits and occurrences can lead to a better understanding of the timing of local metamorphism and shearing.

Acknowledgments: This work was supported by a Fulbright Research Fellowship to HS in 2000, and by the Norwegian Geological Survey in Trondheim. Mr. Richard Markey (AIRIE, Colorado State University) provided the Re-Os age data.

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FMF5 : THam10 : F4

Modelling of Heat and Fluid Flow in the Iberian Pyrite Belt: Implications for Ore Genesis

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South West Iberia, i.e. the Iberian Pyrite Belt (IPB) in the South Portuguese Zone (SPZ), hosts a variety of mineral deposits not commonly matched in other parts of Europe. Many of these deposits, including massive sulphides, are thought to have formed in pull-apart basins during the transpressional stage of the Variscan orogeny. To find answers to specific questions of ore genesis in the area we have employed a quantitative basin modelling approach, in particular to investigate the control that basal heat flow and fluid movement may have had on processes of ore formation. For the approach adopted here the following methodology was selected: 1. Integration of thermal data (vitrinite reflectance, fission track analysis, illite crystallinity) to quantify the magnitude and timing of basin heating during burial, fluid infiltration and exhumation. 2. Computer-aided basin modelling using stratigraphic, structural, thermal and petrophysical parameters to reconstruct and quantify basin subsidence history as well as regional variations of conductive versus convective heat flow. Two areas of investigation were selected, firstly the Puebla de Guzman Antiform in the southern part of the Pyrite Belt and, secondly, as a reference area, the Bordeira Antiform which lies outside the Pyrite Belt in Southwest Portugal. The data obtained allow identification of three stages of heat flow: i) A syn-rift stage is preserved in the syn-rift sediments of the central parts of the Puebla de Guzman Area. This event is characterised by a relatively high, lower Carboniferous heat flow of 80–120 mW/m^2. These values record basin formation with associated lithospheric thinning and magmatism. ii) The arrival of the deformation front in the South Portuguese Zone occurred during the Westphalian and coincides with maximum burial and heating, as is recorded in the post-rift and syn-orogenic sediments. This stage is characterised by heat flow values of some 50 to 60 mW/m^2. iii) Heat flow values obtained in the Bordeira Antiform were much lower during the main stage of rifting than in the Puebla de Guzman Antiform and indicate a tectonic position as a 'graben shoulder'. Due to the fact that both areas show a heat flow anomaly during rifting, and that the stratigraphic make-up of the Bordeira Antiform is conspicuous by the absence of volcanics, the influence of a deep crustal heat source seems to be the major cause for the observed temperature field in the basin. Calculated permeabilities in the lower Carboniferous sediments are in the range of 10^{-6} mD. The maximum temperatures (200-250 °C) and the thermal gradient in the area of investigation in the range of 60–100 °C/km, therefore, does not point to a major contribution of convective heat transfer prior to and during deformation. Taking all findings into consideration, it is concluded that synsedimentary faults may have acted as the major channelways for hot mineralising fluids. This model is further refined by finite element modelling integrating parameters such as basinal heat flow, fluid temperature, duration of fluid flow and heat-transfer.

FMF5 : THam11 : F4

Multiple Fluid-Flow Events and Mineralizations in SW Sardinia: From Variscan Onwards

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The evolution of the Sardinian Palaeozoic basement shows structural, stratigraphical and geochemical analogies with other European Variscan Belts. In the Iglesiente-Sulcis area, considered as the external zone of the Sardinian Variscan chain, an incomplete Palaeozoic succession, spanning in age from Early Cambrian to Devonian, underwent several phases of deformation, followed by calc-alkalic granite intrusions (330-300 Ma) and late-Variscan basement uplift. The post-Variscan sedimentary record starts with a clear trend toward crustal attenuation and tearing, possibly related to a large transcurrent megashear zone and resulting in the inset of Upper Carboniferous-Permian continental basins, associated to coeval magmatic products of still calc-alkalic affinity (290-270 Ma). The Mesozoic successions point to further crustal thinning, to be considered a prelude to the Alpidic rifting. Their magmatic counterparts are sub-alkalic and alkalic dykes, with a mantle Sr-signature, dated at about 230 Ma.

Several quite distinct hydrothermal systems were supposedly active in SW Sardinia, not only at the lower time fringe of the Variscan magmatism (skarn and retrograde contact-metamorphism), but spanned from Permian to Mesozoic, resulting in a variety of hydrothermal products, including ore deposits.

(1) One first prominent episode of hydrothermal mineral formation has been dated at 270 Ma (Boni et al., 1999), at least 30 Ma later than the youngest Variscan granitoid intrusions. This age, recorded also in several magmatic bodies of calc-alkalic character throughout Sardinia, could fit with the Permian post-orogenic extensional phase and wrench fault tectonics, which caused widespread hydrothermal alteration in the basement rocks, locally coupled with important mineralisation in the whole of Europe. The Permian hydrothermal stage produced in SW Sardinia high temperature-low salinity, heavily radiogenic Fe-Cu-Zn-Pb-F-Ba vein ores, as well as a pervasive hydrothermal dolomitization.

(2) Geochronologic analysis showed also that younger hydrothermal phases, related to further episodes of fluid flow, have occurred through the Mesozoic. No unambiguous age determination of these younger phases was possible so far, because the $^{40}Ar/^{39}Ar$ results demonstrate a very complex superposition of hydrothermal alteration events at different times (including Tertiary). However, we propose to relate the first evidence of Alpidic rifting in Sardinia (230 Ma), identified by the alkaline dykes (Vaccaro et al., 1991), with a distinct hydrothermal stage and with the inset of the low temperature-high salinity, poorly radiogenic Pb-Ag-Ba vein- and paleokarst deposits, occurring in Iglesiente and Sulcis. This kind of low temperature-high salinity ores are ubiquitous in Europe, where their age ranges from Triassic to Jurassic, depending on their original position with regard to the European intra-plate geometry.

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FMF5 : THam12 : F4

Two-stage Exhumation during the Mid- to Late-Variscan Evolution of the Western French Massif Central and Implications for W-Sn and Rare Metal Deposits

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Systematic $^{40}Ar/^{39}Ar$ dating of granitoids and surrounding metamorphic rocks has been performed in the western part of the French Massif Central under the GeoFrance 3D program. It aimed to provide new data concerning the Variscan evolution of the French Massif Central, with particular emphasis on the less constrained mid-Variscan stage. A synthesis of the ages obtained shows the existence of two exhumation stages, each preceded by a magmatic episode: (1) A first exhumation stage at ca. 340 ±5 Ma, preceded by Late Devonian to Early Visean magmatism (ca. 350 Ma), corresponds to the end of the convergence regime. This stage is recorded by the cooling ages in the Bourneix, Vienne and northern Limousin areas, irrespective of metamorphic and intrusive rocks. It is interpreted as representing a regional cooling by exhumation, in response to the variation of tectonic regime, with decreasing compressional stress in the chain. This stage is followed by a relatively stable episode during the 330-320 Ma period, for which the exhumation rate was low (about 0.3 mm/y). (2) A second exhumation stage is preceded by Namurian to Early Stephanian peraluminous and rare metal magmatism. This stage is characterised by drastic changes in the tectonic regime with the onset of general extension and granulite-facies metamorphism of the lower crust, induced by the delamination of the lower lithosphere. Dating various late-orogenic events (i.e. intrusives, pegmatites, late hydrothermal circulation and mineralisation) in the Northern Limousin, contemporaneous to this late-orogenic exhumation stage, provide ages varying from Middle Namurian (ca. 325 Ma) to Stephanian (ca. 305 Ma). In the Limousin, extensional tectonics culminated during the Stephanian (ca. 305 Ma) with a transient fast tectonic denudation in the upper crust (1.5 mm/y). $^{40}Ar/^{39}Ar$ thermochronology reveals that this denudation corresponds to downwarping of metamorphic and granitoidic cover along detachment faults. No significant mineralisation is related to the first magmatic episode (ca. 350 Ma). $^{40}Ar/^{39}Ar$ dating reveals that several episodes of W-Sn-Be mineralisation are contemporaneous with intrusives of the second magmatic episode: (i) 325 Ma for the Puy les Vignes and Moulin Barret W deposits, (ii) 310 Ma for the Vaulry W±Sn deposit associated with Rare Metal Granites. In contrast, for U and Au, the mineralisation process covers several tens of My. These mineralisation events are not directly related to the thermal anomalies created during the injection of large volume of crustal melts but rather to the onset of generalised extension contemporaneous with the delamination of the lower lithosphere and LP-HT granulite-facies metamorphism in the lower crust.

FMF5 : THam13 : F4

Relationships between Granitoids and Mineral Deposits: 3-D Modelling of the Variscan Limousin Province (NW French Massif Central)

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In the French Massif Central, the U, Sn, W and Au Variscan mineral deposits are spatially related to leucogranites but they occurred within a time period of about 40 Ma after the intrusion of these granites. In order to decipher the interaction between magmatism, tectonics, thermal regime, fluid circulations and mineralisation, a 3-D reconstruction of the North Limousin crustal block has been performed. The models suggest that the location of the deposits reflects the evolution of the permeability of the crust during the 300 ± 30 Ma period, in response to the regional stress regime. In the Northern Limousin, this period corresponds to an evolution from the beginning of the synconvergence extension and the associated magmatism (Visean), to the end of the general extension (Permian). For the early intrusions (360-320 Ma), emplaced in deep conditions (> 10 km), the low global permeability of surrounding rocks and the tectonic regime did not allow large vertical fluid exchanges. Towards the end of the collision, delamination of the lower lithosphere has probably played a major metallogenic role. Firstly, simultaneous fluid and melt transfers, associated with the emplacement of Rare Metal Granites, occurring at a shallow depth (about 5km), led to the formation of significant W-Sn deposits. These phenomena may also explain differences between the evolution of granites of the same typology, (e.g. Saint Sylvestre and Blond granites). Secondly, the onset of general extension induced a rapid exhumation of the ductile crust, synchronous with the LP-HT granulite-grade metamorphism of the crust. The resulting pressure decrease allowed increasing circulation of cool meteoric fluids and their mixing with deeper hot magmatic or metamorphic fluids, which were of great importance for metal transportation and deposition within reactivated permeable structures. Although the culmination of ore deposit formation seems to have occurred at 310 ± 5 Ma, the deposit processes appear to be specific to each of the metals. For the W-Sn deposits related to RMG at about 310 Ma, dating of mineralisation and spatially associated intrusions indicates that they occurred almost simultaneously. In contrast, for Au and U, the whole mineralisation process involves several metallogenic steps, covering several tens of My, and is controlled by the regional tectonic evolution of the Limousin area during the same period. Furthermore, some permeable zones seem to have been used several times for different metal depositions. For example, the geographic correlation between early W-(Sn) and late Au-As deposits may indicate that the permeable fractured aureole around the granites was reactivated at least once. However, the thermodynamic conditions and the occurrence of adequate traps finally controlled the formation of significant ore bodies.

FMF5 : THam14 : F4

The Q-Au Lodes of Western Europe: Fluid Mixing and Gold Deposition during the Late Carboniferous Uplift of the Variscan Belt

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During the Carboniferous, fluid circulation at the crustal scale occurred in the W European Variscan collision belt, and was in particular responsible for the formation of numerous Q-Au lode deposits. Based on the study of numerous individual deposits, the following generalisation can be made. The existence of Au deposits resulted from a two-stage process.

• The first stage was initiated at c. 330 Ma, under a lithostatic pressure of 3-3.5 kb (11-13 km depth), i.e. at the top of a middle crust already cooled at c. 350˚C. There, fluid circulation and heat advection were restricted to shear-zones of limited horizontal extension. Fluids of the C-O-H-N system were focused from deep middle crust reservoirs, where they had been equilibrated with metamorphic rocks at temperatures ≥ 450˚C, and deposited quartz, Fe-As-S minerals and, sometimes, sulpho-salts, with insignificant amounts of combined gold and apparent lack of native gold. This pattern of circulation was protracted. Meanwhile, steady-state uplift occurred, at an estimated rate of 0.3 $mm.a^{-1}$.

• When the lithostatic pressure was lowered to c. 1.5 kb, a transition from lithostatic to hydrostatic pressure occurred (locally associated with unmixing of the C-OH-N fluids). Fluid circulation, now in the upper crust, became pervasive. Deep crustal fluids were still present, at temperatures up to 400-430˚C in some instances, implying the persistence of heat advection from depth. However, the hydrothermal systems were overflowed by shallow fluids of meteoric derivation, that infiltrated the basement through recently activated normal faults. Fluid circulation is recorded at the 10-km scale in the horizontal dimension, through a set of interconnected multi-directional microcracks. However, fluids were still focused in major drains (usually, reactivated shear-zones of the early stage). There, dilution and cooling of the deep, saline (up to 15 wt % eq. NaCl) fluids by the low-salinity shallow fluids, was the cause for gold deposition, together with Bi, Pb, Sb and Cu sulphides or sulpho-salts. The age of this event is not definitely constrained, but several lines of evidence indicate a c. 305 Ma age.

The transition between the two stages was evidently tectonically controlled. It is thought that it recorded the inception of extensional conditions in the Variscan belt, associated with a transient rapid uplift of the belt (estimated at 1.5 $mm.a^{-1}$). This is consistent with the proposed age. Due to the extensional stresses, opening of interconnected set of microfractures allowed the observed penetrative fluid circulation in the upper crust, and favoured the sudden link between two major fluid reservoirs which eventually resulted in gold deposition.