EUG XI

Theme FMF

Fluid and Mass Flux

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EUG XI

Symposium FMF1

Diagenesis and Low-grade Metamorphism: In Memoriam of Martin Frey and Bernhard Kübler

Sponsored by BP – Amoco

Convenors

Susanne Th. Schmidt
Laurence Warr

Sunday PM Session

FMF1 : SUpm26 : F4
Bituminite Reflectance in Very Low Grade Metamorphic Studies

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In low grade studies organic matter maturation is applied, together with other low grade methods, to determine metamorphic temperatures. Vitrinite reflectance (VR) is the main method used in coal petrology. VR is a parameter sensitive to temperature in the range 0.25 to 8.0%R_{max} (30 to 380±20°C). Vitrinite group macerals are rare in sediments from the deep continental rise to abyssal plains, in carbonate platforms and in anoxic black shales. Samples from these areas usually provide between 0 and 10 measuring points, which is insufficient for correlation with other methods. In the studied areas (I) Austria and Switzerland, (II) Chile, and (III) Romania, VR ranges from 0.50 to 12.0% R_{max} (80 to 400±20°C). Bituminite is a frequent component in (I) Austroalpine carbonate platform rocks, (II) in Vichuquén basin marine to lagunal sediments, and (III) in Danubian window distal marine sediments and black shales. In the three areas the temperature history is different. In the Austroalpine, an Alpine orogenic metamorphism follows burial. In the Vichuquén basin, contact metamorphism by plutonic intrusions effected the shallow buried sediments. In the Danubian window a short HT-LP event due to rapid exhumation overprinted a very low grade Alpine metamorphism. In vitrinite and bituminte bearing rocks maximum and minimum bituminite reflectance (BR) were measured. BR was determined in isotropic or slightly anisotropic bituminite to cata-bituminite fragments (detritic bituminite) and vein fillings (migrabituminite) with a homogeneous extinction. High anisotropic undulating bituminite is not recomended to be used, due to strong scattering values. The homogeneous detritic bituminite occurs as broken particles with a rounded habitus and a low relief. The soft material of migrabituminite is fingering into the pore volume. These bitumens are probably solid residues of oil. Bituminite in shear zones in the Austroalpine and Danubian nappes shows pre-graphitization. At VR > 3.0% the BR reflectance increases rapidly due to the formation of graphitoid sphaeroliths. In less deformed rocks homogeneous bituminite is preserved until VR = 7.0%R_{max} (e.g. Danubian rocks). In samples from the Vichuquén basin in Chile, bituminite has the characteristics of natural coke. These bituminite (pyro-bituminite) show hexagonal joints perpendicular to the rim and contain many fine fissures, pores and vesicles that are typical for a contact metamorphism. The BR shows a significant correlation with VR and can be used as a indicator of metamorphism. BR correlates well with VR between 2.5 and 5.0%R_{max}. Bituminite gives a quantitative information about the metamorphism of rocks without vitrinite. Therefore, BR reflects the temperature during metamorphism in the three areas with a different tectono-thermal history. Consequently, we recommend the use of BR in low grade studies as an alternative method for rocks poor in vitrinite.

FMF1 : SUpm27 : F4
The Influence of Geotectonic Setting on Clay Mineral Assemblages in British Lower Palaeozoic Slate Belts

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Lower Palaeozoic slate belts in Britain were formed when mud-rich sediments were transformed to low-grade metamorphic mudrocks during Caledonian terrane amalgamation, 400 to 600 Ma ago. Although lithologically very similar, XRD analyses of several thousand slate samples show consistent regional differences in clay mineralogy that relate to the different geotectonic conditions of basin evolution. The extensional basins of Wales, the northern Lake District and the Isle of Man are characterised by a greater diversity of species in clay mineral assemblages. Slates in these basins contains both the K-rich and Na-rich products of the 2:1 dioctahedral reaction series. Corrensite, rectorite and pyrophyllite are sporadically distributed but are more common in hydrothermally altered mudrocks. Kaolinite is rarely recorded even in the lowest grade mudstones. In contrast, clay assemblages found in the collisional basins of the Southern Uplands and the southern Lake District contain fewer mineral species, and Na-micas and pyrophyllite are notably rare or absent.

A major difference in the regional clay assemblages is the participation of Na in the dioctahedral 2:1 clay reaction series in extensional basins but its general absence from collisional basins. In the Welsh Basin the greatest diversity of clay minerals, including intermediate Na/K-mica, paragonite, rectorite and pyrophyllite, is found in the aureoles of sub-volcanic intrusions. Recent discoveries of paragonitic alteration in mid-oceanic hydrothermal systems suggest that low temperature seawater circulation may be responsible for reactions that generate Na-clays (Honnorez et al., 1998). The alteration results from low temperature mixing of hydrothermal fluids and seawater, that produces alkali fluids with high Na/K ratios. However, in the Lower Palaeozoic extensional basins Na-clay minerals are not restricted to thermal aureoles and their occurrence across wide areas of British slate belts of suggests that hydrothermal fluids with elevated Na/K ratios may have circulated basin-wide during the early stages of clay diagenesis and burial. By contrast, such fluids appear to have been unavailable in collisional settings during early diagenesis and burial, largely through lack of basin-wide volcanic activity in the early stages of basin development. Such regional differences in clay assemblages suggest that clay mineral reaction progress, particularly the diversity of clay mineral products, depends on basin thermal history: high heat-flow extensional basins appear to generate a greater diversity of clay minerals than low heat-flow collisional basins.

Honnorez, JJ, Alt, JC & Humphris, SE, *In: Herzig, P. M. , Humphris, S. A. , Miller, D. J. & Zierenberg, R. A. (eds). Proc Ocean Drill Prog, Scientific Results*, **158**, 231-254, (1998).

FMF1 : SUpm28 : F4
Low-Grade Metamorphism in Northern New Caledonia: Evolution of Metapelites Under HP-LT Conditions

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The HP-LT schist belt in northern New Caledonia shows an increasing field gradient from SW to NE, ranging from pumpellyite-prehnite assemblages through blueschists and glaucophanitic greenschists into eclogites. Our study is restricted to a metamorphic range from the late diagenetic zone to the epidote-in isograd. Optical microscopy, X-ray diffraction and electron microprobe analyses were performed, showing the occurrence of index minerals such as lawsonite, carpholite, ferro-stilpnomelane and ferro-glaucophane. Such minerals are characteristic for HP-LT metamorphism. The determination of the K-white mica *b* cell dimension, in samples from the lawsonite and glaucophane zones, reveals Barrovian metamorphic conditions. P-T estimation in the late diagenetic display maximum conditions of 240°C and 4 kb. In the carpholite-bearing samples, a minimum pressure of 9 kb at temperatures around 350°C was estimated. The study of metapelites under HP-LT conditions (geothermal gradient < 15°Ckm^{-1}) has revealed, e.g. in a case study from the Diablo Range that metamorphic conditions estimated from coal rank data were low compared to those indicated by Kübler index (KI) values (Dalla Torre et al., 1996). The aim of our contribution to low-grade studies was to verify the assumption from field data and experimentally synthetized vitrinite (Dalla Torre et al., 1997) that pressure retards vitrnite reflectance (VR). K-white mica compositions plot close to the Tschermak exchange line, showing a trend with increasing metamorphism toward the celadonite end-member. Complete transformation of K-white mica polytypes from 1 M_d to 2 M_1 is reached at the transition between low anchizone and high anchizone. Chlorite composition in a diagram of non-interlayer cations versus Al_{total} (apfu) cluster close to the clinochlore end-member with a trend toward the sudoite end-member. The temperatures at the boundaries between the low diagenetic zone-anchizone are estimated by isotopic thermometry (Black, 1974) at 230-240°C and between the anchizone-epizone at 280-300°C. A determination of the VR R_{max}% was also performed. The R_{max} values correlated with the KI at low diagenetic zone-anchizone and anchizone-epizone boundaries are 2.80-3.06% and 4.05-5.44%, respectively. Both methods are equivalent. Comparison of KI and VR data from the literature shows that the correlation is in the same order, as shown for alpine areas with a geothermal gradient > 15°Ckm^{-1}. Comparing different tectono-metamorphic studies, we argue that the pressure effect in retarding VR is overestimated at conditions with a geothermal gradient < 15°Ckm^{-1}.

Black PM, *Contr. Mineral. and Petrol.*, **47**, 197-206, (1974).
Dalla Torre M, De Capitani C, Frey M, Underwood M, Mullis J & Cox R, *Geol. Soc. Amer. Bull*, **108**, 578-601, (1996).
Dalla Torre M, Ferreiro-Mählmann R & Ernst W, *Geoch. Cosm. Acta*, **61**, 2921-2928, (1997).

FMF1 : SUpm29 : F4
Very Low Grade Metamorphism in the Danubian Window, South Carpathians (Romania)

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The structure of the South Carpathians is represented by a Cretaceous nappe pile formed from the structural lower units to the upper ones by the Danubian, Severin-Cosustea and Getic nappe systems. Nappe emplacement was followed by Eocene orogen parallel extension when the Danubian units were exhumed. Pervasive Alpine metamorphism is present only in the Danubian and Severin-Cosustea units. The methods used to constrain the PT conditions are: optical microscopy, X-ray diffraction and electron-microprobe. Illite crystallinity (IC) and organic matter reflectance (OMR) have been determined. An increase in metamorphic grade from southwest to northeast is emphasised by all the methods applied. Also, in the eastern part of the Carpathian bend an increase in metamorphic grade from south to north is observed. In the southern area the metamorphism did not exceed 300°C, due to the occurrence of the prehnite-pumpellyite facies in the Severin and Cosustea units and lack of pyrophyllite and paragonite in the Danubian units. Danubian units were not below 200°C since kaolinite was not identified although primary feldspar is present. Also, the IC data indicate temperatures up to 250°C, based on the upper diagenetic zone-anchizone limit. The chlorite geothermometry gives temperatures between 300 and 330°C. The highest possible pressure is constrained in this area, by the upper stability limit of prehnite to 4 kbar. Highest temperatures have been obtained by chlorite thermometry and mineral reactions, IC and OMR values on samples from the northern border of the Danubian Window (350 to 400°C). On the retrograde path, the occurrence of clinozoizite suggests temperatures >300°C and Bt+Chl indicate temperatures >350°C. Syn-detachment peak pressure conditions of 3 to 4 (±1) kbar are found on the north-eastern border. Andalusite formed on retrograde path, confine also by its stability limits the pressure to <4.5 kbar. In the Severin units at the northern border, the IC, mineral chemistry and parageneses indicate the same syn-detachment metamorphic peak conditions as deduced for the Danubian units. A correlation between the IC data and the OMR data has been calculated. The slope of the regression line for the Danubian Window samples indicates HT-LP conditions. The OMR suggests a higher metamorphism than deduced from the correspondent IC and mineral assemblage or calculated from the geochemical mica-chlorite data. The relative elevated OMR in Danubian Window can be well explained by an isothermal decompression and the probable elevation of the geotherm due to the crustal thinning during the rapid exhumation of Danubian units. Probably a higher heat-flux followed the end of the Getic detachment, time when the retrograde chloritoid decomposition reactions took place. Therefore, retrograde reactions still indicate HT.

FMF1 : SUpm32 : F4
Mineralogic and Organic Responses to the Stratigraphic Irregularities: An Example from the Lower Paleozoic Units in the Eastern Taurus Autochthon, Turkey

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The paleogeographic and diagenetic-metamorphic evolution of Lower Paleozoic sedimentary rocks have been studied by means of optical and XRD methods in the Eastern Taurus Autochthon. Illite crystallinity index (IC), b0 and% 2 M1 proportion of K-white micas indicate a temperature increasing from top (diagenetic conditions) to bottom (anchi-epizone conditions). Organic data show a good correlation with phyllosilicate crystalchemical parameters. All data show that the sedimentary burial diagenesis to very low-grade metamorphism were developed at the original depositional site. Three main and five subzones with distinctly break boundaries have been distinguished through the Lower Paleozoic series. As a whole, the Lower Paleozoic sequence was initially subjected to a sedimentary burial in the extentional marginal basin in the anticlockwise P-T-t pathway on three different stages, finally it is developed in the clockwise P-T-t pathway according to the relative stage or time of diagenesis/metamorphism.These stages seem to correspond to stratigraphical gaps, unconformities and/or irregularities that may have important implications regarding the yet unknown deformational events as well as the distribution of the Perigondwanan terranes during the Paleozoic.

FMF1 : SUpm33 : F4
Temperature Determination Through Fluid Inclusion Microthermometry and Vitrinite Reflectance Values in the Diagenetic- and Anchi-Zones

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Fluid inclusion homogenization temperatures in synkinematically grown fibre quartz from 34 Alpine fissures in the external part of the Central Alps were compared with the vitrinite maturation rank determined by vitrinite reflectance%R_{max} of the surrounding rocks. As the measured methane-bearing water-rich fluid inclusions are related to water-bearing methane-rich fluid inclusions controlled by fluid immiscibility, their homogenization temperatures reveal entrapping temperatures. Fibrous quartz growth in diagenetic and low-grade metamorphic rocks is likely to occur close to the maximum metamorphic temperatures. Thus, the homogenization temperature of methane-saturated water-rich fluid inclusions can be used as a geothermometer (Mullis, 1979).

Based on experimental data (Dalla Torre et al. 1997), numerical kinetic models and maturity inversion techniques (e.g. Gallagher and Sambridge 1992, Ferreiro Mählmann in press) it is possible to derive thermal histories and maximum temperatures in sedimentary basins and in orogenic belts from vitrininte reflectance data. The process of vitrinite maturation is irreversible and it is assumed that the level of organic maturity is a product of temperature and time, but temperature is thought to be the most important factor.

As the maturation rank of vitrinite in orogenic belts indicates temperatures more or less close to their maximum, fluid inclusion homogenization temperatures may be used for independent temperature calibration of vitrinite reflectance. As a result, more accurate kinetic models for metamorphic temperatures derived from vitrinite reflectance in orogenic belts can be established.

In the temperature range from 200 to 270°C, the following relationship between fluid inclusion homogenization temperatures, vitrinite reflectance and maturation characteristics for an orogenic belt like the Central Alps have been established:

200°C VR = 2.4 ±0.4% Transition: Higher hydrocarbon zone / methane zone

235°C VR = 3.8 ±0.5% Transition: Diagenetic / low-grade anchizone

270°C VR = 6.2 ±0.8% Transition: Low-grade anchizone / high-grade anchizone

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FMF1 : SUpm34 : F4
Tobelite in Low-Grade Metamorphic Organic-Rich Shales from Douro-Beira, Portugal

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Organic-rich Carboniferous shales associated with coal seams from the Bacia Carbonifera do Douro-Beira (N Portugal), have been studied by TEM, as well as by a variety of other methods. Micas rich in NH_4 (tobelite) and K, together with berthierine, form small subparallel nanometer scale packets separated by low-angle boundaries. One- and two-layer ordered polytypes, with some spot streaking characteristic of minor disorder, coexist in the NH_4 micas. All the common characteristics described for subgreenschist facies were observed, including a lack of textural and chemical equilibrium. The compositions of both K and NH_4 micas vary considerably, and except for Ti, exhibit similar compositional ranges. The most significant trends of variations are explained by phengitic substitutions (Si from 3 to 3.25, Fe+Mg from 0.1 to 0.3), while no evidence of large changes in interlayer site vacancies has been found. NH_4 in tobelite was determined by analysis of NH_3 using Nessler's reagent, basal spacing and 1-(K+Na). The resulting values suggested that NH_4 contents could range from 38 to 59% of the interlayer site occupation. The presence of N in the white micas was confirmed by electron energy loss spectroscopy (EELS) of crushed grains dispersed on holey-carbon grids. EELS analyses showed that the composition of the interlayer site varied between grains, and that a significant margarite component was present in some of the crystals. In other previously studied localities, the intergrowth of NH_4 and K in micas is on the nm-scale at very low temperatures (e.g., North Sea, Drits et al, 1997). At higher temperatures, NH_4 and K are found in separate micas (e.g., Pennsylvania, Juster et al., 1987). The Douro-Beira samples represent an example of the higher-temperature case. NH_4 and K coexist in the same layer, but one cation is dominant. NH_4- and K-dominated micas have segregated into well-separated packets with scarce intergrowth and almost no mixed-layers. Thus, the evolution of tobelite during low-grade metamorphism follows a path of metastable mixed compositions that increase in segregation as grade increases. This is similar to the evolution of paragonite and margarite.

Drits VA, Lindgreen H & Salyn AL, *Am.Min.*, **83**, 79-87, (1997).
Juster TC, Brown PE & Bailey SW, *Am.Min*, **72**, 555-565, (1987).

FMF1 : SUpm35 : F4
Chloritoid Composition and Formation in the Eastern Central Alps: HP or LP Formation?

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Chloritoid (cld) is well known as an important index mineral for lower greenschist facies Al-rich shales. In the Central Alps, a cld-in isograd was mapped by Frey & Wieland (1975), on the basis of a reaction pyrophyllite (prl) + chlorite (chl) -> cld + qtz + H_2O. In the eastern Central Alps, this reaction isograd roughly follows the southern end of the Helvetic belt, suggesting that cld should represent a common phase within Al-rich Penninic Bündnerschists further south. However, only one report of cld has been published so far (Niggli & Niggli 1965).

Here we report on a new occurrence of chloritoid within the Bündnerschists from the Safien valley. Cld occurs in dark shales, however, is only detected by XRD means and in BSE images. The present mineral assemblage is white mica-chl-qtz-cld-prl-ab. Cld indicates synkinematic growth by a strong grain orientation along the main schistosity, together with chlorite and white mica. The X(Fe) of cld varies between 0,07 and 0,12, Thus, they represent Fe-cld typical for lower greenschist facies, which is in agreement with recently published data by Bousquet (1998). Temperatures calculated by cld-chl thermometry (Vidal et al. 1999) suggest metamorphic peak conditions of 350-400°C during the formation of the two phases and development of the principal schistosity. White mica barometry indicates minimum pressures of 6-8 kbars, which, however, have to be interpreted cautiously due to absence of a critical parageneses. The presence of cld in the rocks is restricted to samples with very low carbonate content (less than 1wt% CaO) and a minimum bulk rock Al content of 15 wt%.

A comparison with neighbouring occurences of chloritoid at the Kunkels pass and Curaglia indicate no differences in cld composition, however, here white micas indicate distinctly lower minimum pressures. At Kunkels pass, the critical assemblage does not contain chl nor prl, and the chloritoids form rosettae, overgrowing the main schistosity, which indicates post-kinematic cld growth.

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FMF1 : SUpm36 : F4
Textural and Chemical Changes in Slate-Forming Phyllosilicates of a Foreland-Hinterland Transition of the Low-Grade Metamorphic Belt in the NW Iberian Variscan Chain

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Differences in chemistry and texture of slate-forming phyllosilicates representative of foreland and hinterland rocks of the Iberian Variscan orogenic Belt have been determined by scanning and transmission electron microscopy. Based on Gutiérrez-Alonso and Nieto (1996) X-ray diffraction study, two couples of rocks were selected as representative of both geological zones; they show neatly different characteristics. Those two corresponding to the foreland rocks present a similar texture at the backscattered electron scale level independently of their respective epizone and anchizone illite crystallinity indices, showing a mixture of sedimentary and metamorphic characteristics. At crystalline lattice level, mica and chlorite packets form subparallel low-angle intergrowths and show strain features, more obvious in chlorite than in mica. The only difference,

that justifies their different cystallinity indices, regards with quantitative characters as crystallite size and frequency of defects. The two hinterland samples are very similar and are formed by perfect defect-free micron-size packets of phyllosilicates in a typically metamorphic parallel orientation. In coherence, the mineral chemistry of the foreland samples is highly heterogeneous, being each individual analysis affected by variable degrees of illitic, phengitic and ferrimuscovitic substitutions (according to the IMA nomenclature for micas, Rieder et al., 1998). In contrast, the hinterland samples have evolved to more homogeneous compositions approaching to the end-member muscovite. The effect of tectonic stress was fundamental both in the developing of a metamorphic texture and the approaching to the chemical equilibrium. Lattice fringe images of phyllosilicates reproduce at the Å level, the same geometry of folds that may be recognised at a kilometric scale in the geologic maps of the region.

Gutiérrez-Alonso G & Nieto F, *J. Geol.Soc. London*, **153**, 287-299, (1996).

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FMF1 : SUpm37 : F4
Inter Laboratory 'Illite Crystallinity' Calibration: Theoretical and Practical Approach

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Abstract: The need of an "absolute "illite crystallinity" (IC) scale requires to define a systematic set of inter-laboratory calibration methods. Such inter-laboratory calibration can be performed either by a reduced major axis regression line (other methods like principal axis are correct) or by a theoretical method using the convolution of the instrumental XRD peak profile determine approximately using a mica powder, with a calculated pure profile. The use of both methods appears to be a suitable inter-laboratory calibration procedure. Another method has been proposed, based on the measured XRD source profile, using a small mica flake, convoluted successively with the theoretical instrumental profile effect and with the pure profile. For the time being the accuracy of this method is not sufficient to be recommended. The advantage of theoretical methods is to link the observed Scherrer Width (SW) with the pure profile SW. This leads to an approximation of the IC anchizone limits in pure profile SW scale of 0.10° for the epizone limit and 0.30°Δ2θ CuKα for the diagenetic one. Consequently a set of several standard samples has to be defined by a group of workers. Those sets must contain a "perfect" mica powder mount, a small mica flake and few standard of various SW not affected by humidity. All standard samples have to be mounted in the same way, in order to obtain an absolute scale.

FMF1 : SUpm38 : F4
Can X-Ray Scattering Domain-Size Really Provide Information About Crystal Growth Mechanisms of Clay Minerals?

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In recent years, there has been a tendency toward using the X-ray scattering domain (so-called crystallite) size of clay minerals for deducing the crystal growth mechanisms of clay minerals. This approach is based on the following assumptions: i) that domain broadening information can be accurately extracted from X-ray diffraction profiles, ii) the X-ray scattering domains correspond only to crystal boundaries, and iii) the changes in the shape of size-distributions can be linked with established crystal growth mechanisms. On the basis of a number of XRD-TEM clay minerals investigations, the validity of these assumptions as applied to low-temperature pelites is questionable. Whereas these methods may be applicable to ideal, clay samples with only one generation of one clay mineral, their application to typically polyminerallic mudstone, shale and slate lithologies is highly limited. Firstly, it is very difficult to extract accurately the domain-size information because of uncertainties of overlapping mineral phases (particularly within the low-tails of reflections) and the problems associated with removing instrumental broadening. Secondly, TEM studies reveal that X-ray scattering domains do not necessarily relate directly to crystal boundaries but are strongly influenced by other defects, such as those induced by intracrystalline deformation. They are additionally sensitive to sample preparation damage, most notably cleavage into smaller domains. Thirdly, we question whether the relationship between size distributions and crystal growth mechanisms are really well enough studied to allow reliable deductions to be made. It is evident from our studies that the above-described methods should only be applied to ideal materials where the above mentioned assumptions can be validated. Such results should then only be accepted when tests of such distributions show correlation with direct measures of crystal size distributions as measured in the intact rock, and for samples of known mineralogical evolution.

Sunday PO Session

FMF1 : SUpo01 : PO
Recognizing Illitization Processes in Very Low-Grade Rocks

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The boundary between diagenesis and metamorphism in pelitic rocks has been defined using omnipresent minerals such as illite or the illite/smectite mixed layer mineral series. However, in such rocks detrital grains may occur alongside phases formed during burial diagenesis. Although X ray diffraction methods bias results towards smaller crystals (i. e. neoformed), complete separation of the neoformed and detrital components is impossible. Thus, for example, the 10Å illite peak may be formed by contributions from both types of components, resulting in complex x-ray diffraction curves. The aim of this work is to use X-ray diffraction methods to investigate the different components that generate diffraction patterns so as to identify the various subpopulations that form illitic assemblages. To achieve this goal we studied a sample suite of Palaeozoic rocks from the Cantabrian Zone (NW Spain) ranging from Cambrian to Carboniferous. The Cambrian to Westphalian A-B is a pretectonic succession, whereas the Westphalian C-D is syntectonic. These rocks have been metamorphosed to the upper anchizone with rare epizonal samples. Diffraction data were treated using decomposition methods and the peaks identified were rationalised in terms of specific discrete or mixed layer illite/smectite phases.

Excluding the 14Å chlorite peak, three and sometimes four, elementary peaks are required for a good fit of the complex area of the diffraction pattern between 5 and 11°2TCuKα. A narrower peak, at higher 2T value (~ 8.79°2T), can be attributed to well crystallised illite (WCI), whereas a wider peak, at lower 2T values (~ 8.43°2T) is attributed to a poorly crystallised illite (PCI). A third elementary peak is mixed layer I/S that has varying percentages of the two components. The variation in the width of the WCI peak is smaller than that of the PCI peak, and, in the pretectonic succession, both peaks increase in width, as stratigraphically rocks become younger.

We have interpreted the different components giving rise to the three peaks in terms of the evolution of a prograde diagenetic - metamorphic sequence, with the WCI representative of the most advanced stage of illitization in response to burial. It might be expected that, at equilibrium, the WCI and PCI populations would have the same width value (such a tendency can be observed in the Cambrian-Silurian samples studied). In the Westphalian C-D samples both peaks are considerably narrower than in the older rocks. In this case we have interpreted the narrower peaks (WCI and PCI) as the signature of detrital micas inherited from the rapidly uplifting Variscan chain, that probably avoided any significant chemical weathering throughout their transport history. The I/S peaks(s) are regarded as recording the new phases formed during the retrograde evolution of these detrital micas.

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FMF1 : SUpo02 : PO
Thermal Evolution in the Townsville Hinterland of Northeastern Australia

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The Ordovician-Carboniferous sequences of the Townsville Hinterland of north-eastern Australia have been grouped into four tectonostratigraphic assemblages: the platform to continental slope Graveyard Creek and Camel Creek subprovinces separated by the obducted Gray Creek ophiolitic zone — construed as tectonically delineated tracts of a former single sedimentary-tectonic unit — and the successor Late Emsian-Early Carbonifeorus Burdekin

basin and Early Carbonifeous Clarke River Basin overlapping south-eastern portions of the Broken River Province. This contribution summarises the results of studies investigating the transition from diagenesis to low grade metamorphism for the Ordovician-Carboniferous sequences for these four tectonostratigraphic assemblages using K-white mica b dimensions and illite crystallinity (IC), together with the conodont colour alteration index (CAI) to give an indication of baric conditions and grade respectively.

CAI values are higher for the Broken River sequence (c. 5 for most conodont units) in accordance with the inferred burial depth of at least 7.4 km of post-Givetian stratigraphic units. The same applies for downslope equivalents of the Broken River sedimentary units in the Camel Creek area. The CAI data indicates a salient regional decline in heat flow having occurred late in the Givetian.

Illite according to XRD analyses, is the most common phase in the pelites studied. In most cases, however, it is accompanied by chlorite and/or the mixed layer chlorite/smectite (C/S) or chlorite/vermiculite (C/V). Glycolation results in a reduction of the IC values in some samples suggesting that minor quantities of illite/smectite (I/S) may also be present. A few samples contain kaolinite or smectite as discrete phases; these are most likely the result of weathering. Most samples yielded IC values within the anchizone limits for both air-dried and glycolated mounts with some rare epizonal values. For each of the sequences, average IC values increase with ascending stratigraphic position and are consistently lower in the Camel Creek region. There is a noteworthy decrease in grade at about the Middle-Late Devonian boundary. The K-white mica b dimensions range from 9.008Å and 9.029Å. The average value is consistent with medium-P/T metamorphic facies series conditions.

In spite of some local discrepancies between IC and CAI values, viewed as a whole, the data obtained confirm the primary pattern expected in accordance with the regional geology, that is that the Camel Creek subprovince experienced deeper burial and possibly higher heat flow during the Ordovician-Devonian interval than for adjoining regions. Both IC and CAI values register a regional decline in heat flow during the Givetian.

This is a contribution to IGCP421.

FMF1 : SUpo03 : PO
Illite as a Maturation Indicator in Irish Upper Palaeozoic Rocks and its Pitfalls

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Extensive studies have been undertaken to establish the thermal history of Irish Upper Palaeozoic rocks. Organic maturation indicators such as vitrinite reflectance and spore colour/fluorescence were used to estimate maximum palaeotemperatures. Clay crystallinity measured by the Kübler Index was used in conjunction with the organic data as an additional indicator of metamorphic grade.

Samples used in these studies include rocks from the Munster Basin, SW Ireland, the Clare Basin, SW Ireland, Ballycastle area, NE Ireland, and Kingscourt Outlier, E Ireland. These areas provide a range of geological settings. The Munster Basin represents a Variscan foreland basin with associated folding and the development of cleavage. The Clare Basin formed as a more distal Variscan foreland basin. In contrast to the relatively strong tectonic deformation of the Munster Basin, it exhibits only very gentle folding and no cleavage. Samples from the Ballycastle and Kingscourt areas have been collected from Carboniferous rocks that have been intruded by Tertiary Doleritic dykes.

All samples were run using standard XRD techniques to measure the Kübler Index. Preparations for crystallite size measurements followed recommendations by Eberl et al. (1998) in order to use 'MudMaster' (Eberl et al. 1996). Samples taken from the Munster Basin, which experienced tectonic deformation to varying degrees, show different illite crystallinity values, but similar crystallite sizes. On a larger scale, illite crystallinity values differ between the Munster and the Clare basins despite similar recorded vitrinite reflectances. A difference between the basins can also be seen in the illite crystallite size distributions. With proximity to the dykes there is a marked increase in illite crystallinity with increasing vitrinite reflectance. However, crystallite size measurements through the dyke aureoles are constant.

A preliminary interpretation of these results indicates that stress affects both illite crystallinity and crystallite size distribution, whereas time seems to be a controlling factor of illite crystallite growth.

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FMF1 : SUpo04 : PO
The Late Orogenic History of the Southeastern Cantabrian Mountains: Illite-Crystallinity and K-Ar Data

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The southeastern part of the Cantabrian Mountains is a zone where contrasting sedimentary facies, tectonic vergencies and zones of very diverse distributed low-grade metamorphism and diagenesis form a complex pattern. In the Valsurvio Dome area metamorphic degrees extends to the lower epizone with a high illite crystallinity and the association of paragonite and pyrophyllite. Lower crystallinities in the central part of the structure are explained by retention of crystal growth due to the calcaroues lithology, while a general increase of metamorphism towards that lower successions is observed by the breakdown of phyrophyllite to produce chloritoid and margarite.

To the north an interlocked metamorphic pattern from early diagenesis to epizone is displayed. As from the lower Carboniferous onwards the metamophic degree seem to be strongly dependent on the tectono-sedimentary position. Paleogeographically high areas show less influence while areas of rapidly subsiding basins with several km of filling had experienced up to low-grade metamorphic overprint caused by very high heat flux. This is corroborated by K-Ar dates which point to the transition of Westphalian to Stephanian. Additionally most of the northern part of the study area is influenced by small intrusive bodies and dykes. This led to an overprint of the diagenetic/metamorphic ages of sediments in the vicinity of the intrusions. The illite K-Ar dates of the samples do not correspond to tectonic events but to magmatic activities and - propably - to concomitant hydrothermal alterations of the sediments during Permian time (264-279 Ma). A few younger ages of 250 Ma and 176 Ma in the very fine grain-size fractions are still matter of debate. They may, for instance, record a further burial diagenesis during Mesozoic times. Alternatively, they could be mixed ages originated by a late influence of Alpine tectonic activities, which caused the uplift of the Cantabrian Mountains associated with southward thrusting and - locally - overturning of strata. If this is the case the extent of Alpine movements in the Cantabrian Mountains may have been underestimated up to now.

FMF1 : SUpo05 : PO
Episodic Neocrystallization of Phases in the Smectite-I/S-Illite-Mica Sequence in Hydrothermally Altered Rhyolitic Hyaloclastite (Ponza, Italy)

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Dioctahedral phyllosilicates in altered rhyolitic hyaloclastite from Ponza, Italy, were studied by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Samples come from a complete sequence from smectite to mica, as characterized by X-ray diffraction (XRD). Back-scattered electron (BSE) images show that samples retain original texture since clay minerals pseudomorph lapilli fragments and preserve vesicular textures. The lowest-grade sample contains obsidian clasts partially replaced by smectite. As alteration grade increases, the proportion of illite increases, with the occurrence of interstratified I-S, zeolites, illitic phases, feldspars and quartz. The most altered sample contains illite, mica and quartz. Lattice-fringe images show that the sequence proceeds through smectite, (R=1) I-S, highly illitic I-S, and illite plus mica. (R=1) I-S is the only interstratified phase detected, with a lack of interstratification between (R=1) I-S and either smectite or illite implying steps between discrete phases, including a gap in mixed-layering between (R=1) I-S and illite. BSE and TEM images show irregular cavities filled by subhedral dioctahedral clay minerals and mordenite, providing direct evidence for neocrystallization from a fluid. The presence only of discrete phases without features such as along-layer transitions at the TEM scale further implies that all clay minerals may have formed simultaneously by direct crystallization from fluids. This mechanism occurs without prior crystallization of, or transformations from, lower-grade I-S, and reaction progress may be determined by variations in temperature and/or rock/fluid ratio. Selected-area diffraction patterns indicate the predominance of 1 Md polytypism both in I-S and illitic phases, and the coexistence in the more altered samples of 1 Md illite and a 2-layer polytype mica (probably 2 M1), without the intermediate 1 M polytype generally assumed to exist in prograde sequences. XRD studies indicated progressive changes from cis-vacant, turbostratically stacked smectite, to interstratified cis- and trans-vacant, 1 Md I-S, to trans-vacant, 1 M illite, and then to 2 M1 illite in Ponza Island samples. There is a clear correlation between the chemical compositions determined by analytical electron microscopy and the proportion of cis-vacant determined by XRD, because both the distribution and composition of octahedral cations changes with increasing degree of illitization.

FMF1 : SUpo06 : PO
Low Grade Metamorphism in the Montagne Noire (S-France): Conodont Alteration Index (CAI) in Palaeozoic Carbonates and Tectonic Implications

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The Montagne Noire at the southern margin of the French Massif Central is a dome of LP gneisses (Zone Axiale) flanked by low-grade Palaeozoic sediments. In order to constrain the formation and exhumation of the metamorphic core, metamorphic studies were extended to the southern flank. CAI data were determined from c. 250 samples of Late Devonian to Early Carboniferous Limestones. The CAI values obtained range between 2 and 7. In the Arrhenius plot of Rejebian et al. (1987), these values would correspond to temperatures between c. 70 and = 500°C, for a heating period of 20 million years. As revealed by illite crystallinity and fabric studies in adjacent rocks, these temperature estimates are regarded as too high. The erroneous temperatures result from extrapolation of heating experiments carried out only over a few weeks to geological time spans. Nevertheless, CAI data permit to establish a relative zonation of metamorphism. High CAI values (i.e., higher metamorphic grades) are observed in areas close to the Zone Axiale, such as the northern part of the Minervois Nappe (CAI 5), the St.Pons area and the Par-Autochthon (CAI 5), and the Faugères unit (CAI 5-5.5). In the overturned limb of the Mont Peyroux Nappe, CAI is seen to decrease from the N (Antiform de Vieussan, CAI 5-5.5, rarely 6) toward the S (Synform der Roquebrun, CAI 2-3.5). Peak values around 6 occur in the crest of the Antiform of Vieussan. Weak metamorphic alteration also characterizes the Écailles de Cabrières in the E part of the Mont Peyroux Nappe (CAI 2-4). In samples with CAI 4 and higher, the conodonts as well as the encasing limestones often show strong ductile deformation. The areal distribution of CAI mirrors that of illite crystallinity data obtained by Engel et al. (1981). It appears that the metamorphic zonation in the S flank of the Zone Axiale continues the concentric pattern of isograds observed within the crystalline rocks (Demange 1985). This would imply, that peak metamorphism was attained after the assemblage of the tectonic pile, and during the exhumation of the hot gneisses of the Zone Axiale. This is also suggested by the observation that the CAI zonation cuts across the overturned limb of the Mont Peyroux Nappe: heating affected a sedimentary sequence which had already been overturned. Still, northerly parts of the Palaeozoic

sequence may have reached higher temperatures already during the phase of nappe stacking (see the discussion in the poster). We plan to complement our studies by O-Isotope thermometry and fluid inclusion studies.

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FMF1 : SUpo07 : PO
Fabric Rearrangement in Mudstones Assessed using High Resolution X-Ray Texture Goniometry (HRXTG): Towards a Quantification of Non-Mechanical Compaction?

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Previous studies of mudstone compaction have assumed it to be a purely mechanical phenomenon: the rearrangement of grains in response to an increase in (usually vertical) effective stress. The assumption is critical; the relationship between porosity and effective stress is one of the most basic equations within basin models and underpins the use of porosity as an indicator of pore fluid pressure in mudstones. We know of course that chemical and mineralogical changes occur in mudstones at all stages of burial. At low temperatures (say 601/4C), the changes probably have little influence on the rate of compaction. But above 601/4C, mineralogical changes become more pronounced, most obviously but not uniquely as a result of the conversion of smectite to illite. Textural, chemical, mineralogical and isotopic evidence all suggest that above ~601/4C, clay minerals continue to recrystallize throughout the diagenetic realm and on into low grade metamorphism (e.g. Hower et al. (1976), Yeh and Savin (1977), Peacor (1992)). A lack of systematic studies means that the effects of mineralogical change on the physical properties of mudstones are very poorly constrained. For example, we do not know to what extent mineralogical change drives change in the porosity and permeability characteristics of mudstones, or whether the changes result in adjustments to the mudstones' mechanical properties. Both seem likely; chemical compaction is a well known phenomenon in both carbonates and sandstones, and one would imagine that mineral recrystallisation cements and embrittles mudstones. The core of the problem is that it is difficult to quantify the extent to which the fabric of a mudstone has been altered by non-mechanical processes. Differentiation and quantification of the relative importance of mechanical and non-mechanical diagenetic change in mudstones is thus very problematic. We are using High Resolution X-ray Texture Goniometry (HRXTG; van der Pluijm et al. 1994) in an attempt to quantify the nature and extent of fabric changes within mudstones. By comparing the fabric changes with other changes in physical properties (porosity, pore size distributions, permeability, specific surface area), we are trying to identify and quantify the relative roles of mechanical and chemical processes on mudstone compaction. In this study we analyzed a sample set comprising mudstones (core material and cuttings) from various wells of the North Sea and Gulf of Mexico. By choosing samples of similar lithology and age but different thermal history, we show the effects of temperature on the particle orientation and compare these to changes in the physical properties of these rocks.

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FMF1 : SUpo08 : PO
Hydrograndites from Low-grade Altered Granitoids: A Mineral Chemistry Study using Electron Microprobe and Raman Spectroscopy

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Within Hercynian calcalkaline granitoids from the Massif Central (France) and Fichtelgebirge (Germany), secondary F-bearing hydrogarnet was identified. It is frequently associated with prehnite, pumpellyite and/or pistacite. Hydrogarnet generally forms elongated lenses parallel to the 001-cleavage of unaltered magmatic biotite. It shows a rather sharp contact to the host biotite, however fingering into the interstitial spaces between the biotite sheets. The hydrogarnets are composed of 47.3 to 73.2% andradite, 12.8 to 44.5% grossular and 2.6 to 12.7% hydrogrossular. Thus, the main variation is found within the Al_2O_2 - Fe_2O_2 ratio. The hydrogarnet frequently contains up to about 3% TiO_2 and up to 2% F, which are most probably inherited from the biotite host. Both, low SiO_2 contents and low analytical totals suggest significant quantities of water within the garnet structure. OH^- and also F^- may enter the garnet structure at the Si-position following the 'hydrogrossular substitution' $[SiO_4]^{4-}$ $[(OH,F)_4]^{4-}$. The calculated formula of the investigated hydroandradite-grossular may be written as $(Ca,Fe^{2+})_3(Al,Fe^{3+},Ti^{4+})_2(SiO_4)_{3-x}(OH,F)_{4x}$ with x = 0.1 to 0.35. Raman spectroscopy of hydrogarnet reveals significant peaks for OH. The intensity of the Raman OH-peak is positively correlated with the calculated water content based on microprobe data, since slightly higher OH-peaks can be observed for garnet grains with higher calculated water contents. The mineral stabilities of hydrogarnet, prehnite, pumpellyite and pistacite and the crystallization sequence - hydrogarnet predating prehnite and pumpellyite - suggests a retrograde alteration of the granitoid rocks. This retrograde formation results from a subsolidus alteration during cooling of the plutonic rocks early after intrusion and emplacement (Freiberger et al., in review).

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FMF1 : SUpo09 : PO
Hydrothermal Pyrophyllite in Diagenetic Grade Mudstones and Shales from the Cinera-Matallana Coal Basin of Northern Spain

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Pyrophyllite is known as a clay mineral that grows typically within a hydrothermal environment or during anchizonal metamorphic conditions. Equivalent minimum temperatures for the prograde reaction 1Ka + 2 Qz = 1Py + $1H_2O$ are given at around 240-260°C, as calculated from the system $CaO-Al_2O_3-SiO_2-H_2O$ (FREY 1987). We report the widespread occurrence of pyrophyllite in diagenetic grade mudstones and shales from the Stephanian Cinera-Matallana coal basin of northern Spain and suggest a hydrothermal origin. In this contribution, the clay mineral growth relationships are addressed and the conditions of formation discussed in context to the geological setting.

On the basis of vitrinite reflectance data (1.3-2.1% Rm, MENDEZ 1985), the maximum temperatures of the pyrophyllite-bearing pelitic lithologies does not appear to have exceeded ca. 200°C. Illite and chlorite crystallinity also indicate widespread diagenetic conditions, with only local diagenetic to anchizonal transitions. Based on over 100 samples from different structural positions within the coal basin, no relation is recognisable between subsidence, stratigraphical/structural position and clay mineral growth.

The mineral paragenesis of the pelites is illite, kaolin minerals, chlorite, quartz, pyrophyllite and minor amounts of albite. The most striking feature of this paragenesis is the coexistence of kaolin minerals and pyrophyllite within pelitic rocks of diagenetic range. To explain this coexistence we suggest polyphase clay mineral growth of metastable mineral phases occurred. The idea is supported also by the relation between illite and chlorite crystallinity, which indicate a disordered imbalance in the growth of their crystallites (WARR 1997). Polyphase formation is also evident from SEM investigations of the clay mineral phases, which display a variety of growth fabrics.

The presence of pyrophyllite in the diagenetic pelites of the Cinera-Matallana coal basin, forming apparently at temperatures <200°C, is not easy to explain. One possibility could be the lowering of the reaction temperature by the presence of methane (CH_4), derived from the maturation of adjacent coal beds. The complex relationship and interaction of fluid chemistry, lithology, temperature and pressure (lithostatic/hydrostatic) could be the reason for the growth of pyrophyllite at diagenetic temperatures.

The occurrence of syn- to post-tectonic intrusions (sills and dykes) in the lowermost formations of the coal basin could be inducing stages of polyphase clay mineral growth. Localised temperatures of up to 600°C were attained at igneous contacts to produce natural cokes (MENDEZ 1985) and circulating hydrothermal fluid temperatures of 200-300°C are considered likely. According to KISCH (1987) this type of clay mineral paragenesis is typical for coal basin sequences combined with intrusional activities. We therefore conclude that polyphase clay mineral growth was related to hydrothermal fluid conditions, leading to the formation of pyrophyllite in diagenetic grade rocks.

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FMF1 : SUpo10 : PO
Composition of Pumpellyite and Chlorite from New Caledonia- How Important is Metamorphic Grade and Whole Rock Composition?

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During Eocene time, New Caledonia was involved in a collision with an island-arc system. This collision generated in the north of the island a HP-LT schist belt. The Poya nappe containing pillow basalts, pelagic sediments, dolerites and gabbros was thrust over the HP-LT schist belt from NE to SW, which in turn was immediately covered by another ophiolite nappe. The Poya nappe represents the upper part of a slice of oceanic crust and the ophiolite nappe is considered to be part of the lower oceanic crust and includes also ultramafic rocks. In central New Caledonia, a Pre-Senonian sequence contains a disrupted ophiolitic suite with a volcano-sedimentary cover, which was affected by a probably Cretaceous metamorphic event.

In the HP-LT schist belt, the field gradient of the Eocene metamorphic event increases from SW to NE ranging from pumpellyite-prehnite assemblages through blueschist facies and glaucophanitic greenschist assemblages to eclogites. In the ophiolitic suite, an increasing field gradient of the Cretaceous metamorphic event is observed from NE to SW or from E to W, ranging from pumpellyite-prehnite to blueschist facies.

In the Poya nappe, the mineralogical assemblage of the metabasalts is composed of Prh±Pmp+Chl+Ab+Qtz±Ms±Ttn±sulphides whereas the sediments contain Ab+Chl+Ms+Qtz. In the HP-LT belt, the metabasalts show a mineralogical assemblage of Rbk±Ms±Ep±Pmp±Act±Stp±Chl+Ab+Qtz±Ttn±sulphides and the sediments are characterized by the assemblage Ab+Chl+Ms+Lws+Stp or Ab+Chl+Ms+Qtz+Gln depending on metamorphic grade. In the ophiolitic suite, the mineralogical assemblage of the metabasalts is composed of Pmp+Chl+Epi±Ms+Ab+Qtz±Ms±Ttn±sulphides and the sediments show Ab+Chl+Ms+Lws or Ab+Chl+Ms+Qtz+Gln.

The pumpellyite compositions (determined by EMP analysis) for all analyzed metabasalts are Al-rich with a ratio for Al/(Al+Fe+Mg) between 0.70 and 0.90. Data seem to indicate that the composition of the pumpellyites is not a function of metamorphic grade nor of whole rock composition. Total aluminium content of chlorite and pumpellyite show a good correlation independent of metamorphic zone. The composition of pumpellyite of a metapelite within the ophiolitic suite shows a shift towards more Mg-rich compositions as compared to pumpellyite in the metabasalts. In a diagram of non-interlayer cations versus Al_{total} (apfu) the chlorites of the metapelites cluster close to the clinochlore end-member with a trend toward the sudoite end-member. In contrary, the chlorites of the metabasalts associated with the above mentioned metapelites fall within the clinochlore field with a trend towards smectite/chlorite mixed-layering.

FMF1 : SUpo11 : PO
Tectonic Structure of the S Flank of the Montagne Noire (S-France)

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The Montagne Noire at the S margin of the French Massif Central consists of a dome of LP gneisses (Zone Axiale) surrounded by low-grade Palaeozoic sediments. Deformation of the Palaeozoic sequence on the S flank of the dome is characterized by originally recumbent folds, which were later refolded into large, open syn- and antiforms. The grossly southward facing of the recumbent folds has traditionally been taken to indicate tectonic transport of fold nappes toward S. Low-grade metamorphism (see contribution by WIEDERER et al.) as well as tectonic strain are seen to increase from S to N, i.e., towards the Axial Zone (ARTHAUD 1970). In the northern part of the profile, Devonian to early Carboniferous fine-grained limestones and radiolarian cherts show a strong, ENE-trending stretching lineation. We have found out, that the S-facing folds, described from this area represent, in fact, the flanks of non-cylindrical folds with antiparallel hinges. This means that tectonic transport was not directed perpendicular, but parallel to the trend of the orogen. Biostratigraphic considerations and shear criteria suggest that the non-cylindrical folds were formed in a regime of simple shear with top to the ENE displacement of the southern and higher units. This kinematic pattern is the same as that observed in the gneisses in the Zone Axiale. It is suggested, therefore, that the non-cylindrical folds in the Palaeozoic mantle have once been kinematically coherent with the Zone Axiale. In Devonian early diagenetic dolomites, which structurally overlie the fine-grained carbonates, top-to-the-E transport was performed by brittle thrusting. It appears that the non-cylindrical folds owe their formation to a favourable combination of elevated temperatures and rheologically weak lithologies. Since the zonation of strain and low-grade metamorphism cut across the inverted limb of the Mont Peyroux fold nappe, we propose that the non-cylindrical folds developed after the formation of the recumbent fold nappes. This observation, together with the parallelism of non-cylindrical folds and stretching in the gneisses, suggest that the non-cylindrical folds were formed during the exhumation of the Zone Axiale. Structure and fabric relating to the emplacement of the fold nappes have only survived in higher levels such as the Pardailhan nappe, where ECHTLER (1990) has described tectonic transport toward the SW. Models for the exhumation of the gneisses are discussed in the contribution by FRANKE.

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FMF1 : SUpo12 : PO
Exhumation of LP Gneisses in the Montagne Noire (S-France): Isotopic Constraints

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The Montagne Noire at the S margin of the French Massif Central belongs to the S flank of the Variscan orogenic collage. It contains a core of LP/HT gneisses and granites (Zone Axiale), flanked by very low grade Palaeozoic sediments. Exhumation of the gneisses probably occurred in a pull-apart setting in an EW-trending dextral shear zone (see discussion in the contribution by Franke). Late Viséan/earliest Namurian flysch sediments have been incorporated into crustal stacking, and a Stephanian half-graben at the eastern termination of the Zone Axiale is the latest increment of EW-extension. Hence, the tectonic evolution must be bracketed between c. 325 and 295 Ma. Tectonic observations in the eastern Zone Axiale indicate that the main foliation was formed during E-directed normal faulting which propagated toward the E. At the same time, the Zone Axiale was shortened in N-S. Therefore, older shear zones were folded, while new, flat ones were being formed in higher levels to the E. Granitoid melts intruded at various stages of this process. Rb-Sr data of Hamet & Allègre (1976) indicate a first, syn- to late-orogenic peak of magmatic intrusion at c. 330 Ma, followed by a second, post-orogenic phase at c. 290 Ma. The late-tectonic Vialais granite (Brunel et al. 1997) crystallized during the first phase (U-Pb monazite and zircon ages of 327±5 Ma, Matte et al. 1998). In the Gorges d'Héric of the eastern Zone Axiale, we have sampled a suite of granitoid dikes: aplite dikes with a relatively strong tectonometamorphic overprint, two generations of coarse-grained pegmatites with decreasing grade of deformation, and one undeformed microgranite. U-Pb dating of a single zircon from a foliated aplite dike yielded a concordant age of 313±1 Ma, which dates magmatic crystallization. This indicates that ductile shearing and refolding were still active in Westfalian time (time-scale of McKerrow & Van Staal, 2000). Subsequent rapid cooling is documented by a Ar-Ar biotite age of 316±4 Ma from neighbouring orthogneisses (Maluski et al. 1990). The youngest ages of micas from the S margin of the Zone Axiale give 297±3 Ma (Maluski et al. 1990). Taken together, the available isotopic data indicate that exhumation of the Zone Axiale was active from the Viséan/Namurian boundary up to Stephanian times, i.e., extended over a time-span of c. 30 Ma. This argues against the latest Carboniferous "orogenic collapse" evisaged by Van den Driessche et al.(1991), see also Matte et al. (1998).

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FMF1 : SUpo13 : PO
Exhumation of LP Gneisses in the Montagne Noire (S-France): The Collapse has Collapsed

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The Montagne Noire at the southern margin of the Franch Massif Central is a complex antiform with a core of granites and LP/HT gneisses (Zone Axiale), encased between EW-trending, dextral strike-slip faults. The core is overlain by a mantle of very low grade Palaeozoic rocks. The reduction of the metamorphic profile implies crustal extension. A prominent stretching lineation indicates transport to the W at the W end and to the E at the E end of the Zone Axiale. Diapiric rise of low-density, felsic rocks (Faure 1995) may have eased the ascent of the metamorphic rocks, but cannot be the main cause, since the kinematic evolution is clearly strike-slip controlled. Orogenic collapse in latest Carboniferous time (van den Driesche & Brun 1992, Echtler & Malavieille, 1990) is contradicted by the early Carboniferous age of the main ductile deformation (Matte et al. 1998). The collapse model also fails to consider the importance of strike-slip movements and of orthogonal (NS) shortening. On the other hand, NS-shortening alone (Matte et al. 1998) or transpression (Demange 1999) cannot explain the reduction of the metamorphic profile. It is proposed instead, that the LP gneisses of the Zone Axiale represent a solid-state, low-density intrusion into a growing pull-apart structure, which, at the same time, underwent NS-shortening. EW-extension, vertical shortening and NS-shortening combined imply a prolate bulk strain, which is often observed in ortho-augengneisses of the Zone Axiale. Examination of the Palaeozoic schist mantle has revealed that the internal part of the schist mantle originally formed part of the metamorphic core (contributions by Doublier and Wiederer). Contraction of the Zone Axiale into its present contours probably occurred when the core cooled down, and marginal parts sequentially "froze" to the cool, rigid frame. We are presently trying to constrain the growth and contraction of the pull-apart dome by isotopic dating of zircon and monazite (contribution by Klama & Dörr). Our new data demonstrate that exhumation of the Zone Axiale was controlled by plate margin rather than body forces: the collapse model has collapsed.

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Monday AM Session

FMF1 : MOam02 : F4
Isotopic Constraints to Illitization Process: A Review

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Illitization is a widely studied and recognized record of water-rock interactions in sedimentary-rock systems. It was detailed in many ways from mineralogical to isotopic insights, from cristallographic to morphologic aspects. Different models were suggested based on open or closed system evolution throughout a dissolution-precipitation or a solid-state transformation pathway. However, a general consensus has not yet been reched, and it is envisaged in this presentation dedicaded to two giants of this research field, to review the inputs of isotopic studies to the understanding of this process. Recent isotopic studies were applied to illite fundamental particles separated from illite/smectite mixed-layers (I/S) of bentonite units. The thickness of these particles (<0.03 microns) allows to envisage that they represent the initial germs and that their study will improve our knowledge of how illitization initiates and progresses. This isotopic approach has been detailled for illite fundamental particles of two diagenetic I/S mixed-layers collected in two bore holes located closely in the same sedimentary basin, and of a hydrothermal I/S collected nearby. The K-Ar and Rb-Sr systematics and the oxygen isotope compositions of several size fractions consisting in illite fundamental particles of progressive thickness and in particle aggregates allow to discuss the period of illitization, its duration, its physical and chemical conditions, as well as cinetic aspects of the reaction during the whole process. Comparison of these results with some obtained on similar fundamental particles extracted from sandstones and shales, outlines a lithology-dependent behavior suggesting that fundamental aspects such as dissolution-precipitation and solid-stade transformation are monitored by the host-rock type. In summary, isotopic tracing and dating of the illitization process in varied host-rocks points to essential clues of the process such as period, duration, conditions and cinetic.

FMF1 : MOam03 : F4
Constraining Timing of Dyke Emplacement and Alteration in the Northern Sydney Basin, Australia

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The Sydney Basin of eastern Australia is composed of Permian and Triassic sedimentary strata including economically significant coal deposits, and minor igneous intrusions that have deleterious effects on coal mining. Dating the emplacement of these intrusions has been hampered by the alteration of primary minerals to secondary clays (kaolinite/illite) and carbonates by interaction between magma and fluids from the coal. In the present study K-Ar age data for illite from altered, basaltic dykes located near Dartbrook in the northern part of the basin are presented.

Eight samples from four altered, basaltic dykes were selected and disaggregated using a gentle freeze-thaw technique. Grain size fractions (<1, 1-2 and 2-6 microns) were separated and characterized by XRD, SEM, TEM and laser granulometer. XRD traces indicate that kaolinite and illite/smectite are the major clay mineral components with no major additional K-bearing phase being present. K-Ar data for authigenic illite from these fractions yielded 22 ages ranging from 109.6 to 69.2 Ma.

The <2 micron fractions recovered for three samples from three relatively thin dykes consistently record 80-84 Ma ages. These ages are interpreted to reflect the approximate time of emplacement of these dykes on the basis that growth of authigenic illite is presumed to commence during initial alteration during magma emplacement.

The other five samples originate from a 14 m horizontal section (~60% altered igneous rock and ~40% cindered coal) through a single dyke. The intensity of alteration decreases inwards from the margins towards the centre of the intrusion. The K-Ar ages for the <1 micron fractions for four samples along this section decrease with increasing distance from the margin towards the core of the dyke (96, 84 and 73 Ma) and increase again at the other margin (96 Ma). These ages record the timing of different alteration events with the outer part of the intrusion being altered at the time of emplacement at ~96 Ma, and the progressively younger ages recording the timing as alteration pervaded farther into the intrusion.

The major tectonic activity that affected the whole Sydney Basin was doming and initial rifting of the Tasman Sea which caused rapid uplift and erosion 100-70 Ma, together with attendant intrusive igneous activity responsible for the elevated coal rank in the basin. The coincidence between this 70-100 Ma interval and the range of K-Ar illite ages recorded from Dartbrook intrusions provides additional evidence for the timing of this major event. The current study implies that K-Ar dating of authigenic illite from altered dykes provides a viable mechanism for dating the emplacement of altered intrusions.

FMF1 : MOam04 : F4
Parameters Controlling the Process of Volcanic Glass Palagonitisation

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The chemical composition of palagonite and the thickness of palagonite rinds were studied as a function of parent material composition, alteration environment and time by applying a range of analytical methods (EM, AFM and XRD). Our goal was to determine the influence the following parameters might have on the process of glass palagonitisation:

(1) climate (annual rain fall, average annual air temperature); (2) hydrogeologic system; (3) initial fluid properties (composition, pH, Eh, temperature); (4) glass composition; (5) glass structure; (6) properties of the interfacial region between glass and altering fluid and later palagonite and altering fluid.

Despite the fact that the initial altering fluid leaves a compositional 'finger print' in the palagonite (seawater derived palagonite having higher Na- but lower Ca-concentrations than palagonite formed during meteoric alteration), the general lack of correlation between palagonite composition, palagonite structure, palagonitisation rate and the parameters climate, hydrogeologic system, initial fluid properties, glass composition and structure suggests that the process of palagonitisation as a whole is controlled by the properties of the interfacial region. We conclude that the parameters (1) to (5) provide the general setting being either favourable or not favourable for the formation of palagonite. Favourable conditions given (sufficient supply of aquatic fluids, low enough fluid flow rate, initial fluid-pH of 5 to 8, presence of mafic glasses) palagonite precipitation will proceed controlled by the properties of the interfacial region between glass and fluid - respectively later glass, palagonite and fluid.

FMF1 : MOam05 : F4
Geochemical Variations during Early Low-Temperature Alteration in Young Mid-Ocean Ridge Basalts

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Mid-ocean ridge basalts are affected early after their eruption by a low-temperature alteration process characterized by the formation of 'black halos', before halmyrolysis starts at about 2 my. Black halos, ranging in thickness from <1 to 30 mm, are parallel to exposed surfaces and cracks, and surround a core of generally fresh rock. They result from the filling of primary voids, e.g, cracks, vesicles and miarolitic cavities, by various secondary minerals (smectites, celadonite and Fe-oxyhydroxides) without replacing the primary minerals.

The aim of this paper is to characterize the mechanisms and geochemical fluxes associated to the formation of black halos. The study samples were drilled into the flanks of the Galapagos Rift (Galapagos Spreading Center, Pacific Ocean) : 26 pairs, i.e. one halo and one corresponding fresh core from DSPD sites 506 (0.54 my), 424 (0.62 my), 507 (0.69 my), 508 (0.85 my), 425 (1.8 my) and 510 (2.8 my) were analyzed. Site 510 samples exhibit the beginning of halmyrolysis which also affects the core. Some samples from site 425 also show a slight alteration in the core.

Compared to fresh cores, black halos are enriched in ^{18}O, Fe^{3+}, K, Rb, Cs, B and H_2O^+, whereas their Fe^{2+} and Mo contents are smaller. Ba, U and Th do not show systematic variation. All of the other analyzed elemental concentrations are unchanged. The enrichment in alkali elements is explained by the crystallization, within the black halos, of the secondary phyllosilicates from an oxidizing fluid, i.e. probably a mixture of seawater and hydrothermal fluid. The Fe enrichment is progressive until 1.8 my and may result from two sources : (1) an external source such as a seawater-derived hydrothermal fluid circulating along exposed surfaces; (2) an internal source : the fresh cores have been affected by the maghemitization releasing iron which would diffuse from the cores into the black halos. A combination of the two hypotheses is also possible.

Bulk rock oxygen isotope analyses indicate a systematic $\delta^{18}O$ increase in the black halos. The mean value of the black halos for each site also increases with age. These results suggest that the secondary minerals formed at low temperature, and their total amount increased with time until about 1 my. The bulk rock $^{87}Sr/^{86}Sr$ data show no or little variations, without simple, systematic correlation with the other geochemical tracers.

FMF1 : MOam08 : F4
Chlorite Composition Controlled by Whole-Rock Geochemistry; A DRX-EMPA-HRTEM-AEM Study in Cambrian Basaltic Rocks from the Ossa Morena Zone, SW Spain

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Chlorite is one of the most common very low-grade metamorphic minerals filling vesicles in basaltic rocks. Its composition has been usually used as an indicator of the metamorphic grade, and some empirical geothermometers has been proposed. Also, in these mafic systems, the evolution from smectite to chlorite with increasing temperature is well documented. This transition is normally expressed as the Xc (chlorite content) value, which range from 0.0 (pure smectite) to 1.0 (pure chlorite). In Cambrian formations from the Zafra area (Ossa Morena Zone, SW Spain), a metamorphic evolution from diagenesis to epizone has been previously documented (Lopez-Munguira et al., 1998, Lopez-Munguira & Nieto, 2000). Porphyritic plagioclase basaltic vacuolar lavas, intercalated with shales, are in the upper zone of this sequence. Secondary minerals neoformed in these shales are typical of the diagenesis conditions (IC = 0.50 ±0.07, b0 = 8.997 ±0.005). Good correlation between whole-rock geochemistry and chlorite composition has been found. Meanwhile, chlorites filling vesicles are characterised by relatively high Xc values, as determined from the microprobe data. They range from 0.81 in the top to 0.98 in the bottom (almost 900 m deeper). The application of the empirical Cathelineau's geothermometer gives temperatures ranging from 285 to 350ºC. Both Xc and temperature calculations are too high for the diagenetic conditions stablished according to the interestratified-shale mineralogy. HRTEM study indicates the complete absence of any smectite layer in the structure of these chlorites; that is, according to lattice images the actual value of Xc is 1. The explanation to the chlorite composition in these basaltic lavas must be in relation with their whole-rock geochemistry. They are characterised by low MgO values (3.08 ±1.53%), high total iron (13.99

±1.30%) and relatively high FeO/MgO ratios (3.28 ±1.66). In this particular case, these basaltic rocks are not a typical Mg-rich system, and must be considered as an Fe-rich system, with similar behaviour to those of the pelitic rocks. In these Fe-rich systems, direct chlorite formation, without a previous smectite precursor, is a normal case and, consequently, the Xc calculations, as well as some empirical geothermometric calculations, are not adequate.

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FMF1 : MOam09 : F4
Chemical and Structural Evolution of Phyllosilicates in Associated Low-T Metamorphic Pelites and Basic Magmatites: A Case Study from the Graz Paleozoic, Eastern Alps, Austria

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Reaction progresses of chlorite and dioctahedral K-mica from various lithologies (pelitic-marly metasedimentary rocks, metatuffs, -tuffites, lava and subordinately, intrusive rocks of mostly basic composition) are compared using XRD, EMP and bulk rock major element composition data. Samples derive from various nappes of the Graz Paleozoic, Upper East-Alpine Nappe System. The grades of mostly Variscan regional alteration of the Silurian and Devonian samples span between late diagenesis (prehnite-pumpellyite facies) and epizone (greenschist facies), representing mainly the anchizone.

Obvious discrepancies found between the EMP data (obtained necessarily from larger grains or aggregates) and XRD properties of <2µm fraction samples prove metastable inequilibrium conditions. XRD illite crystallinity (IC) indices measured on air-dried and glycolated mounts refer to decreasing amounts of swelling mixed-layers with increasing grade. By contrast, no correlation was found between IC and total interlayer charge, indicating that EMP-measured larger authigenic mica flakes reflect more evolved stage in reaction progress as compared to the matrix-forming finer-grained population. In addition, IC shows significant positive correlations with celadonite content and with $Fe^{2+}/(Fe^{2+}+Mg)$ ratio, referring to effects of bulk rock chemistry (lithology).

Differences in chlorite crystallinity (ChC) indices measured on air-dried, glycolated and Mg-saturated mounts refer to subordinate amounts of swelling mixed-layers in chlorite, the amounts of which seem to decrease with advancing grade. EMP data from larger grains or aggregates represent more evolved stage than that indirectly implied for matrix-forming chlorite from XRD data. Chlorite end member ratios were calculated from those analyses which prove poor chloritic phase ($Ca+Na+K<0.05$ pfu.). In addition to the $Fe^{2+}Mg_{-1}$ and Tschermak's substitutions, the di-trioctahedral substitution plays also an important role in chlorite chemistries. However, the proportion of sudoite end member is generally lower than 0.2. Although the compositional ranges are strongly overlapping, chlorites from metasedimentary rocks are characterized by mostly higher amesite and sudoite, chlorites from metabasic lava and intrusive rocks with higher clinochlore+daphnite contents. Chlorites of metatuffs and -tuffites are of intermediate compositions. ChC indices show significant negative correlations with Al^{iv}, and Al^{vi} contents, while no relation was found with Fe^{2+}/Mg ratios.

Thus, in addition to swelling mixed-layered inpurities, crystallite size and lattice strain relations, IC and ChC are also influenced by chemistries of illite-muscovite and chlorite, which, in turn, are related to bulk rock compositions. Having considered the bulk rock effects, XRD chlorite crystallinity proved to be a reliable tool for estimating relative differences in metamorphic grade.

FMF1 : MOam10 : F4
Hydrothermal Origin of Pumpellyite-Amphibole Parageneses in Subgreenschist Facies Metabasites, Sierra Nevada, USA

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The association Pmp - Prh - Amph - Chl - Ep - Ab - Qtz is common in regionally metamorphosed, very low grade, volcanic rocks. Thermobarometric calculations and the petrogenetic grid of Frey et al. (1991) suggest that such assemblages represent normal metamorphic field gradients of 20 - 33 °C/km (Beiersdorfer and Day, 1995). In Jurassic rocks of the northern Sierra Nevada, this assemblage also occurs in hydrothermal aureoles formed where metadiabase intrudes metavolcanic rocks. Several mineralogical features distinguish the hydrothermal association from the more common regional metamorphic assemblage. Actinolite ($Ca > 1.92$; $Na+K < 0.08$; $Fe < 2.22$; calculated on 23 O) is the common amphibole in Prh-Pmp facies metavolcanic rocks that are not affected by hydrothermal alteration. Amphibole in the hydrothermal assemblages is sub-calcic hornblende, edenite, or actinolite ($Ca = 0.96$-1.42, $Na+K = 0.20$-0.73; $Fe = 1.97$-5.0) in which the deficiency of Ca in the "B" site is satisfied primarily with Fe. This amphibole contains substantially higher Fe^{3+} (0.70-1.91 Fe^{3+}; 15eK calculation) than the regional actinolite (< 0.5 Fe^{3+}). Pmp, Ep, and Prh in the hydrothermal association also are more oxidized than their regional metamorphic counterparts and rare andradite is present. The partitioning of Fe^{2+} and Mg between coexisting phases is also different in the two associations. In the regional assemblage, Pmp is mostly more iron-rich than coexisting Chl, and Act is more magnesian than both Chl and Pmp. In the hydrothermal association, Pmp is more magnesian than coexisting Chl, and the hydrothermal amphibole is commonly more iron-rich than either the Chl or Pmp. Independent evidence suggests that the unusual amphibole-bearing association was formed in an hydrothermal environment. This unusual assemblage is common to intrusive diabases and volcanic rocks within a five km² area, which is completely surrounded by Pmp-and Prh-bearing volcanic rocks with the typical regional assemblage. The sub-calcic, iron-rich amphiboles are found as rims around amydules enclosed in the Pmp-bearing groundmass of volcanic flows that are otherwise barren of amphibole. This suggests that the location of the amphibole is controlled in part by the original porosity of the rock. We also find isolated, monomineralic patches of amphibole that are cut by late Pmp veins. We infer, therefore, that the sub-calcic amphibole and Pmp, were formed by hydrothermal interactions during the intrusion of the mafic diabases into the volcanic sequence. If our interpretation is correct, the presence of similar amphibole in other metamorphosed diabases (Munha and Kerrich, 1980; Offler, 1984) suggests that metamorphic assemblages previously attributed to very low-grade, regional metamorphism in other arcs and ophiolites may have had a similar hydrothermal or autometamorphic origin.

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FMF1 : MOam11 : F4
The Very Low-Grade Metamorphism of the Portage Lake Volcanics, Keweenaw Peninsula/Michigan/USA– Results Based on Stable Isotopes (O, H, C) and Fluid Inclusions

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Exploration and mining of the native Cu-deposits in the ca. 5 km thick Keweenawan (Precambrian) Portage Lake Volcanics (PLV) on the Keweenaw Peninsula, Michigan/USA have provided drill core material which was studied with respect to the hydrothermal and burial metamorphic history of the sequence. Eleven drill cores were selected which represent three vertical profiles throughout the PLV along an E-W-profile on the Upper Peninsula. The drill cores were correlated stratigraphically by different interbedded sediments.

Two different very low-grade metamorphic facies are distinguished within the lava flows of the PLV. An older prh-pmp-facies is observed mainly in amygdules and in early veins. A younger zeolite-facies overprints the older very-low grade metamorphic mineral assemblage and is found in some amygdules and in all cross-cutting, later veins.

The range for the stable oxygen isotope composition of the phyllosilicates of the prh-pmp-facies is around 4 to 14 per mille. The values decrease with stratigraphic depth or from stratigraphically younger to older flows. This is characteristic for an increase of temperature during metamorphism. The same trend is also observed for epidote ($\delta^{18}O$ between 5 and 7 per mille) and quartz ($\delta^{18}O$ between 14-17 per mille) which are considered to have formed contemporaneously during the same conditions. Fluid inclusion populations in quartz show a low-salinity - high temperature fluid which is consistent with the temperatures derived from the mineral assemblages of the prh-pmp facies. The zeolite facies (laumontite and wairakite) or the youngest hydrothermal event ends with a late calcite filling. The oxygen stable isotope composition of this calcite shows significantly higher $\delta^{18}O$ values and ranges from 20 to 27 per mille. The values of calcite are interpreted as having formed from a different fluid as compared to the early formed phyllosilicates of the prh-pmp facies. The study of the fluid inclusion populations confirms that the calcite precipitated from another fluid characterized by a low salinity and low temperature.

The pattern observed based on mineral assemblage and stable isotope composition of secondary minerals as well as the fluid inclusion population points to a burial metamorphic event with a high geothermal gradient followed by a later and cooler hydrothermal event.

FMF1 : MOam12 : F4
Low Grade Metamorphism in the Argentine Precordillera: A Record of Extension at the Margin of Gondwanaland?

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The Precordillera terrane of western Argentina is a Late Tertiary fold and thrust belt exposed in the foothills of the Andes, but is believed to be a terrane developed on the margins of Gondwanaland and later accreted onto South America. Here we examine the character of the Palaeozoic metamorphism as a means of resolving the origin of this terrane (Dalziel et al., 1994). The succession in the eastern part of the Precordillera is dominated by Cambrian to Ordovician platform carbonate rocks, while in the west there are Ordovician clastic basinal sediments and intercalations of basic pillow lavas, layered mafic intrusions and ultramafic bodies.

The metamorphic character of the region has been established from examination of some 60 samples of basic igneous and clastic rocks. Silurian and Ordovician pelitic samples have IC values indicative of an increase from diagenetic level through anchizone values implying an increase in grade from east to west.

The basic igneous rocks mostly show assemblages diagnostic of either prehnite-pumpellyite facies or greenschist facies metamorphism. Plotted on an epidote projection, the samples show consistent trending tie-lines for the actinolite - chlorite pairs, suggestive of an equilibrium relationship, while the pumpellyite - chlorite pairs are more variable suggesting a less equilibrated relationship. These results confirm the general increase in grade from east to west. The development of extensive prehnite-pumpellyite facies assemblages indicates that the metamorphism is not of an ocean-floor hydrothermal metamorphic character as previously suggested for this sequence.

The samples can be constrained by the petrogenetic grid for the NCMASH system as representing lower pressure conditions of <4 kbar. Overall, the character of the meta-

morphism is suggestive of a low-pressure setting with higher than normal thermal gradients, and thus is not in accord with previous suggestions of metamorphism in an early Palaeozoic subduction zone lying to the west of the Precordillera (Gosen, 1997). This area of the Precordillera has evidence of large-scale mid-Ordovician to Silurian extensional tectonics (Gosen et al., 1995). In addition recent work on mafic and ultramafic units of the Precordillera has indicated that they do not represent an ophiolite association, as previously suggested, but represent a range of units with ages from 580 to 418 Ma (Davis et al., 2000). The characteristics of the higher level units of these complexes are interpreted as providing strong support for generation in a well-developed rift setting. Thus the initial results of the work on the metamorphic character of these rocks provide supporting evidence that the metamorphism is more closely linked to the extensional development of the basin, at the margin of Gondwanaland, rather than to the tectonics linked to the basin closure, in keeping with the findings of Davis et al. (2000).

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FMF1 : MOam13 : F4
Low-Grade and Contact Metamorphism in Volcanic and Volcaniclastic Successions, Rio Tinguiririca Valley, Central Andes of Chile

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A ca. 6000 m thick section of mainly volcanic, volcaniclastic and a few marine sedimentary rocks is exposed in the upper Rio Tinguiririca valley comprising the Upper Jurassic Rio Damas Formation (4000 m), shales of the Upper Jurassic Banos del Flaco Formation (390 m), conglomerates and sandstone of the Cretaceous Brownish-Red-Clastic Unit (BRCU, 250 m) and volcanic and volcanoclastic units of the Tertiary Coya-Machali Formation (ca. 1600 m). Two metamorphic zones are observed. A zeolite zone with laumontite as the main index mineral in the Tertiary Coya-Machali Formation, as well as in the upper Cretaceous Brownish-Red-Clastic Unit and the Upper Jurassic Banos del Flaco Formation. The Upper Jurassic Rio Damas Formation lying below the Banos del Flaco Formation has experienced prehnite-pumpellyite facies in the lower part of the unit, wheareas the upper part displays a non-diagnostic celadonite-K-mica-chlorite assemblage. No discontinuity in metamorphic grade is observed along the major unconformities, as between the Tertiary Coya-Machali Formation and the Cretaceous Brownish-Red-Clastic Unit or the Cretacous Brownish-Red-Clastic Unit and the Upper Cretaceous Banos del Flaco Formation. In the Coya-Machali Formation, higher metamorphic prehnite-pumpellyite assemblages are observed within sills and dikes. In addition, illite crystallinity, chlorite crystallinity and coal rank were determined and confirm the metamorphic facies pattern. The minimal formation temperatures of a fluid inclusion study in veins and amygdules agree well with the temperature estimates from the other methods. The Coya-Machali formation, belonging to the zeolite facies, yield values of 220-280°C based on the "chlorite geothermometer" and minimum temperatures of 140-190°C based on fluid inclusion data. The Ba-os del Flaco Formation has experienced conditons of the late diagenetic zone according to illite and chlorite crystallinity data. Vitrinite reflectance data indicate peak temperatures of 150-170°C for a burial metamorphic model and 170-205°C for a hydrothermal metamorphic model. The Rio Damas Formation recording the transition from zeolite to prehnite-pumpellyite facies, yield values of 220-270°C based on the "chlorite geothermometer" and minimum temperatures of 290-310°C based on fluid inclusion data. The mineral chemistry of the alteration minerals was determined. Pumpellyite shows a broad compositional range with FeO values between 13 and 30 wt%. In contrast to other low-grade metamorphic terranes where the smectite to chlorite transition is characteristic going from the zeolite to a prehnite-pumpellyite zone, a K-mica/celadonite transition occurs which seems to be characteristic of the K-rich rocks of the study area.