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Middle/Upper Devonian tuffs and Eo-Alpine tectonic evolution in the central Western Greywacke zone, Austria

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Abstract

Greenschists intercalated within calcareous phyllites of the Western Greywacke zone of the Eastern Alps yield a U-Pb zircon age of 384.5±1.9 Ma enabling dating of the calcareous phyllites at the Middle to Upper Devonian boundary. No such facies has been dated until now in the fossil-bearing respectively low-grade metamorphic Austroalpine basement and we here introduce the term Hochglocker facies for this unit. The Hochglocker facies occurs in the limb of a kilometer-sized ESE-plunging synform, which is mantled by thick dolomites and marbles of assumably Early to Mid Devonian age, and a thick succession of grey phyllites intercalated by greenschists and Silurian graphitic phyllites. At the outcrop-scale, the area is dominated by two stages of ductile deformation structures. The entire area is dominated by penetrative foliation S1 and a gently ESE plunging stretching lineation L1 which formed during Cretaceous low-grade metamorphic conditions. The S1 foliation is refolded by tight upright ESE-plunging D2 folds with a steep WNW-trending axial plane foliation indicating Cretaceous-aged NNE–SSW shortening.

Das U-Pb-Zirkonalter von 384.5 ± 1.9 Ma einer Grünschieferlinse in einer Abfolge von karbonatischen Phylliten der westlichen Grauwackenzone (Ostalpen) erlaubt die Einstufung dieser Abfolge an die Mittel-/Oberdevongrenze. Eine faziell und altermässig vergleichbare Abfolge (Mergel/Kalkmergel mit eingeschalteten basaltischen Vulkaniten) ist bisher aus dem ostalpinen Sockel nicht bekannt und wir schlagen für diese Einheit den Arbeitsbegriff Hochglockerfazies vor. Die Hochglockerfazies tritt im Arbeitsgebiet in einer engen ESE-abtauchenden Synform auf, die von fraglich unter- bis mitteldevonischen Dolomit- und Kalkmarmoren tektonisch überlagert und silurischen Graphitphylliten mit seltenen Grünschiefereinlagerungen ummantelt wird. In Aufschlüssen können zwei Stadien duktiler Deformationsstrukturen erkannt werden: Dieses Segment der westlichen Grauwackenzone ist von einer penetrativen Schieferung S1 und einer flach ESE abtauchenden Streckungslineation L1 geprägt, die während der kretazischen niedriggradigen Metamorphose gebildet wurden. Die Schieferung S1 ist homoachsial durch aufrechte, enge ESE abtauchende D2-Falten überprägt, die eine kretazische NNE–SSW-Verkürzung anzeigen.

1. Introduction

To reveal stratigraphy and tectonics of a mountain belt, ´a bad fossil is more valuable than a good working hypothesis´ (Trümpy 1971). This famous saying might include geochronology, too, like ´a bad fossil or a good geochronological age is more valuable than a good working hypothesis´. Tectonic and paleogeographic reconstructions of mountain belts ideally base on well dated non-metamorphic lithostratigraphic units containing well preserved fossils (e.g., Schönlaub and Heinisch, 1993). The lack of fossils in metamorphic successions makes such correlations and reconstructions sometimes very difficult. This is particularly true for Paleozoic units of the Eastern Alps (Fig. 1), within which only subordinate thin carbonates (predominantly dolomites and some magnesites) were biostratigraphically dated by means of conodonts due to their high potential for preservation even in metamorphic settings of temperatures up to ca. 450 °C (Mostler, 1968, 1969, 1975; Schönlaub, 1979; Neubauer and Friedl, 1997). On the other hand, clastic and volcanic rocks remained largely undated. Consequently, low-grade metamorphic carbonate successions of the Austroalpine basement are well dated particularly when they comprise dolomites, whereas the knowledge of the (chrono)stratigraphy of much thicker clastic and volcaniclastic successions (e.g., so-called "Quartzphyllite units") is poor. Such successions have only been dated based on thin layers of dolomite or magnesite (e.g., Schönlaub, 1979; Heinisch, 1988; Neubauer and Sassi, 1993 and references therein). Only limited reports of preserved palynomorpha in quartz-rich dark phyllites are available (e.g., Reitz and Höll, 1989, 1991). Geochronological dating of magmatic rocks, particularly of tuffs, provides an additional new possibility to date metamorphic units of the Eastern Alps. First attempts yield interesting results strongly deviating from previous knowledge. Until now, mainly acidic tuffs like the Blasseneck Porphyroid have been dated from the Greywacke zone (Söllner et al., 1997) as well as a few examples of shallow plutonic mafic rocks (Loth et al., 2001; Dong et al., in press).

Based on a new geological map of the area near St. Johann (Fig. 2 for location), we here report a new U-Pb zircon age of a mafic tuff, which is the youngest mafic volcanic rock known from the pre-Variscan sedimentary succession in the low-grade metamorphic basement of the Austroalpine nappe complex of the Eastern Alps (Neubauer and Sassi, 1993; Schönlaub and Heinisch, 1993 for compilations of all previous data). The new age also allows a reconstruction of the tectonic structure of the central western Greywacke zone including the superposition of two stages of Cretaceous (eo-Alpine) ductile deformation.

2. Geological setting

The lithological correlation of the low-grade metamorphic Lower and lower Upper Paleozoic formations exposed within the Noric nappe of the Eastern and Western Greywacke zone (Fig. 1) is still a matter of debate (Heinisch, 1988; Schönlaub, 1982). According to recent detailed stratigraphic studies, the Noric nappe of the Western and Eastern Greywacke zone is subdivided into an eastern and a western part with some different tectonic and lithological associations (e.g. Heinisch, 1988; Loeschke and Heinisch, 1993; Schönlaub and Heinisch, 1993; Neubauer et al., 1994 and references therein).

The Western Greywacke zone is composed mainly of slates and phyllites (referred to as the Wildschönau Formation; Mostler 1968 and references therein), metasandstones, metatuffs, metabasites, and metadolomites with some metamorphosed mafic/ultramafic slices (Heinisch 1988 and references therein). Due to overprinting by several phases of deformation and two stages of metamorphism (Variscan and early Alpine), their field relationships and stratigraphic succession are difficult to reconstruct. The Greywacke zone was subdivided into four tectonic units by means of stratigraphic studies (Mostler 1973; Loth et al. 2001). Subsequently, a detailed lithostratigraphic subdivision was presented for the Kitzbühel and Zell am See areas (Heinisch et al. 1987; Heinisch 1988). However, many ambiguous field relationships between different formations and an intense debate on stratigraphy, tectonic setting and evolutionary history still exist (e.g., Dong et al., in press).

The western sectors of the Western Greywacke zone comprise four units with different facies development (Heinisch, 1988) (Fig. 3): The Wildseeloder unit of Heinisch (1988), or Alpach unit according to Mostler (1970), is characterized by weakly deformed and non-metamorphosed Devonian dolomite, while the Glemmtal unit respectively Jochberg unit also termed by Mostler (1970) comprises mostly clastic rocks. The Hochhoerndl (in part Hohe Salve unit of Mostler, 1970) and Utten-

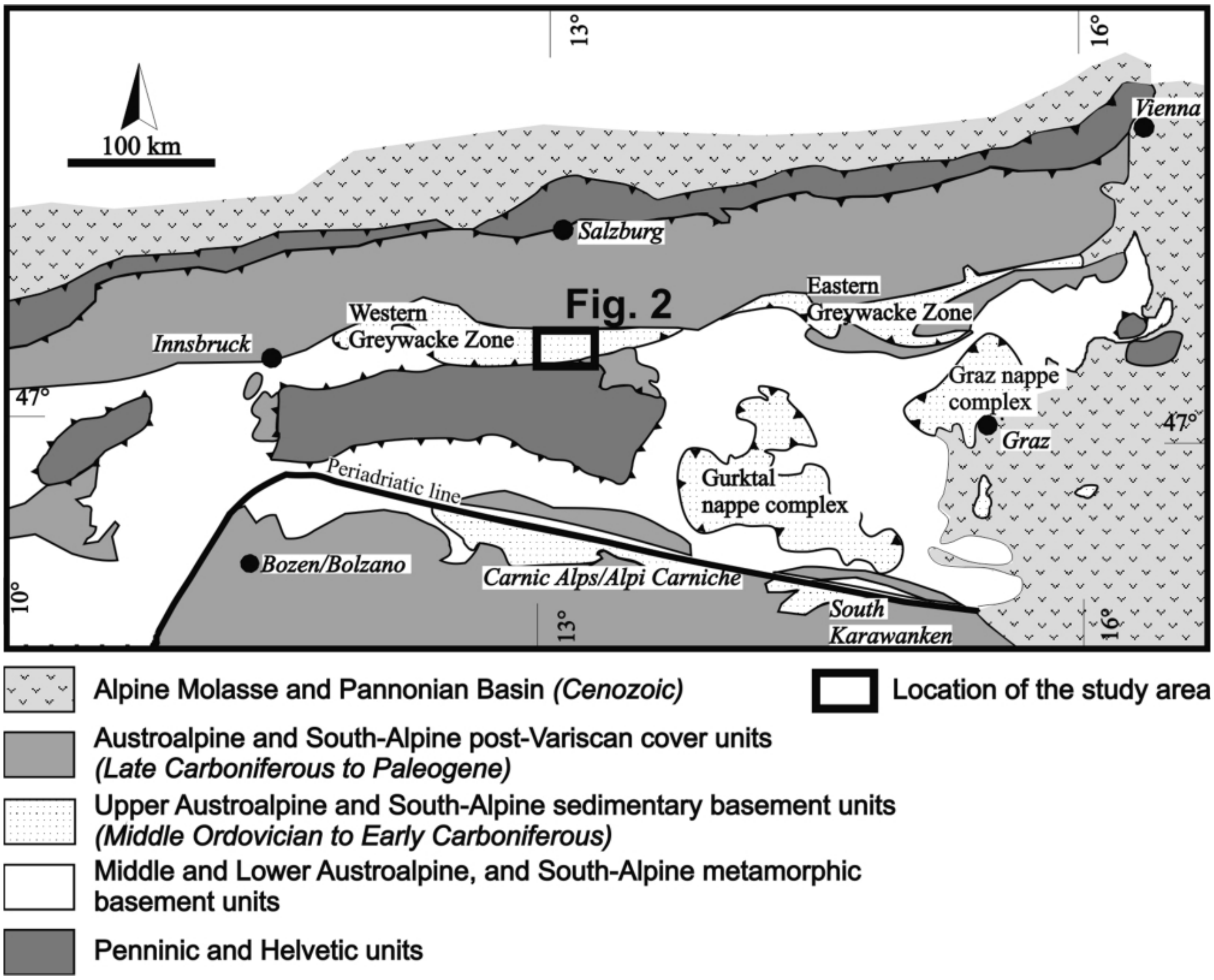


Figure 1: Simplified geological map showing the principal tectonic units of Eastern Alps and location of the working area (modified after Mader and Neubauer, 2004).

dorf Imbricate zones are characterized by intense imbrication with N–S trending structures (folds, meso-scale thrusts). Magmatic rocks only occur in the Glemmtal unit and the Uttendorf Imbricate zone. The Glemmtal unit and related units are considered to comprise the entire Western Greywacke zone exposed between the Glemm Valley and Radstadt and the working area is considered to represent part of it (Bauer et al., 1969; Heinisch, 1988; Exner, 1979) (Fig. 2).

The Noric nappe of the Greywacke zone mainly contains phyllites with intercalations of metabasites, felsic tuffs and metasandstones (Mostler, 1968, 1969, 1973; Heinisch 1988; Loeschke and Heinisch, 1993; Neubauer et al., 1994; Loth et al., 2001). This unit is biostratigraphically well dated and comprises some Ordovician ophiolite-type successions (Loth et al., 2001; Schauder, 2002), the thick Upper Ordovician Blasseneck Porphyroid (Flajs and Schönlaub, 1976), representing an acidic ignimbrite (Heinisch, 1981), and Silurian mafic tuffs with some intraplate geochemical characteristics (Schlaegel, 1988: Schlaegel-Blaut, 1990). Zircon grains from metarhyolites (Blasseneck Porphyroid) of the Eastern Greywacke zone yield an U-Pb age of 467.6 ± 4.4 Ma, which was interpreted as the maximum formation age (Söllner et al., 1997) or the emplacement time of the lavas and pyroclastics (Loth et al., 2001). Conodont findings prove the Caradocian (Flajs and Schönlaub, 1976), now Sandbian to Katian age (according to Ogg et al., 2008) of the Blasseneck Porphyroid in the Eastern Greywacke zone. Zircons from the Maishofen gabbro yield a laser-probe ICP-MS 206Pb/238U average age of 464 ± 2.9 Ma, which represents the crystallization age of the Maishofen gabbro (Glemmtal unit) and the formation age of the E-MORB-type Maishofen ophiolite (Dong et al., in press). Heinisch et al. (1987) dated some mafic volcanic tuffs as late Early Devonian with conodonts.

3. The Greywacke zone between the Dienten and Salzach Valleys

Before going into details, the lithostratigraphy and large-scale structure of the western Greywacke zone between the Dienten and Salzach Valleys is considered (Fig. 2). This area has been mapped by Trauth (1925, 1927), Exner (1979), and Bechtold (1985). Hirschmann et al. (1990) contributed a geochemical study on black phyllites and greenschists. The entire area is low-grade metamorphosed under greenschist facies conditions (Colins et al., 1980; Schramm et al., 1980; Kralik et al.,

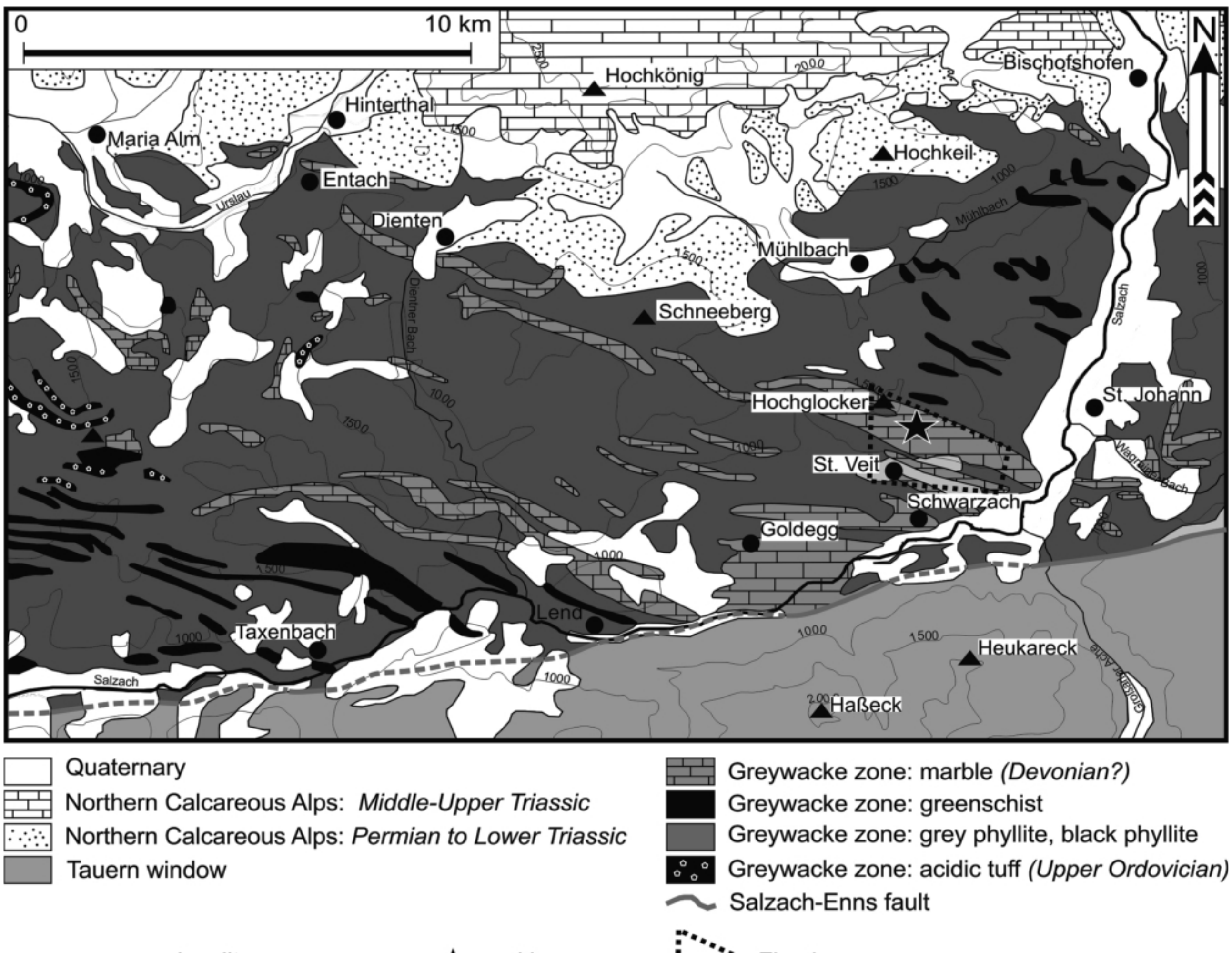


Figure 2: Simplified geological map of the central part of the Western Greywacke zone (modified after Braunstingl et al., 2005).

1987) of early Alpine age (ca. 95 Ma) according to white mica $^{40}Ar/^{39}Ar$ ages of Urbanek et al. (2001) and Neubauer and Handler (2005). Consequently, no fossils have been found until now except for old reports on Silurian graptolites in graphitic phyllite and cherts (lydites) from the Dienten area (Aigner, 1931; Heritsch, 1929; Haiden, 1936; Jaeger, 1978; see Fig. 2 for the locality). In nearby, tectonically overlying locations at Dienten, Mostler (1969, 1973) found Upper Silurian conodonts in magnesite. On the other hand, thick dolomite and calcite marbles are known, which obviously show an east-plunging antiform closing in the east in the Schwarzach–St. Johann area (Fig. 2; see also Exner, 2008). Previous geological mapping enables us to distinguish three distinct successions partly different from other sectors of the Western Greywacke zone (Figs. 2, 3). The successions include (Fig. 2):

1) A strip of mainly black/graphitic and greyish phyllites intercalated by black metacherts ("lydites" of the older literature), and many greenschist layers and lenses in the north and southwest of these marbles are distinguished from greyish and calcareous phyllites in the core of the anticlinorium. Furthermore, Mn-rich carbonates also occur as thin layers within black phyllites (Braunstingl et al., 2009). This lithostratigraphic unit comprises the locality at Dienten with Silurian graptolites (Jaeger, 1978). We here introduce the term Dienten facies for this peculiar black-shale dominated facies of the Western Greywacke zone. These black phyllites differ from the widespread greyish Wildschönau slates by their black, graphitic appearance.
2) Up to one kilometer thick, often massive but intensely folded dolomitic and calcitic marbles, for which a dominant Early to Middle Devonian age can be assumed from correlations (Schönlaub, 1979; Schönlaub and Heinisch, 1993; Neubauer and Sassi, 1993). These carbonates also contain magnesite (Friedrich and Peltzmann, 1937; Haditsch, 1969). In the western part of the Western Greywacke zone, thick Lower-Middle Devonian dolomites are representative for the Schwaz Dolomite (Mostler, 1968, 1970). Upper Ordovician to Silurian and Upper Devonian-Lower Carboniferous carbonates of the Austroalpine and Southalpine basement are always subordinate and thin. Several tens of meters thick Upper Devonian-Lower Carboniferous limestones are characterized as partly phyllosilicate-rich pelagic limestones (Schönlaub, 1979; Schönlaub and Heinisch, 1993). The interpretation of thick, massive marbles as to represent mainly Lower-Middle Devonian allows us to interpret the two different phyllite units: the graphitic and greyish phyllites, in part Silurian in age, intercalated by many greenschist layers and lenses in the fold limbs as mentioned above (for details, see above), and
3) grey and calcareous phyllites in the core of the antiform (Braunstingl et al., 2005, 2009). The greyish phyllites form the dominant lithology and they are nearly free of green-

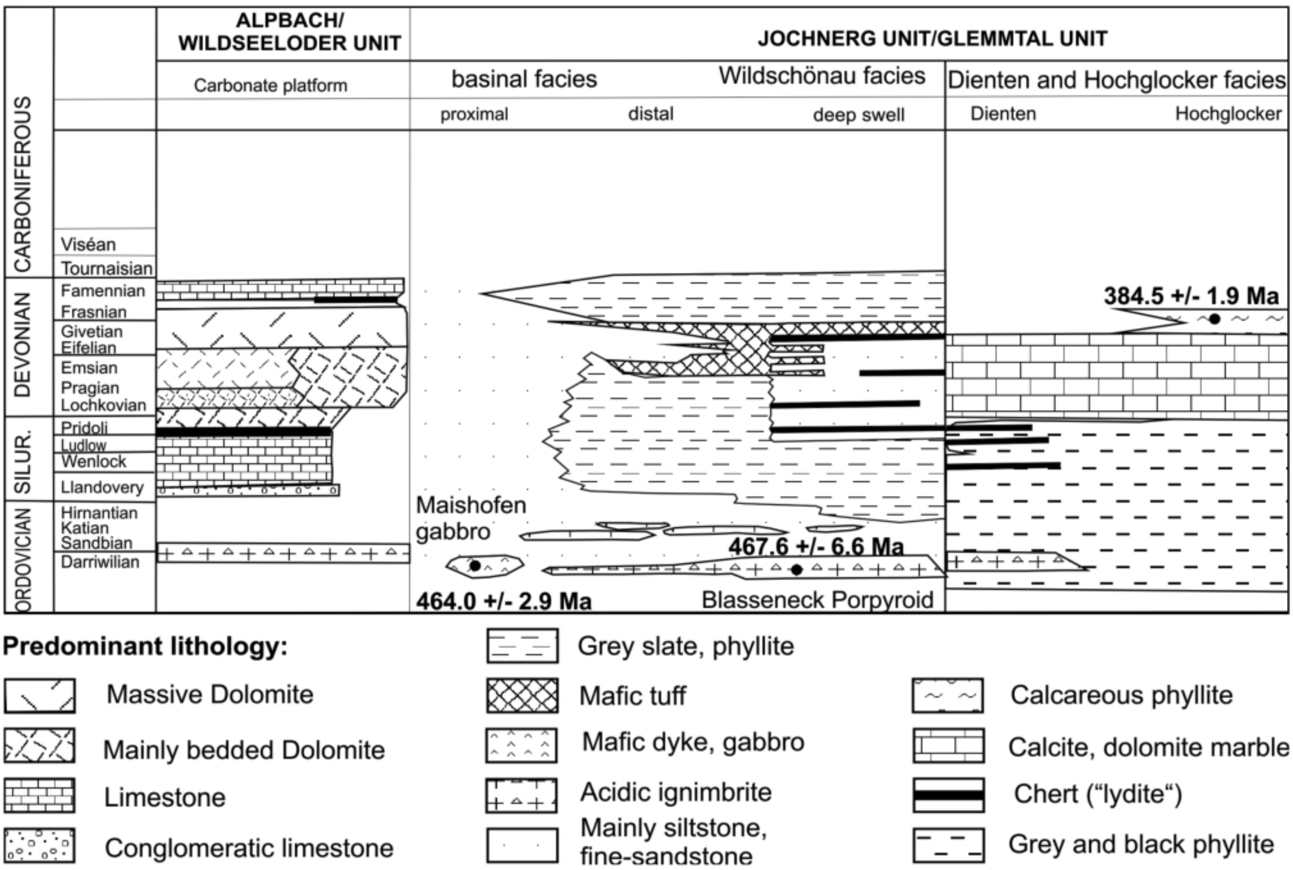
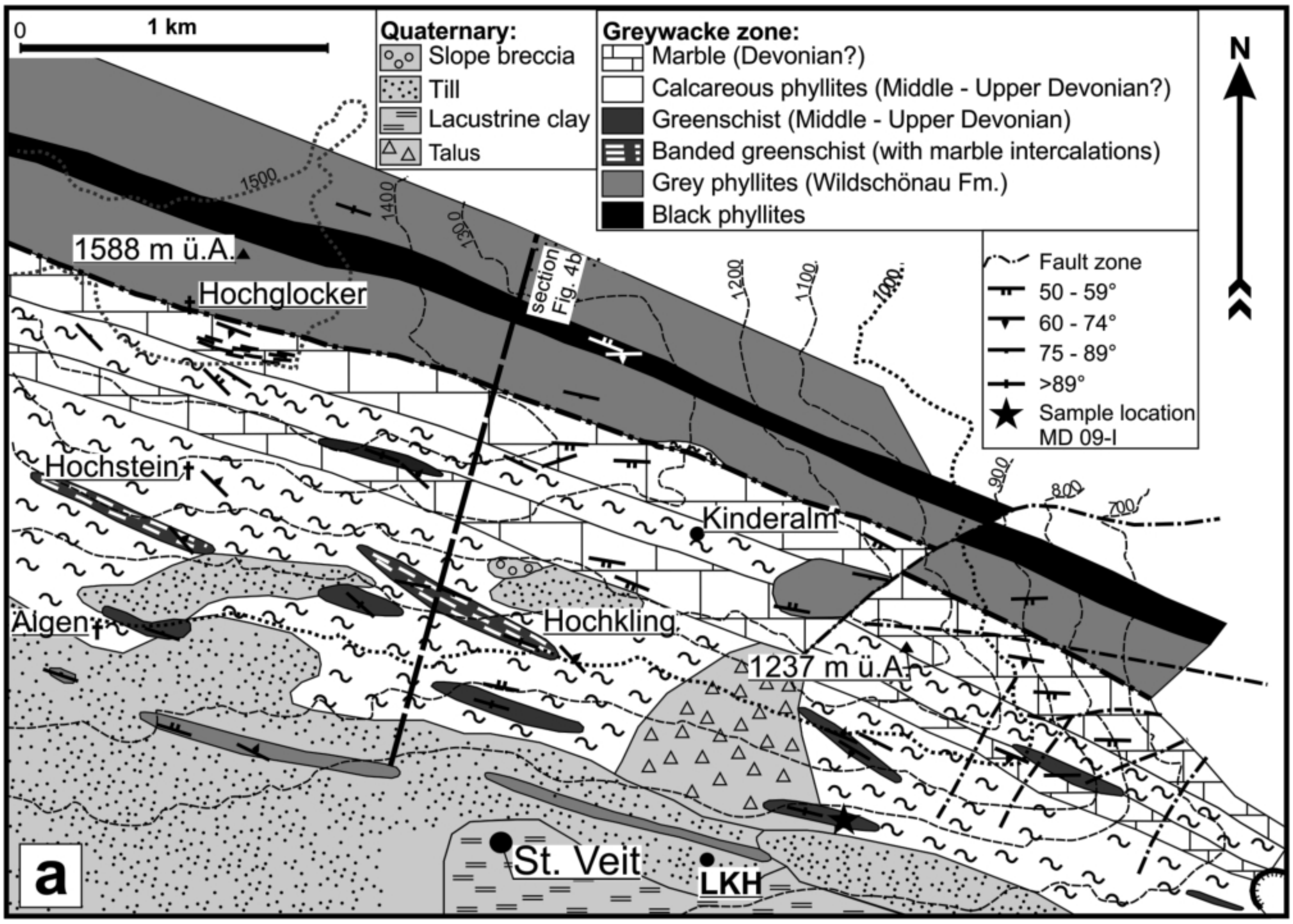


FIGURE 3: Strongly modified and extended lithostratigraphic section of the western Greywacke zone after Heinisch (1988) modified by results of Dong et al. (in press) and this study (with new-introduced Hochglocker and Dienten facies units).



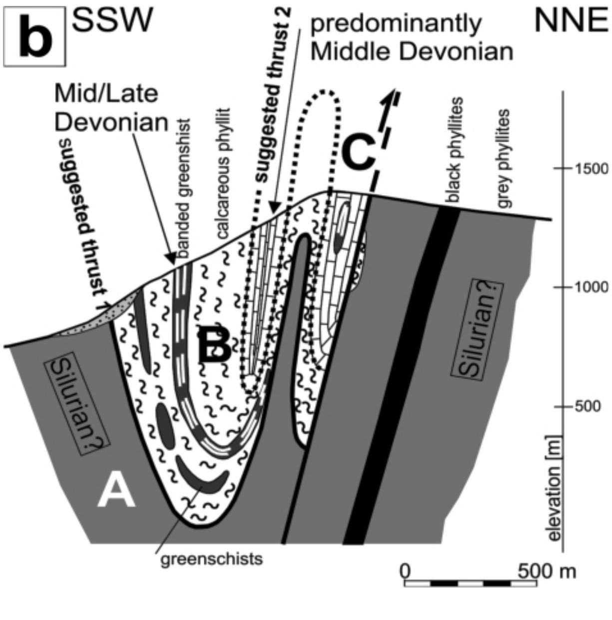


Figure 4: a – New geological map of the Hochglocker. b – Section across the Hochglocker area with supposed stratigraphic ages of various lithostratigraphic units. The interpretation of thrusts is tentative, particularly the thrust between calcareous phyllites and calcite/dolomite marbles. A, B and C are possible nappes (for details, see text (chapter 8.2).

schists. The calcareous phyllites are intercalated by centimeter- to decimeter thick calcite marbles. Only some thin greenschist layers occur within calcareous phyllites in the Hochglocker area (see below).

4. The Hochglocker section

The Hochglocker area is located at the northern, NNW-trending fold limb (Fig. 2) and is characterized by thick WNW-trending steeply NNE-dipping to subvertical calcitic marbles. From the base to top, the following succession is observed (see also map and section shown in Figs. 3, 4a, b): (1) greyish phyllites, (2) a several 100 m thick succession of calcareous phyllites with several lenses of greenschists, (3) a thick, massive whitish to yellowish-brownish marble, calcareous phyllites, (4) a second thick marble layer, (5) a few lenses of calcareous phyllites, and (6) grey phyllites with a several 10 meter thick layer of black phyllite. Based on the presence of many outcrop-scale tight upright folds, we assume that the two thick marble layers represent one single lithostratigraphic entity, which is duplicated by folding. If this is true then the calcareous phyllite between the two marble layers is a repetition of the calcareous phyllite of the southwestern slope of the Hochglocker area. Both marble layers comprise thin lenses of greenschists. The northeastern edge of the northeastern marble layer exposes a tectonic boundary towards the greyish phyllite with black phyllite intercalations of the largely Silurian Dienten facies.

5. U-Pb zircon dating

Several samples were collected from various greenschist layers, but only sample MD-1 (sample location: N47° 19´59.2´´, E13° 09.50.6´´; Fig. 4a) yielded zircon grains. The greenschist comprises up to several millimeter thick layers mainly composed of either chlorite, chlorite and epidote, or plagioclase. Because of this banding and the presence of primary plagioclase grains, we interpret the protolith as a mafic or intermediate crystal ash tuff.

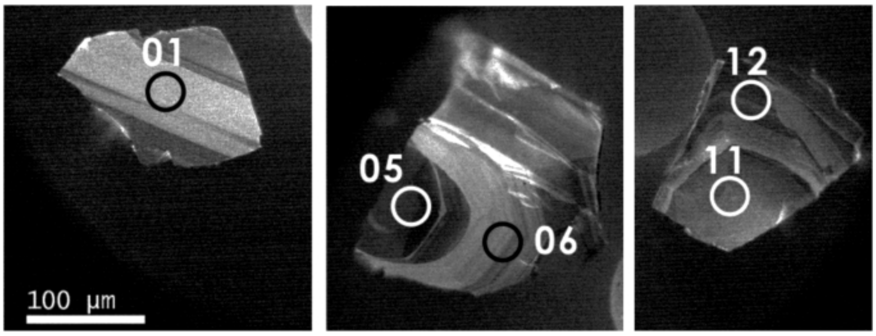


Figure 5: Representative cathodoluminescence images of some dated zircons.

5.1 Analytical technique

Concentration of the zircon crystals was achieved by means of magnetic separator and heavy liquids. The zircons were separated carefully by handpicking according to size, color, turbidity and shape. The best quality zircon grains, characterized by homogeneity, transparency, homogeneous color, fluorescence and absence of inclusion were chosen for dating. No inherited cores were detected. Zircon grains were mounted together with epoxy on a 20 mm diameter disc and polished to obtain an even surface and cleaned in an acid bath prior to Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) analysis. They were also photographed and examined by cathodoluminescence (CL) imaging at the Beijing University, China. The isotopic analyses by means of LA-ICP-MS were performed in the State Laboratory of Continental Dynamics, Northwest University, Xi´an, China. The Laser Ablation Instrument (Geolas200M) was made by the Microlas Company, Germany while the ICP-MS (Agilent7500a) was manufactured by the Agilent Company, USA. Zircon U-Th-Pb measurements were made on 30 µm diameter spots of laser ablation in a single grain, and the analytical procedures are similar to those described by Yuan et al. (2004). The result of dating was corrected by the international zircon standard (91500), and the data was processed and plotted using Isoplot 3.0 (Ludwig 2003). Compositions of the common Pb were corrected following the method of Andersen (2002). Age uncertainties are quoted at the 95% confidence level.

5.2 Results

15 spots on 13 zircon grains from sample MD-1 were dated. Examples of cathodoluminescence images are shown in Fig. 5. Nearly all the zircon grains were broken, but exhibit magmatic zoning and sometimes several magmatic zones, but no inherited cores. Results of dating are given in Table 1 and are graphically presented in Fig. 6. All 15 grains are concordant or subconcordant and have the same age within the error (Fig. 6a) although core and rim composition have been measured in two grains (Fig. 5). The internal mean of all 15 spots gives an age of 384.5±1.9 Ma (95% confidence level; MSWD = 0.57, probability = 0.89; Fig. 6b). We interpret this age as geologically significant and as a means to date the age of the volcanic eruption during deposition of marls, the precursor rocks of calcareous phyllites. This age is at the boundary Givetian to Frasnian with the numerical age of 385.3 ± 2.6 Ma (according to Gradstein et al., 2004 and Ogg et al., 2008).

6. Eo-Alpine structures

All the rocks of the Hochglocker area display a penetrative foliation S_1 and a gently ESE plunging stretching lineation L_1

Spot	^{232}Th	^{238}U	$^{207}Pb/^{206}Pb$	1 s	$^{207}Pb/^{235}U$	1 s	$^{206}Pb/^{238}U$	1 s	$^{208}Pb/^{232}Th$	1 s	$^{207}Pb/^{206}Pb$ age [Ma]	1 s	$^{207}Pb/^{235}U$ age [Ma]	1 s	$^{206}Pb/^{238}U$ age [Ma]	1 s	$^{208}Pb/^{232}Th$ age [Ma]	1 s
1	493	529	0.05349	0.00111	0.4561	0.0053	0.06185	0.00063	0.01868	0.00009	350	46.27	382	4	387	4	374	2
2	214	313	0.05349	0.00116	0.45722	0.00597	0.06201	0.00064	0.01855	0.00012	349	48	382	4	388	4	372	2
3	359	275	0.05402	0.00117	0.46192	0.0061	0.06203	0.00064	0.0194	0.0001	372	48	386	4	388	4	388	2
4	752	478	0.05369	0.00111	0.45562	0.00528	0.06155	0.00063	0.0187	0.00009	358	46	381	4	385	4	375	2
5	281	262	0.05271	0.00115	0.44597	0.00594	0.06136	0.00063	0.01906	0.00011	316	49	375	4	384	4	382	2
6	1435	871	0.05433	0.00111	0.45713	0.00496	0.06102	0.00062	0.01857	0.00009	385	45	382	3	382	4	372	2
7	105	147	0.0562	0.00138	0.47225	0.00813	0.06094	0.00064	0.01912	0.00016	460	55	393	6	381	4	383	3
8	167	292	0.05446	0.00118	0.46177	0.00592	0.06148	0.00063	0.01975	0.00013	390	48	386	4	385	4	395	3
9	344	265	0.0538	0.00119	0.45785	0.00621	0.06171	0.00063	0.01948	0.00011	362	49	383	4	386	4	390	2
10	666	580	0.05347	0.00113	0.45467	0.00541	0.06166	0.00062	0.01875	0.0001	349	47	381	4	386	4	376	2
11	568	399	0.05406	0.00115	0.4532	0.00548	0.06079	0.00061	0.0197	0.0001	374	47	380	4	380	4	394	2
12	225	200	0.05386	0.00126	0.45576	0.0071	0.06135	0.00063	0.02026	0.00013	365	52	381	5	384	4	405	3
13	515	358	0.05603	0.00121	0.47048	0.006	0.06088	0.00062	0.0193	0.0001	453	47	392	4	381	4	386	2
14	169	169	0.05294	0.00124	0.45508	0.00713	0.06233	0.00064	0.01949	0.00013	326	52	381	5	390	4	390	3
15	5612	1458	0.05457	0.00111	0.45921	0.00484	0.06101	0.00061	0.01886	0.00009	395	45	384	3	382	4	378	2

Table 1: LA-ICP-MS zircon U–Pb isotope data for a greenschist from the Hochglocker.

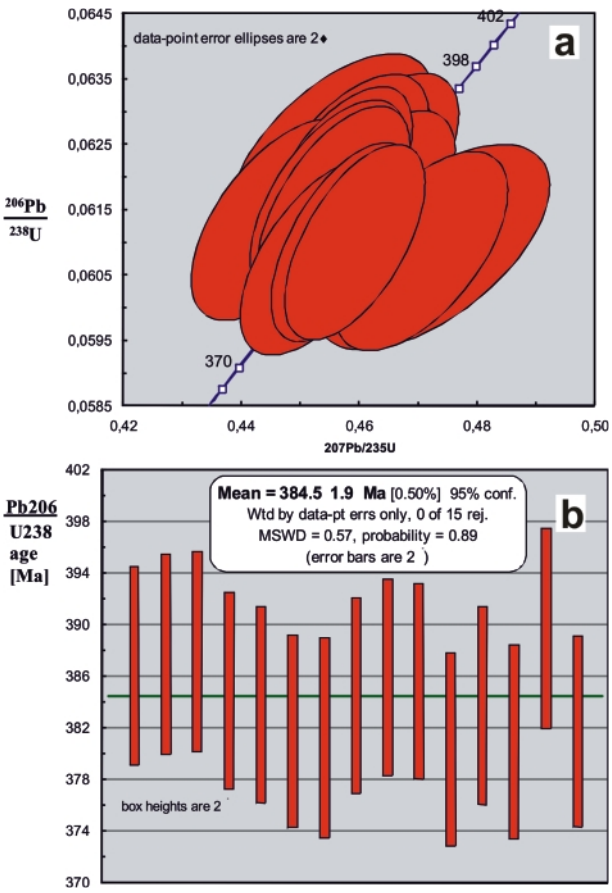


Figure 6: a - U-Pb concordia diagram for zircons from a greenschist lens within calcareous phyllites of the Hochglocker facies. b - Mean ^{206}Pb/^{238}U age of zircons.

(Figs. 7, 8) assigned to a deformation stage D_1. This fabric was likely formed during low-grade metamorphic conditions revealed by thin sections. The stretching lineation is dominant in calcareous phyllites (Fig. 7a). Because of subsequent folding, no clear shear criteria have been found, so it remains unclear whether shear of the hangingwall units occurred towards WNW or ESE. The formation of the large-scale ESE plunging fold (deformation stage D_2) postdates the formation of the penetrative foliation S_1. On the outcrop scale, the penetrative foliation S_1 is folded in upright folds with a steep ESE trending axial plane foliation with ESE plunging fold axes and crenulation lineations (Fig. 7b, c). The axial plane foliation S_2 steeply dips to the NE. The D_2 folds indicate NNE–SSW shortening and are in line with the large-scale antiform mentioned above.

7. Remarks to brittle structures

The working area is located in a distance of several kilometers to the Salzach-Enns fault with its polyphase shear/fault history since Oligocene times (Wang and Neubauer, 1998; Fig. 2). The main activity there was a sinistral transtensive motion, and a similar succession of brittle deformation events could be expected in the working area. There, we recognized a dextral NE-trending strike-slip fault with an offset of ca. 100 m (Fig. 4a). Orientation and shear sense perfectly fit as a conjugate fault with sinistral strike-slip offset along the ca. E-trending Salzach-Enns fault. In the outcrops of the eastern part of the Hochglocker area, we observed brittle faults, and the dominant faults are ca. west-dipping normal faults with a dip-slip striation (Fig. 9a, d). Paleostress assessment of all faults yield five different paleostress sets. We used a similar approach and methodology as described in Kargaranbafghi et al. (2011) and assessed data using the program TectonicsFP (Ortner et al., 2002).

Deformation stage D_3 (paleostress tensor A) is dominated by ca. ENE-trending sinistral strike-slip faults largely parallel to the orientation of the Salzach-Enns fault, and conjugate N-trending dextral strike-slip faults. Together, these faults prove NE–SW strike-slip compression (Fig. 9b). The relatively poorly constrained deformation stage D_4 (paleostress tensor B) is dominated by roughly NNW-trending dextral and NNE-trending sinistral strike-slip faults proving N–S strike-slip shortening (Fig. 9c). Paleostress tensor group C (deformation stage D_5) is dominated by roughly W-dipping normal faults proving ESE–WNW extension (Fig. 9a, d). Paleostress tensor D (deformation stage D_6) is dominated by ENE-trending dextral strike-slip faults proving inversion of former sinistral fault motion and represents an E–W strike-slip compression (Fig. 9e). Paleostress tensor group E (deformation stage D_7) is dominated by steeply N- respectively S-dipping normal faults with dip-slip lineation. Together, these faults prove N–S extension (Fig. 9f).

8. Discussion

The new data from the Hochglocker area in combination with data from the literature add new knowledge on the geological history of eastern sectors of the Western Greywacke zone. In the following, we first discuss the significance of the new data for the facies development of eastern sectors of the Western Greywacke zone, and then the possible nappe structure of the Greywacke zone between the Dienten and Salzach Valleys. We then argue for the timing of formation of large-scale structures and we conclude with a short remark on the significance of brittle structures.

8.1 Hochglocker facies

The new U-Pb zircon age of 384.5 ± 1.9 Ma of the greenschist allows dating of the calcareous phyllites near the Middle to Upper Devonian boundary. This also implies that calcareous phyllites, i.e. the matrix of the greenschist, are of the same age. The presence of Middle/Upper Devonian mafic tuffs (i.e. the assumed protolith of the greenschists) is unique within the Paleozoic basement in the Austroalpine domain of the Eastern Alps. No such facies was dated until now in the fossil-bearing respectively low-grade metamorphic Austroalpine basement (see Loeschke and Heinisch, 1993, and Neubauer and Sassi, 1993 for compilation of ages from mafic metavolcanics) and we here introduce preliminarily the term Hochglocker facies for this lithologic unit, which is dominated by calcareous phyllites. The uncertain lower and upper boundaries exclude a formal definition as a formation.

Possible correlations of the metamorphosed tuff may exist to similar Upper Givetian tuffs of the Paleozoic of Graz (Tschelaut, 1984; Flügel and Hubmann, 2000). Ebner (1998) described thin tuffs of possible Frasnian age intercalated within pelagic limestones of the Spatl Member of the Kogler Formation (Flügel and Hubmann, 2000) and Flügel and Hubmann (2000) note similar Frasnian tuffs in the Fahrneck Formation. However, no detailed data exists on these two occurrences. All other mafic volcanic rocks within Paleozoic basement units found up to now are of Ordovician, Mid-Late Silurian, Early Devonian, and rarely early Givetian age. The only further exception is being the presence of discordant hitherto undated mafic dykes in Middle Devonian massive calcitic marbles in the northern Gurktal nappe complex, which are younger than Middle Devonian (Neubauer, 1989).

8.2 Possible nappe structure between the Dienten and Salzach Valleys

Widespread Middle Devonian marble overlying Middle/Upper Devonian calcareous phyllites in the Hochglocker section (Fig. 4b) indicate that either (1) the entire succession is tectonically inverted or (2) a nappe boundary (suggested thrust 2 in Fig. 4b) is present in between. In the case of tectonic inversion, this structure must cover nearly the entire basement region between the Dienten Valley and N-trending Salzach Valley underlying massive marbles (Fig. 2). In the case of tectonic inversion, a further thrust is expected in the footwall of calcareous phyllites (suggested thrust 1 in Fig. 2b) separating them from underlying grayish phyllites (Wildschönau Fm.). On the northern side of the section, the Dienten facies unit with Silurian successions is overlain, although with a fault contact, by

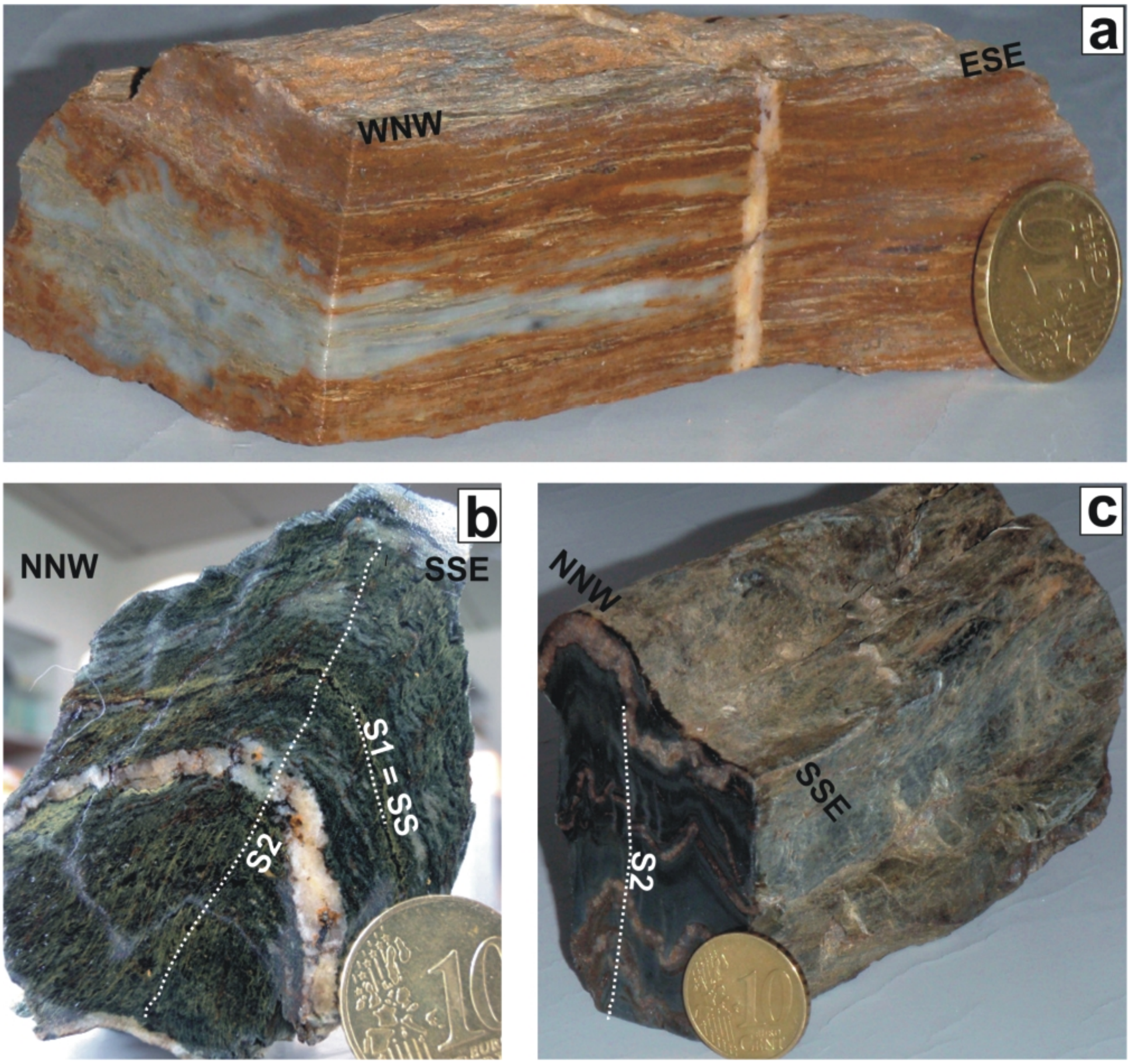


Figure 7: Field photographs and photomicrographs of structures of the Hochglocker area. a – calcareous phyllite with penetrative foliation, stretching lineation, and calcitic extensional vein perpendicular to the foliation S_1 and the stretching lineation L_1. b, c – Banded greenschist with penetrative foliation S_1 and axial plane foliation S_2 with chlorite and epidote.

thick marbles of suggested Early-Middle Devonian age. The thick marbles are overlying the calcareous phyllites of the Hochglocker facies. Consequently, a second nappe boundary is expected at the interface between these two units (suggested thrust 1 in Fig. 4b). In any case, this hypothesis requires further proof by more biostratigraphic and/or geochronologic data. If the tectonic interpretation, which is based in the new age findings, is correct, then unit A (Fig. 2b) extends in the core of anticlinorium further to the west representing the Glemmtal unit sensu stricto.

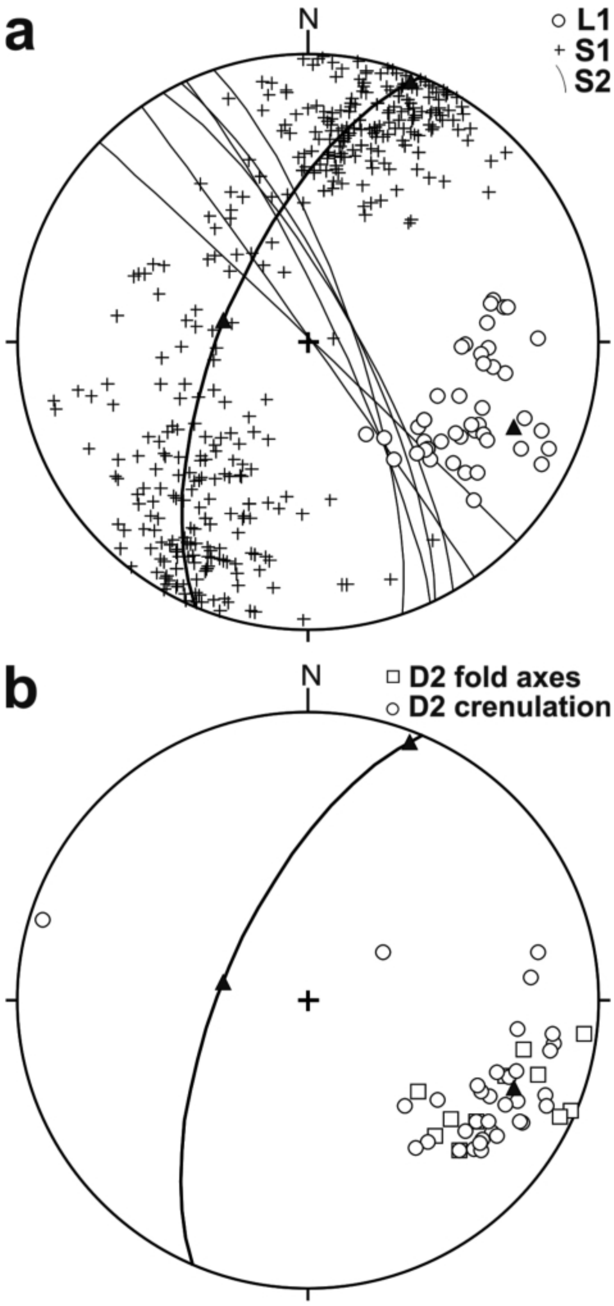


Figure 8: Orientation data of ductile structures of the Hochglocker area. a – Poles to foliation S_1 displaying a girdle distribution (thick great circle and corresponding eigen vectors, filled triangles) and an axial plane foliation S_2 (great circles) and poles of fold axes and crenulation lineation L_2. b – Poles to crenulation lineation L_2 and fold axes F_2. Great circle of S_1 girdle distribution is from Fig. 8a.

8.3 Significance of ductile structures

We recognized two stages of ductile deformation. The penetrative foliation S_1 (deformation stage D_1) is characterized by pervasive mineral growth within greenschist facies metamorphic conditions (Hoschek et al., 1980; Schramm, 1980). This is in line with $^{40}Ar/^{39}Ar$ white mica ages ranging from ca. 80 to 105 Ma from the base of the Greywacke zone to its top (Urbanek et al., 2001; Neubauer and Handler, 2005; Frank and Schlager, 2006; Schmidlechner et al., 2006). Only few pre-Alpine white mica ages have been found in this segment of the Western Greywacke zone west of Bischofshofen (Neubauer and Handler, 2005). These ages also prove the Cretaceous age of the pervasive deformation D_1, which occurred, therefore, between 95 and 105 Ma (late Early Cretaceous according to Gradstein et al., 2004; Ogg et al., 2008) obliterating nearly any record of Variscan metamorphism. The argon retention temperature in white mica was experimentally tested at 425 ± 25°C (Harrison et al., 2009). Consequently, this temperature must have been reached during Cretaceous times within this sector of the Western Greywacke zone.

The subsequent deformation stage D_2 refolded not only all lithologies but also the penetrative foliation S_1. A subvertical axial plane foliation formed due to NNE–SSW shortening while still within greenschist metamorphic conditions as epidote and chlorite grew on the axial surface foliation S_2. Similar ductile fabrics have been reported from the Eastern Greywacke zone (Ratschbacher, 1986), and we suggest an age of the deformation stage D_2 at ca. 80 Ma during Late Cretaceous as testified by low-temperature overprint on $^{40}Ar/^{39}Ar$ white mica ages in the Western Greywacke zone (Schmidlechner et al., 2006). Similar compressional structures in underlying Lower Austroalpine units were dated at this time (Dallmeyer et al., 1998 and references therein).

8.4 Remarks to brittle structures

The observed brittle structures and their paleostress assessment fits well into the succession of events described from the Salzach-Enns fault (Wang and Neubauer, 1998) and the eastern sectors of the Northern Calcareous Alps (Peresson and Decker, 1997). The main activity is a sinistral transtensive motion (paleostress tensor group A, deformation stage D_3), which is overprinted by E-W extension deformation stage D_4) and dextral inversion of the Salzach-Enns fault deformation stage D_4). Paleostress stage A is considered to be of Oligocene age, B of Miocene age, and C and D of the Miocene to Pliocene boundary by Peresson and Decker (1997), and the age assignment is similar to that suggested by Wang and Neubauer (1998) for the Salzach-Enns fault.

9. Conclusions

Based on the above discussion we reconstruct the tectonic history of previously undated low-grade metamorphic sectors of the Paleozoic basement exposed in the central Western Greywacke zone as follows:

1) Greenschists intercalated within calcareous phyllites of the

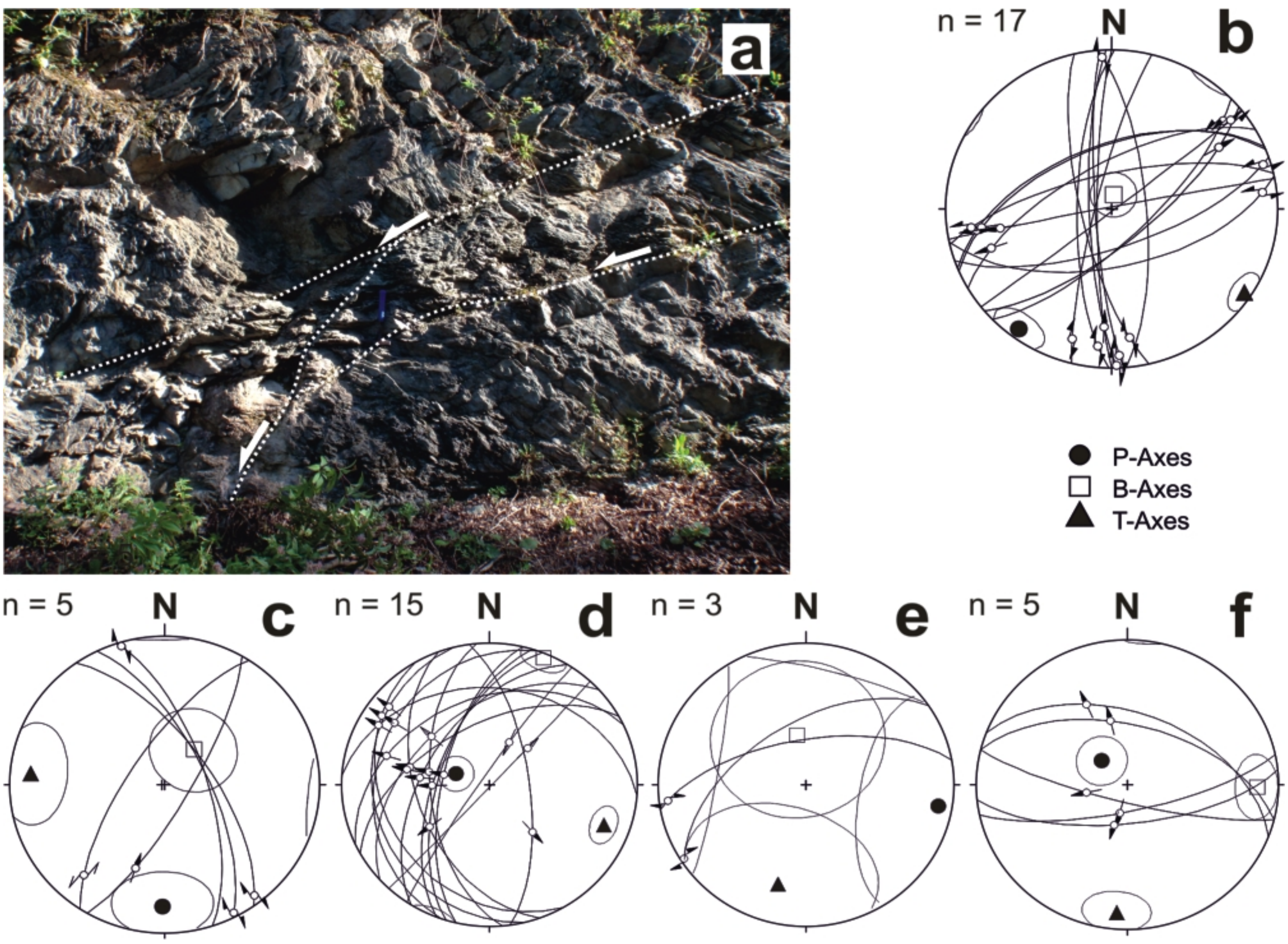


Figure 9: Brittle structures in phyllites and marbles of the Hochglocker area. a – Field photograph of W-dipping normal faults in greyish phyllite. b – Faults and slickensides and P-, B-, T-axes of paleostress tensor group A, NNE–SSW strike-slip compression. c – Faults and slickensides and P-, B-, T-axes of paleostress tensor group B, N–S strike-slip shortening. d – Faults and slickensides and P-, B-, T-axes of paleostress tensor group C, E–W extension. e – Faults and slickensides and P-, B-, T-axes of paleostress tensor group D, NW–SE strike-slip compression. f – Faults and slickensides and P-, B-, T-axes of paleostress tensor group E, N–S extension. Abbreviation n in b – f gives the number of fault-striae sets.

Western Greywacke zone of the Eastern Alps yield a U-Pb zircon age of 384.5 ± 1.9 Ma and allow dating of the calcareous phyllites at the Middle to Upper Devonian boundary. We here introduce the term Hochglocker facies for the lithologic unit, which is dominated by calcareous phyllites.

2) The Hochglocker facies occurs in the limb of a kilometer-sized ESE-plunging anticlinorium, which is mantled by thick dolomites and marbles, and thick successions of grey phyllites intercalated by greenschists and graphitic phyllites suggesting a later folded nappe structure.
3) The area is dominated by two types of ductile deformation structures. The entire area is dominated by a penetrative foliation S_1 and a gently ESE plunging stretching lineation L_1 which formed during Cretaceous low-grade metamorphic conditions. The foliation is folded in upright folds with a steep WNW–ESE trending axial plane foliation and ESE plunging fold axes indicating Cretaceous-aged NNE–SSW shortening.

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