North of Naran in the Kaghan Valley (NE Pakistan), the metabasities of the mélangé units lying below the Kohistan Arc, contain glaucophane. Typically they reflect blueschist-metamorphic conditions (0.7 GPa, 400°C). Associated graphite-rich metapelites with quartz veins underwent upper greenschist to amphibolite conditions. Near Naran we observed in quartz grains of type 3 veins first minute relics of Fe-Mg carpholite indicating earlier blueschist metamorphic conditions. P-T estimates indicate 1.2-1.6 GPa at 380-410 °C, pressure and temperature values typical for blueschist metamorphic conditions. Changes in mineral assemblages and abundant sudoite component in associated chlorite point to a pressure drop after peak I conditions. We assign the observed changes to peak I conditions occurring during a Cretaceous subduction event. Temperatures estimated with Raman graphite-thermometry clearly indicate a significant subsequent rise of post-peak I temperatures up to 500°C. This is compatible with the amphibolite peak II assigned to the Tertiary continental collision that leads to subduction of the Indian Plate and ultra-high-pressure metamorphism. During subduction the blueschist metamorphic metabelites underwent dehydration, which caused alteration in the overlying lithospheric mantle. In a hydrated lithospheric mantle density is significantly reduced which enhanced subduction of continental crust in the Higher Himalaya. This P-T evolution is typical for a collision orogen with a high plateau but remarkably contrasting findings from Eastern Anatolia, where plateau building is in “statu nascendi” (e.g., Oberhänsl, 2010).

Introduction

Discovery of HP in the Himalaya

Continental collision resulting in the formation of the Himalayan belt has long been recognized to be the result of subduction of the Indian plate below the Asian continental plate (Gansser, 1964). First reports of eclogites within the higher Himalayan crystalline (Pognante and Spencer, 1991) were followed by a discovery of coesite reflecting ultra-high-pressure (UHP) conditions within the Indian plate (O’Brien et al., 2001; Mukherjee and Sachan, 2001) and glaucophane-bearing eclogites (e.g., in the upper Kaghan nappe, Lombardo and Rolfo., 2000), where glaucophane marks post-eclogite conditions. Blueschists, representing lower grade high-pressure and low-temperature (HP-LT) realms are also reported along the Indus-Tsangpo Suture zone. It separates the Himalayan nappe pile to the south from the Kohistan Arc, the Ladakh and Lhasa blocks to the north with several blueschist occurrences (Fig. 1). The main suture dominated by remnants of a Tethyan accretionary wedge evolved before the continental subduction of the Indian margin (Higher Himalaya, Kaghan Valley and Ladakh). It is composed of ophiolitic mélanges and wedge type meta-pelitic to volcaniclastic metasediments.

While most subduction related HP and UHP rocks are known from mafic and continental rocks related to the Indian Plate in the Higher Himalaya Units, blueschists related to the accretionary wedge of the Indus Suture were only reported from mélanges so far.

Evidence of blueschists in ophiolitic mélanges was detailed from Shangla in the Swat area west of the Nanga Parbat Syntax (Shams, 1972; Desio, 1977; Bard, 1983). East of the Nanga Parbat Syntax, blueschists were reported from Ladakh (Frank et al., 1977; Virdi et al., 1977; Hoegger et al., 1989). Further to the east blueschists occur south of the Lhasa block near Sans Sang (Xiao and Gao, 1984) and eclogites in Ama Drime (Lomabrdo and Rolfo, 2000a). P-T estimates for the blueschists along the Indus-Tsampo Suture range around 0.9 - 1.1 GPa at 350 - 420°C (Honegger et al., 1989), 1.0 - 1.2 GPa at 510-600°C (Jan and Karim, 1995), respectively. Blueschist metamorphism in the Shangla area is determined by 0.7 ± 0.05 GPa at 400 ± 20°C (Guiraud, 1982; Jan, 1985) and was dated to Late Cretaceous (Malusky and Matte, 1984; Anczkiewitz et al., 2000).

The Shangla blueschist bearing mélanges are reported to be in contact with phyllite-schists mapped as a coherent meta-sedimentary unit assigned to the Indus Suture Zone (Anczkiewitz et al., 1998, 2000). Meta-sediments of the Tso Morari area were compared with those of the Kaghan Valley and assigned to the northern margin of the Indian Plate (Guilliot et al., 1997). These meta-sedimentary units outline the Indus Suture, while blueschist bearing mélanges occur only locally. The concept that blueschist metamorphism affected oceanic material of the accretionary prism, while the Indian Plate and parts of the arc substratum suffered eclogite metamorphism (Le Fort et al., 1997) is
widely accepted, since up to now blueschist metamorphism is only reported from mélanges along the suture zone.

In this paper new data on the metamorphic history of the coherent meta-sedimentary Parla-Sapat Unit near Naran in the Kaghan Valley will show that blueschist metamorphism is wide spread along the suture even where ophiolitic mélanges are absent.

Geology and metamorphic conditions of the Parla-Sapat Unit

Geological setting

The Kaghan Valley in NE Pakistan, is built up by three major tectonic units: Lesser Himalaya, Higher Himalaya Crystalline and a mélangé unit along the main mantle thrust (MMT) below the Kohistan Arc. This mélangé unit comprises mafic blocks with blueschist parageneses (Shams, 1972; Bard, 1983, Anczkiewitz et al., 2000).

The mélangé with blueschist bearing mafic blocks was observed to the NE towards Babusar (Bard, 1983) but apparently missing near Naran. In subsequent investigations of the Gitidas-Babusar area it was not mentioned either (Greco and Spencer, 1993; Lombardo et al., 2000, O’Brien et al., 2001; DiPietro and Pogue, 2004). Instead of ophiolitic mélanges, a coherent meta-sedimentary unit, the Banna-Parla-Sapat Unit (Fig. 2), consisting of graphite-rich schists with grey marbles, is distinguished (DiPietro et al., 2002). It sits below the MMT.

At Naran the units of the Lesser Himalaya and the Higher Himalaya exhibit remnants documenting a high-grade metamorphic evolution. The Lesser Himalaya meta-pelitic units hold paragenesis with garnet and staurolite, typically reflecting amphibolite-facies conditions. Rocks of the Higher Himalaya contain eclogites and relics of UHP with coesite (Pognante and Spencer, 1991; O’Brien et al., 2001; Mukherjee and Sachan, 2001, Wilke et al., 2010).

The meta-pelitic gneisses were compared to the typical graphite-rich meta-sediments overprinted by Barrovian metamorphism. They contain garnet, staurolite, kyanite and diopsidic pyroxene and often show post-kinematic retrogression to greenschist-facies assemblages (Greco et al., 1989).

Uphill Damla Hamlet, a location not far from Naran, graphite-rich schists in the roof of the meta-pelitic gneisses exhibit a lower metamorphic degree. They contain three types of quartz veins. Type 1 veins formed late and crosscut the country rocks and likely the earlier quartz veins. Some earlier veins (type 2) form sigmoidal lenses that can be associated with the main metamorphic phase. A few veins (type 3) show refolded isoclinal folds with typical fibrous quartz and mica-rich borders. The type 3 veins contain minute relics of Fe-Mg carpholite (Fig. 3) indicating earlier blueschist metamorphic conditions.

Metamorphic conditions

The graphite-rich meta-pelites of the Parla-Sapat Unit contain quartz veins/exsudates that show a conspicuous fibrous texture. The nodules are composed of quartz, calcite, white mica and chlorite. The quartz contains needles of relic carpholite, which is mostly altered to phengite and chlorite. Kyantite and chloritoid are absent.

Carpholite was identified by Raman spectroscopy and analysed
with EMPA. Due to the extremely small size (< 1mm) of the carpholite needles in quartz (Fig. 3), analyses always show excess quartz. Microprobe analyses were thus re-calculated according to Goffé and Oberhansli (1992), which resulted in an average $X_{\text{Mg}}$ value of 0.47. The composition of carpholite can be given as $\text{Mg}^{0.47}\text{Fe}^{2+}^{0.53}\text{Fe}^{3+}^{0.08}\text{Al}^{1.92}\text{Si}^{2.00}(\text{F}^{0.07}\text{OH}^{3.93})$. Mineral analyses of phengite and chlorite are compiled in Table 1 and 2 and plotted in Fig.4. While the white mica embedded in the foliation planes is phengite-rich, the one associated to pseudomorphic carpholite or carpholite primarily enclosed in quartz shows a high pyrophyllite component. Chlorite from the carpholite-bearing assemblage is rich in the sudoite end member. Pressure and temperature estimates derived from the Si content of phengite (Oberhansli et al. 1995) and $X_{\text{Mg}}$ in carpholite (Vidal et al., 1992, 1996) indicate 1.2 - 1.6 GPa at 380-410 °C (Fig. 5). These values can be assigned texturally to early pressure peak metamorphic conditions ($P_1$). The lack of chloritoid and or kyanite as well as abundant sudoite components in post-carpholite chlorite points to a pressure drop below ~ 0.6 GPa outside the stability field of carpholite after $P_1$ conditions. Temperatures estimated with Raman graphite-thermometry (Beyssac et al., 2002; Rahl et al., 2005) in the graphite–rich schist containing the type 3 quartz veins clearly indicate a significant rise of post-$P_1$ temperatures up to 500°C. This is compatible with reported amphibolite conditions for rocks in the Lesser Himalaya (Greco and Spencer, 1993; Smith et al., 1994).

Discussion

The new P-T estimates are in contrast to earlier estimates. Values for blueschists from Shangla (0.7 GPa, 400°C; Guiraud, 1982; Jan, 1985), the Parla-Sapat Unit (0.4 - 0.8 GPa, 380 - 480°C; Smith, 1994).
or the Batal Thrust (1 GPa, 540 °C; Smith 1994) are mostly considerably lower. They also differ significantly from the Higher Himalayan crystalline rocks (0.9 ± 0.2 GPa, 650 °C; Treolar 1998) or the UHP eclogites (2.7–2.9 GPa, 690–750; O’Brien et al., 2001) and glaucophane eclogites (2.4 GPa, 610 °C; Lombardo et al., 2000).

The metamorphic age of the Shangla blueschists was at first determined with K/Ar method to 84 ± 1.7 Ma (Shams, 1980). Later laser-Ar analyses on fine glaucophane needles revealed 65 ± 15 Ma, while the Ar stepwise heating method yielded on phengites 75 ± 5 Ma and 80 ± 10 Ma (Maluski and Schäfer, 1982) and 83.5 ± 2 Ma, respectively (Maluski and Matte, 1984). Phengite 40Ar/39Ar ages of 80 Ma were finally interpreted as metamorphic peak age (Anczkiewitz

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### Table 1. Representative analyses of white mica and chlorite from quartz veins of the graphite-rich meta-pelites of the Parla-Sapat Unit. Fe is calculated as ferric and total kations are normalized to 11 oxides.

| Pak04 | 14c-1-2 | 14c-6-7 | 14c-6-8 | 22a-2-1 | 22a-2-15 | 13a-2-7 | 13a-2-8 | 22a-3-2 needle |
|-------|---------|---------|---------|---------|---------|---------|---------|---------------|
| SiO₂  | 3.137   | 3.259   | 3.176   | 2.977   | 3.288   | 3.271   | 3.147   | 3.237         |
| TiO₂  | 0.008   | 0.005   | 0.007   | 0.002   | 0.008   | 0.007   | 0.011   | 0.007         |
| Al₂O₃ | 2.741   | 2.570   | 2.714   | 3.013   | 2.525   | 2.498   | 2.727   | 2.648         |
| Fe²⁺  | 0.055   | 0.054   | 0.047   | 0.038   | 0.088   | 0.105   | 0.065   | 0.071         |
| MnO   | 0.000   | 0.000   | 0.000   | 0.001   | 0.000   | 0.001   | 0.001   | 0.002         |
| MgO   | 0.107   | 0.163   | 0.080   | 0.003   | 0.134   | 0.166   | 0.097   | 0.127         |
| CaO   | 0.005   | 0.000   | 0.005   | 0.000   | 0.003   | 0.001   | 0.000   | 0.001         |
| Na₂O  | 0.124   | 0.075   | 0.230   | 0.933   | 0.072   | 0.084   | 0.117   | 0.002         |
| K₂O   | 0.734   | 0.724   | 0.630   | 0.026   | 0.706   | 0.760   | 0.741   | 0.677         |
| Cr₂O₃ | 0.001   | 0.000   | 0.000   | 0.000   | 0.002   | 0.000   | 0.000   | 0.000         |
| NiO   | 0.000   | 0.000   | 0.000   | 0.000   | 0.000   | 0.000   | 0.000   | 0.000         |
| P₂O₅  | 0.000   | 0.031   | 0.000   | 0.000   | 0.033   | 0.000   | 0.000   | 0.000         |
| ClO   | 0.000   | 0.000   | 0.000   | 0.000   | 0.000   | 0.000   | 0.000   | 0.000         |
| Total | 94.35   | 95.09   | 93.36   | 96.88   | 94.30   | 94.25   | 95.19   | 95.99         |

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**Figure 4.** Trinagular plots for white mica and chlorite from the carpholite bearing quartz veins in graphite rich metapelites from the Parla Sapat Unit.
reflecting the crustal exhumation (Wilke et al., 2010). The peak greenschist-facies minerals were dated to 31.7 - 34.5 Ma (Wilke et al., 2010), published a P-T path assigning 47.4 ± 0.5 Ma to the UHP event, and 46 to 41 Ma to the post-eclogitic exhumation of the mantle. At ca. 41 Ma a phase of stagnation occurred heating the rocks by more than 100°C at/in the lower crust. After this thermal peak greenschist-facies minerals were dated to 31.7 - 34.5 Ma reflecting the crustal exhumation (Wilke et al., 2010). The P-T evolutions for the two UHP areas are in good agreement.

### Significance of Fe,Mg-carpholite occurrence

P-T conditions (0.7 GPa, 400°C) presented for the Shangla rocks (Guiraud, 1982; Jan, 1985) are clearly influenced by retrograde processes or even significantly overprinted by a second metamorphic event (P II). The published P-T values do not point to real blueschist-metamorphic condition, while the mineral assemblage clearly does. Contrastingly the Fe,Mg carpholite relics from vein type 3 and the lack of either kyanite or chloritoid as well as the abundant sudoite component in chlorite of the graphite-rich meta-pelites of the Banna-Parla-Sapat Unit point to a blueschist HP-LT peak and a rapid decompression typically associated with exhumation processes in an accretionary wedge during subduction. The dynamic setting, in combination with the ages reported for the different blueschists, eclogites and UHP rocks allows to separate the two metamorphic events (P I, P II), with their respective P-T paths (Fig. 5). The graphite-rich meta-pelites of the Parla-Sapat Unit as well as the Shangla blueschist record an early subduction stage in an accretionary wedge setting with an early, Cretaceous, almost isothermal exhumation. However, only the armoured relics of carpholite, white mica and chlorite included in quartz of syn-metamorphic veins record the pressures at peak conditions.

The glaucophane-bearing parageneses of the Shangla blueschists show the effect of retrogression during the subsequent collision stage, which was leading to amphibolite-facies conditions. Similarly the Lesser and Higher Himalaya rocks of the Indian plate, record mainly the later Tertiary collision phase that brought continental crust to various depths. Peak conditions and exhumation paths deduced from UHP rocks (Wilke et al., 2010) indicate that the rocks were amalgamated with other parts of crustal rocks showing amphibolite-facies conditions. This is recorded by significantly different P-T evolutions (Fig. 5). The identification of carpholite inclusions in quartz veins allows a better characterisation of the two-step HP-evolution in the Khaghan region. Moreover the juxtaposition of the Tertiary HP/UHP unit to the Cretaceous blueschist unit at mid crustal levels during exhumation at ca. 44-41 Ma (Wilke et al., 2010) is evidenced.

The occurrence of Fe,Mg carpholite relics within the Banna-Parla-Sapat Unit points to blueschist-facies overprint of the entire meta-sedimentary section and not only of the mafic portions in the mélangé zones. The meta-pelitic low-grade high-pressure sediments contain characteristic associations of subduction related metamorphism similar to other collision orogens such as the Bethics, the Western Alps or Anatolia. The sediments of the Banna-Parla-Sapat Unit point to an extended blueschist belt along the Indus-Tsampo Suture zone in the Kaghan Valley that possibly spreads all along the suture zone towards east. This assumption is based on observations from the Tethyan realm in the Alps and especially in Anatolia where recently an extensive HP belt of over 600 km length characterised by carpholite was identified (Candan et al., 2005, Pourteau et al., 2010).

The observation of carpholite in the Himalaya adds to the record of Tethyan blueschist-facies meta-sediments (Fig. 6). They stretch from the Rif in Morocco to New Caledonia. However, the absence of Fe,Mg carpholite in Iran remains enigmatic. Besides the late Cretaceous to Tertiary meta-sediments of the Tethyan realm carpholite was also reported from Palaeozoic rocks of Svalbard (Agard et al. 2005) and the North Qilian suture zone (Song et al., 2007). Yet no Fe,Mg carpholite has been found along the circum-Pacific subduction belt with its volcanic arcs. This must be attributed to the volcaniclastic nature of the sediments and their high sodium, low potassium content. Up to now Fe,Mg carpholite associated with albite was not observed.

Models of crustal collision and crustal flow assign fluids, which enhance flow, an important role. The observation from the Kaghan Valley, corroborates these hypotheses. The area consists of three tectonic units: Lesser Himalaya, Higher Himalaya and a mélangé unit associated with meta-sedimentary units below the Main Mantle thrust of the Kohistan arc. Around Naran the first two units exhibit remnants of a high-grade metamorphic evolution. The Lesser Himalaya meta-pelitic units hold paragenesis with garnet and staurolite, typically indicating amphibolite facies conditions. Rocks of the Higher Himalaya contain Tertiary eclogites and relics of UHP with coesite. During Cretaceous subduction the wedge sediments, represented by

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Figure 5. Synthetic P-T Diagram showing the P-T data deduced from carpholite relics using Oberhäsili et al. (1995). The high-T side of the stability field of carpholite is constrained by $X_{\text{Mg}}$Carphe according to the experimental work of Vidal et al. (1992). The dark grey field represents the compositional variation in the Kaghan rocks the light grey box a possible P-T evolution. Numbered dotted lines indicate Si content in phengite. Blue square: P-T Estimate for the Shangla blueschists (Guiraud, 1982; Jan, 1985) with a metamorphic age of ~80 Ma (Anczkiewicz et al., 2000). The grey ellipses cover representative P-T space compiled from published data for Lesser and Higher Himalaya (Smith 1994), the glaucophane eclogites (Lombardo et al., 2000) and the UHP rocks (Treolar 1998; O’Brien et al., 2001). Simple dashed line indicates suggested P-T paths. Double dashed line represents the P-T Evolution for the UHP rocks in the Kaghan Valley after Wilke et al. (2010).
the Banna-Parla-Sapat Units along the Kohistan Arc, underwent significant dehydration. By integration into an accretionary wedge, deep-seated portions of the wedge sediments (not exhumed) allowed for the incorporation of water-rich fluids into the overlying lithospheric mantle. The rheologic behaviour of a probably amphibole and/or phlogopite bearing hydrated mantle, with a significantly lower density (>5%, Bousquet and Oberhansli, 2010), is possibly a prerequisite but surely enhanced later subduction of the Indian continental crust.

A template for the situation in the Himalayas, where after the subduction events continent - continent collision finally lead to building of a high plateau, can be identified in eastern Anatolia where the plateau formation is still in “statu nascendi”. At this location the Arabian continental crust it just about to impinge with the Eurasian continental plate. For Eastern Anatolia the carpholite bearing metasediments of the Bitlis Complex indicate a rapid, cold exhumation (Oberhansli et al., 2010). A successive second event representing greenschist- to amphibolite-facies conditions has yet to develop or to be exposed along the Arabian indenter, while it is already expressed in the Southern Caucasus where the south Armenian Block collided with the Eurasian plate (Rolland et al., 2008; Oberhansli et al. 2011).

Conclusions

The occurrence of carpholite in the graphitic metapelites of the Parla-Sapat Unit near Naran in the Kaghan Valley associated with the ophiolitic mélanges along the Indus-Tsampo suture indicate a much wider extension of a blueschist belt along the suture. The identification of minute carpholite inclusions surviving later high-temperature metamorphic evolution in quartz veins allowed to characterize the two-step HP evolution of the Khagan region and documents the juxtaposition of the Tertiary HP/UHP unit to the Cretaceous blueschist unit within the subduction channel. It is noteworthy that the blueschist from the mélanges do not preserve the Cretaceous HP peak but only stored the post-HP evolution.

With the new data presented, a clear distinction between the subduction event forming blueschists and the later collision event producing amphibolite/migmatite is possible. This dual peak metamorphic evolution is representative for an area in progressing full continent - continent collision such as the Himalaya.

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