BONES, ROCKS, AND FLAMES:

Mineralogy and petrology of slags and cremated bones from ritual immolation sites in Tyrol

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Introduction

Impetus for these investigations:

•Slag samples from an archaeological site in Oetz.

•Petrology of these slags as examples of pyrometamorphic rocks.

•Close collaboration between mineralogy/petrology and archaeology in the frame of the research center HiMAT.

•HiMAT stands for: **The history of Mining in the Tyrol and Adjacent Areas**.

Question:

Is it possible to find **mineralogical** evidence for fire/bone/rock interactions at ritual immolation sites?

Introduction

Research history

Research on ritual immolation sites in the Alps started in 1966 by a paper by **Werner Krämer.**

He describes: ***... where masses of calcinated bones allow the interpretation of ritual immolation....***

...as well as the occurrence of large masses of ceramic fragments which can also be interpreted as sacrifical offerings....

For the **first time** these sites were considered from an archaeological standpoint as a group of their own.

Introduction

His research focussed on the ritual immolation site at the **Schlern** in South Tyrol. This site is one of the **most impressive ritual immolation sites** in the Eastern Alps!

Steiner (2013)

Introduction

Structure of this talk

1. **Overview** of ritual immolation sites in the western part of the Eastern Alps.

2. **Mineralogical/petrological investigations** of slags from two ritual immolation sites as well as on calcinated bones from two sites.

3. **Experimental investigations on pyrometamorphism** of rocks and minerals and comparison to the slags from ritual immolation sites.

4. **Experimental investigations of bone-rock interactions**.

5. **Discussion:** the relevance of P-bearing phases in pyrometamorphic slags.

6. **Conclusions**

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Part 1

Overview of ritual immolation sites in the western part of the Eastern Alps

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Part 1

Ritual immolation sites in the Eastern Alps: Steiner (2013)

From when on? Beginning roughly in the **Early Bronze Age** occasionally lasts until the Roman period.

Who did it? Farming populations.

Why did they do it? Sacrifices for the gods for **good harvests and herds**.

What was sacrified? In the mountains **goats and sheeps** were sacrified in the valleys **cows, pigs, deer** etc. Usually **skulls** and **extremities** of the animals were sacrified.

Where did this take place? In the Bronze Age in **isolated sites**, in the Iron Age in the **vicinity of dwellings**.

Part 1

Ritual immolation activities coincide with:

- **Increasing populations and hence**
- **Increasing farming**

from the **Middle Bronze Age** on.

What is the idea behind it?

Fire is considered to have **cleansing properties**. The so „cleansed“ sacrifice is transferred to the gods **via smoke**.

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Part 1

What are the characteristics of alpine ritual immolation sites?

Not always easy to define!

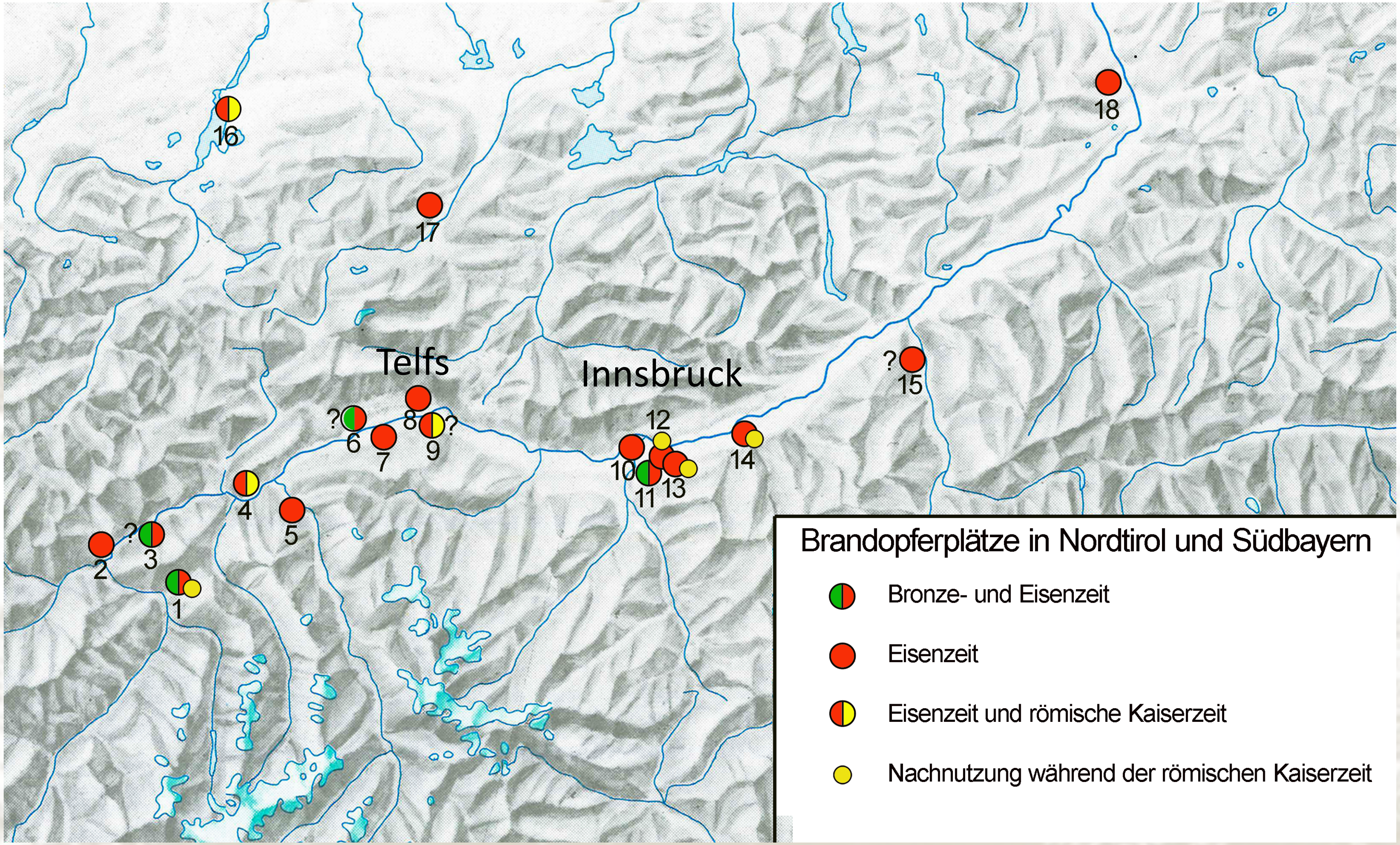
- Exposed position
- Ash layers
- Altars
- Calcinated bones
- Bone deposits
- Ceramic fragments and other sacrified goods
- Pyrometamorphic slags

Part 1

Exposed position

Part 1

In the western part of the Eastern Alps (S-Bavaria to S-Tyrol) ca. **200 known ritual immolation sites** exist. Shown here is only a selection from Tyrol.



Tomedi (2013)

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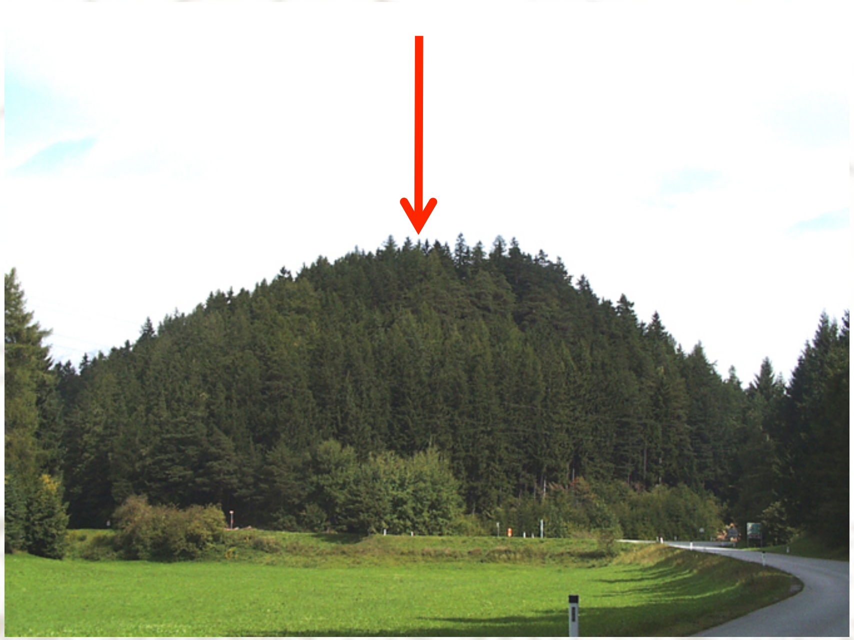
Part 1

Many of them can be found on **exposed positions**.

Schlern/Seis

Steiner (2013)



Goldbichl/Igls

Tomedi (2013)

Ash layers

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Part 1

These ash layers vary in thickness.

Stratification occurs

Pillerhöhe

Tschurtschenthaler (1996)

St. Walburg/Ulten

Steiner (2010)

Part 1

Stratifications imply **frequent re-use**! This is an **important** criterium!

Tschurtschenthaler (1996)

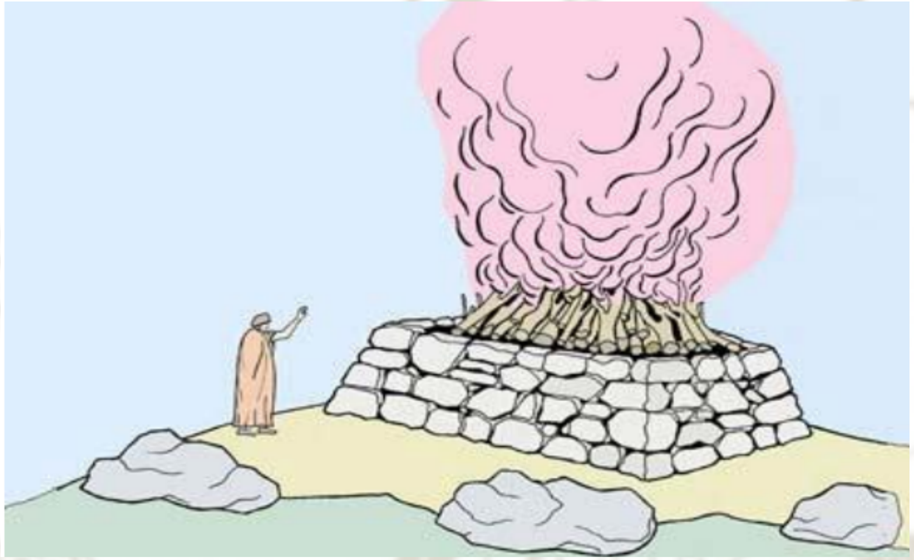
Pillerhöhe

Part 1

Altars

Part 1

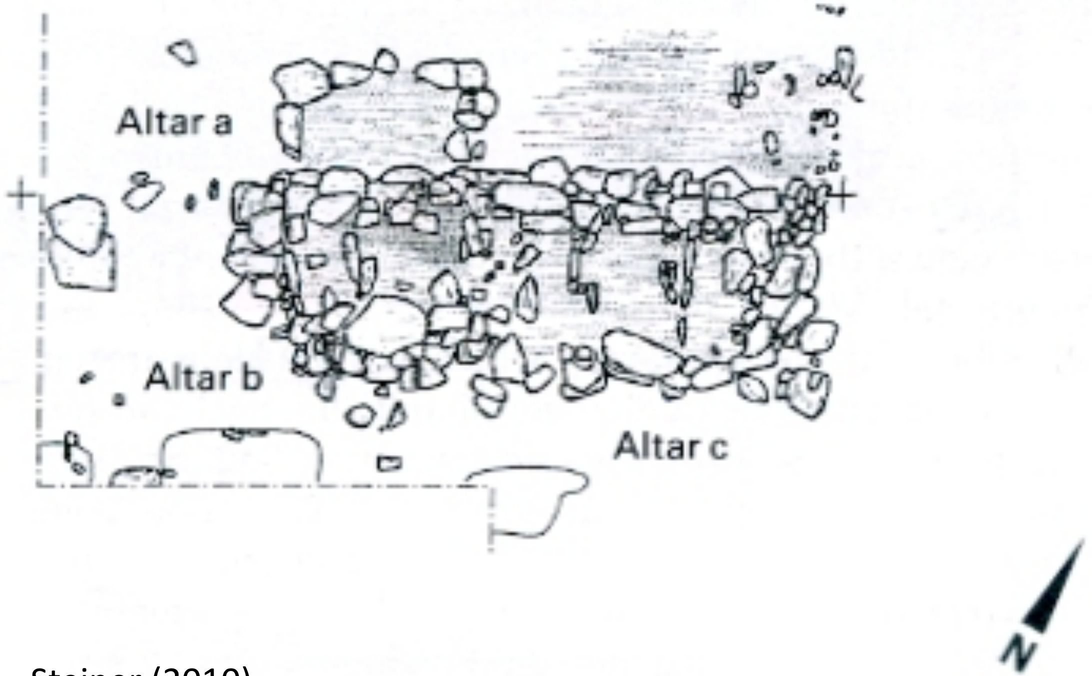
What do altars look like? They are **circular structures** made from rocks from the **vicinity**!



Links oben: Steinaltar
URL: //www.goldbichl.at/goldbichl%20fuer%20schuele.pdf
Rechts oben: *Steinaltar aus Ulten, Südtirol*
Gleirscher et al. (2002)

Part 1

Very often **several altars** occur!



Steiner (2010)

St. Walburg/Ulten

Part 1

Calcinated bone fragments

Part 1

This is one of the **most characteristic and visible features** of ritual immolation sites!

Schlern/Seis Steiner (2010)

Scheibenstuhl/Nenzing Wink & Kaufer (2013)

Part 1

Schluderns

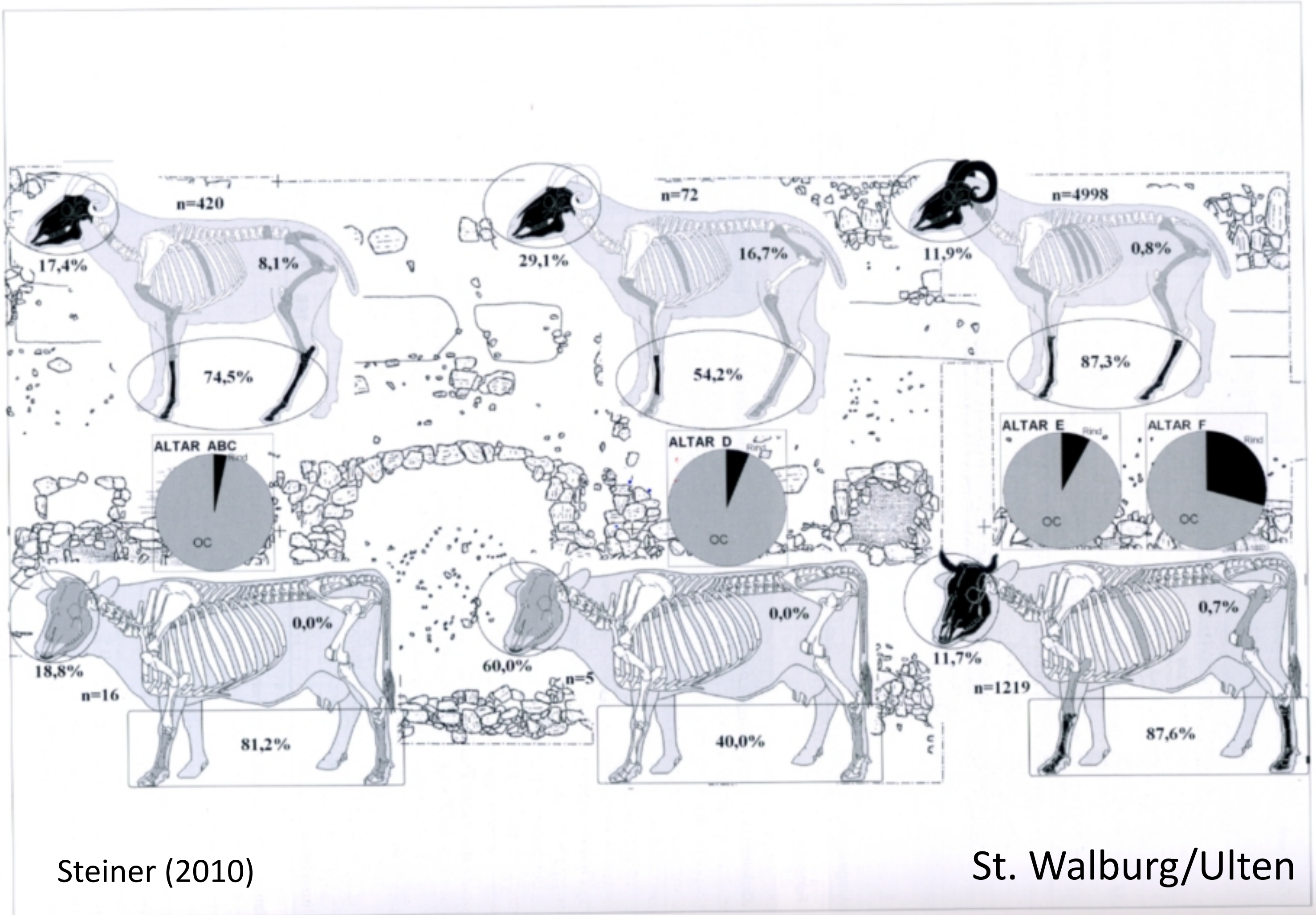
Steiner (2010)

Masses of small calcinated bone fragments occur.

St. Walburg/Ulten

Part 1

Most bone fragments are either from **the skulls or the extremities** of the animals.



Steiner (2010)

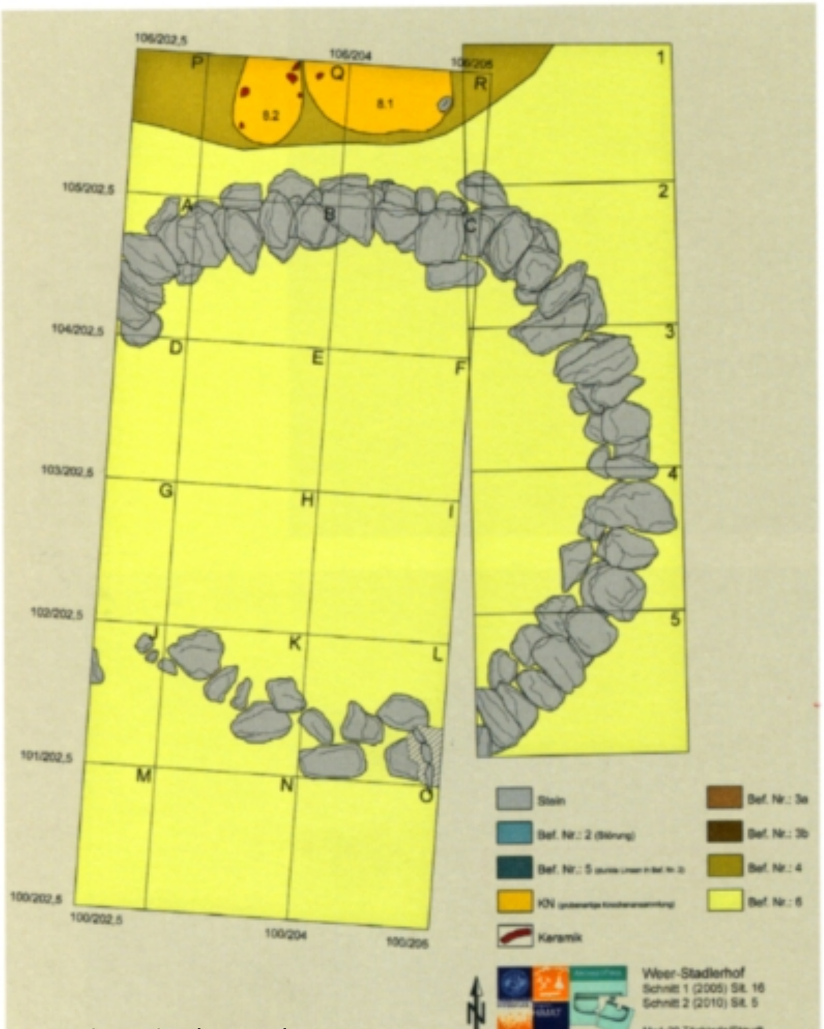
St. Walburg/Ulten

Part 1

Bone deposits

Part 1

In the **vicinity** of some sites, **bone deposits** occur. This indicates **ritual cleansing** of the site after the immolation process.



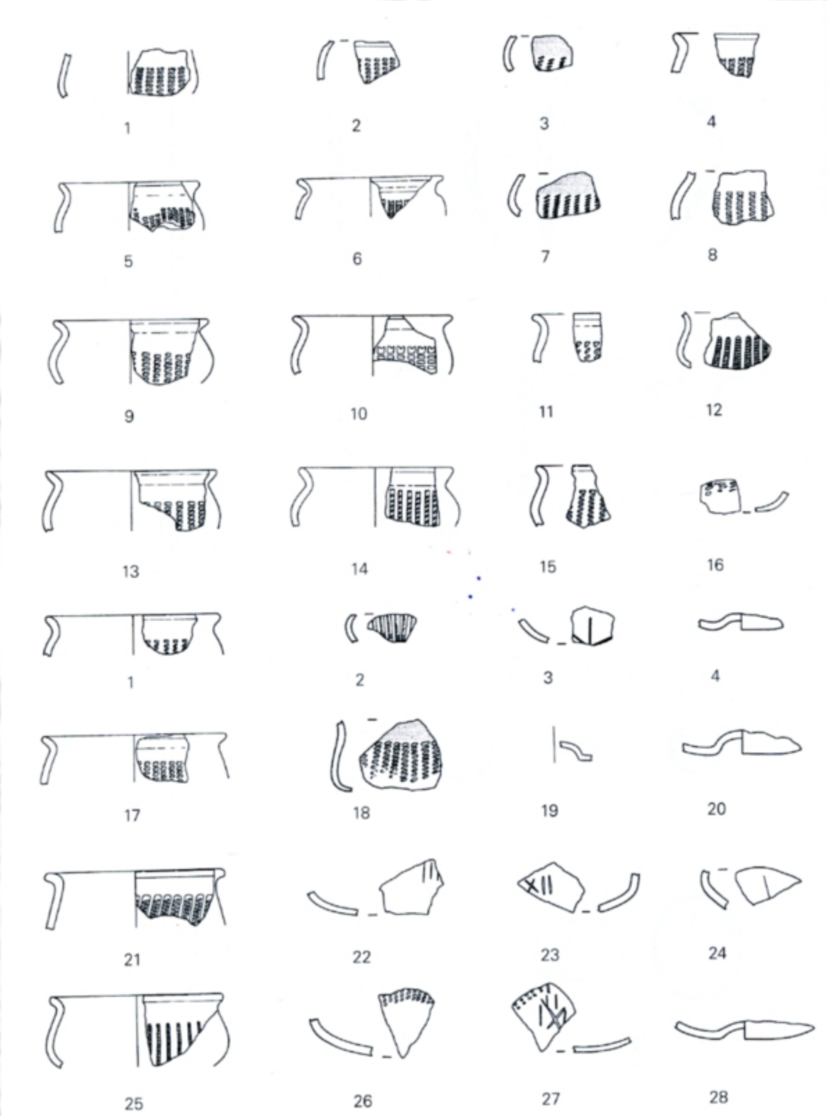
Töchterle (2012)

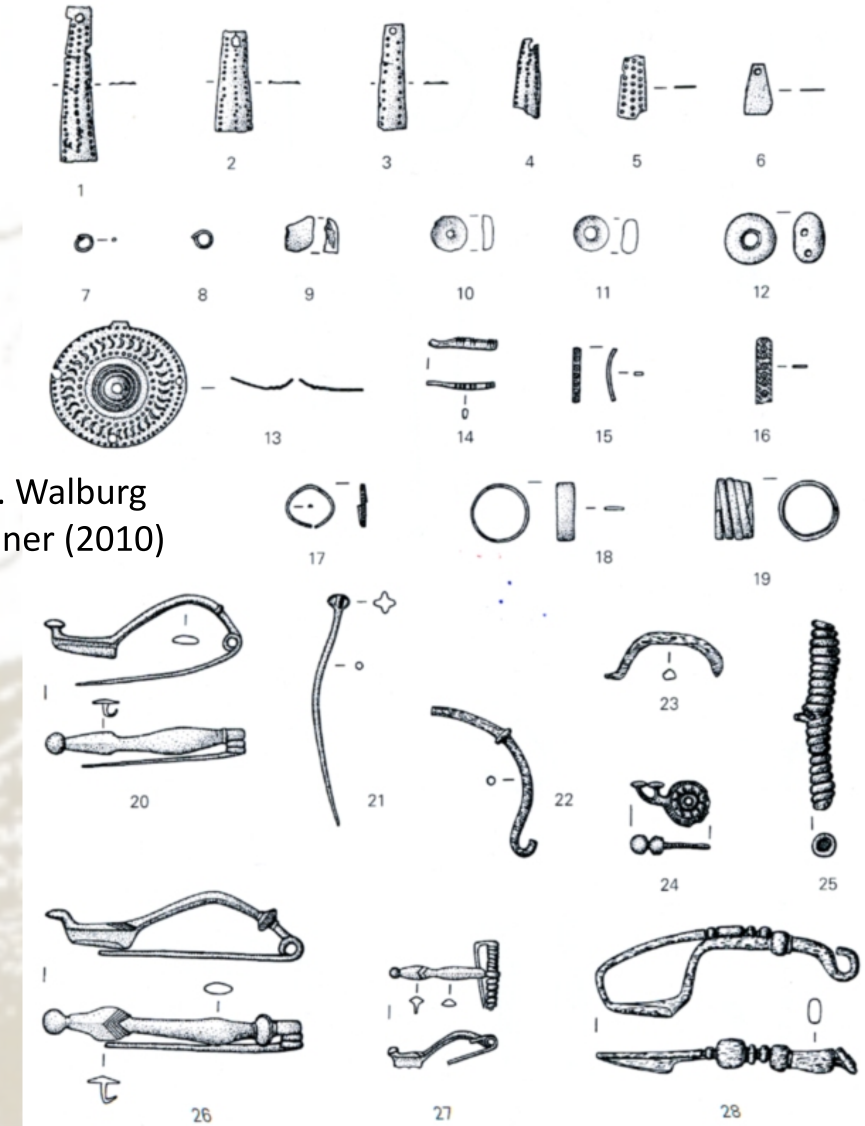
Weer

Ceramic fragments and other sacrified goods

Part 1

Frequently **ceramic fragments** and **metal objects** can be found!





St. Walburg
Steiner (2010)

Pyrometamorphic slags

Part 1

Depending on the rock type: **pyrometamorphic slags** occur sometimes.

Tropper et al. (2004)

Goldbichl/Igls

Steiner (2010)

Karneid

Mineralogical/petrological investigations of pyrometamorphic slags from two ritual immolation sites in Tirol

Part 2

- Mineralogical/petrological investigations allow **putting constraints on firing temperatures as well the O_2-availability** in the fire (fO_2). This information is based upon the occurrence of newly-formed phases.

- Which **new high-temperature phases** form?

- Are they **diagnostic for the firing process**?

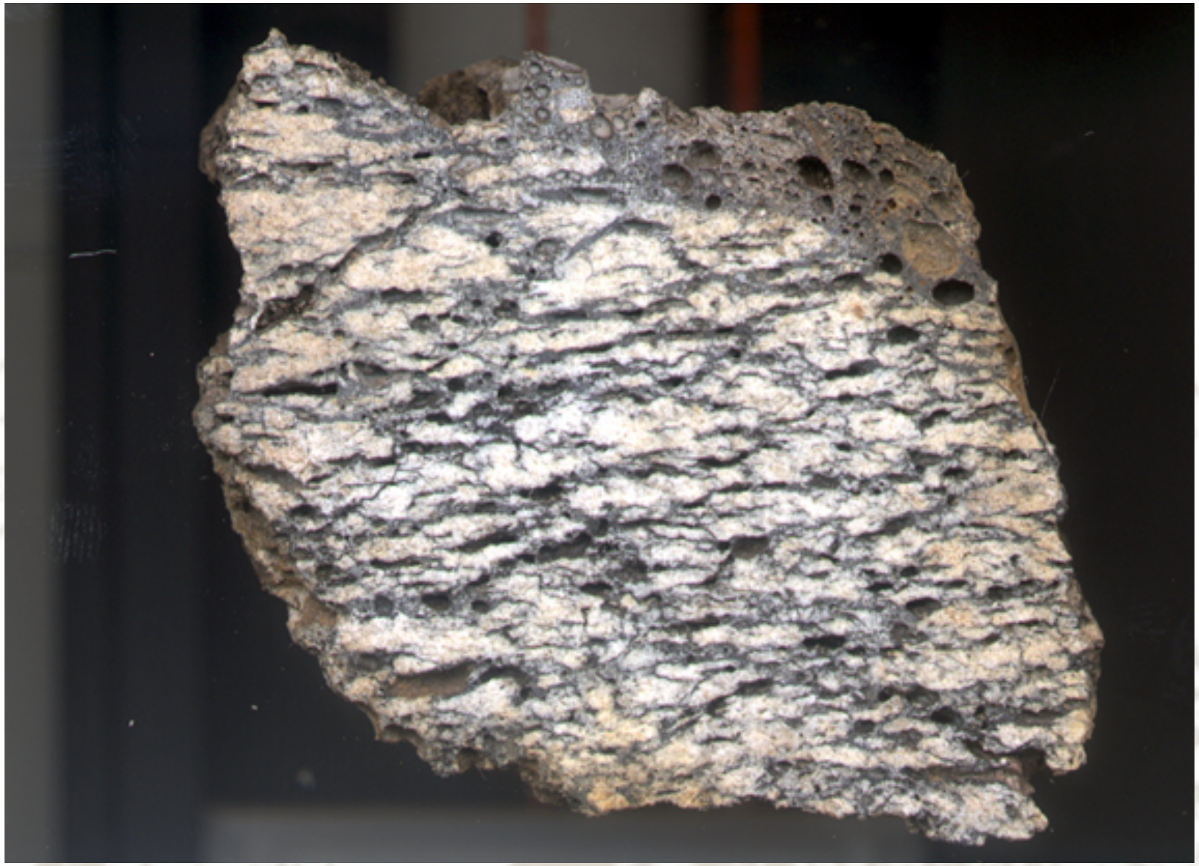
- Do **P-bearing phases** occur and if are they **diagnostic**?

- What are the **temperature constraints** based on **calcinated bones**?

Part 2-1

Pyrometamorphic slags from Oetz

Part 2-1



Tropper et al. (2004)

This site was active during the **late La-Tène Time** (500 – 15 v. Chr.). It is located on **top of a small hill** outside of Oetz. Large amounts **ceramic fragments and animal bones** (sheep, goat, cow) were found.

Slagging occurs only on the **surface of the orthogneiss rocks**.

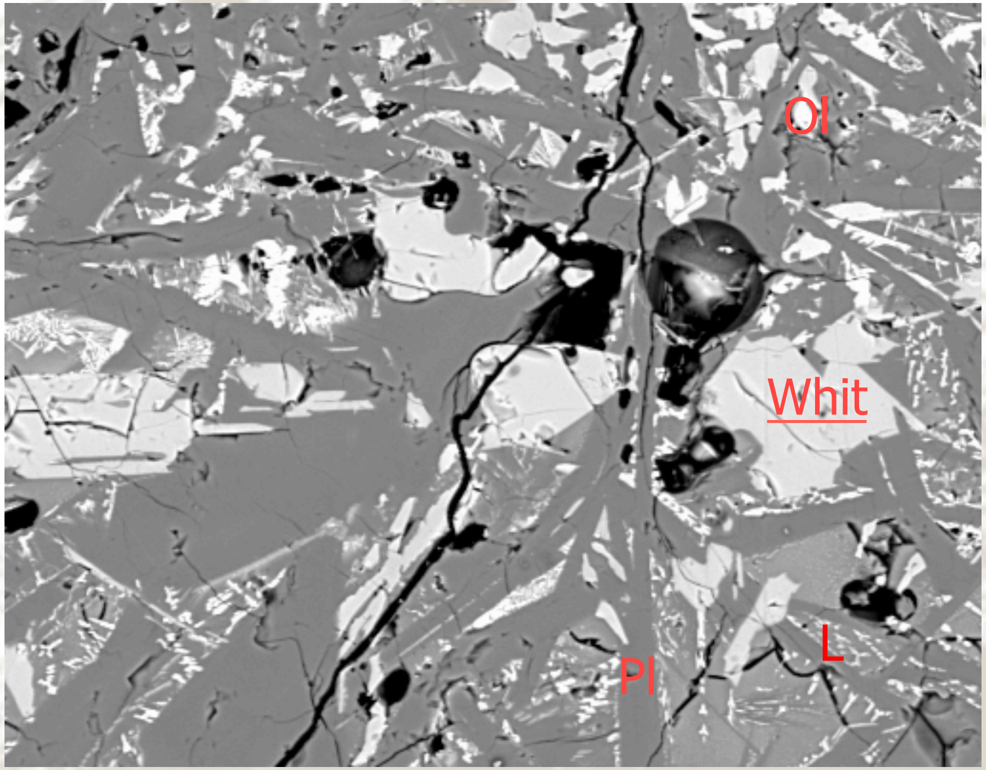
Part 2-1

The mineral assemblage of the protolith orthoneisses is:

biotite + plagioclase + K-feldspar + muscovite + quartz.

The high-*T* mineral assemblage is:

P-bearing olivine + whitlockite + anorthite + glass.

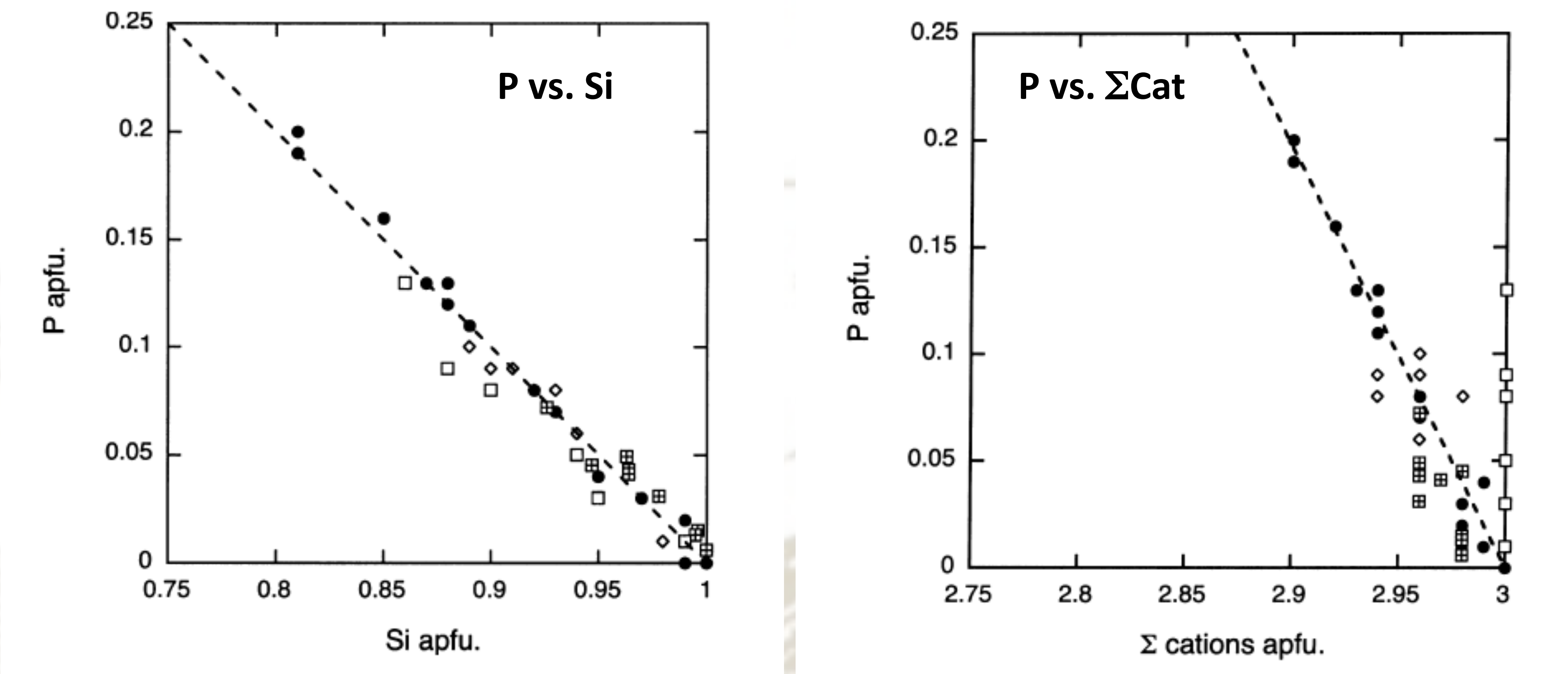


This is a highly unusual P-rich mineral assemblage!

Tropper et al. (2004)

Part 2-1

Olivines are mineralogically interesting: **high P-contents**!



Mineral chemistry shows that olivine **contains P (max. 9 wt.% P_2O_5)**. This substitution affects Si contents and total sum of cations according to the following vector:

Tropper et al. (2004)

$$2P + (\square)M_{1,2} \leftrightarrow 2Si + (Mg,Fe)M_{1,2}$$

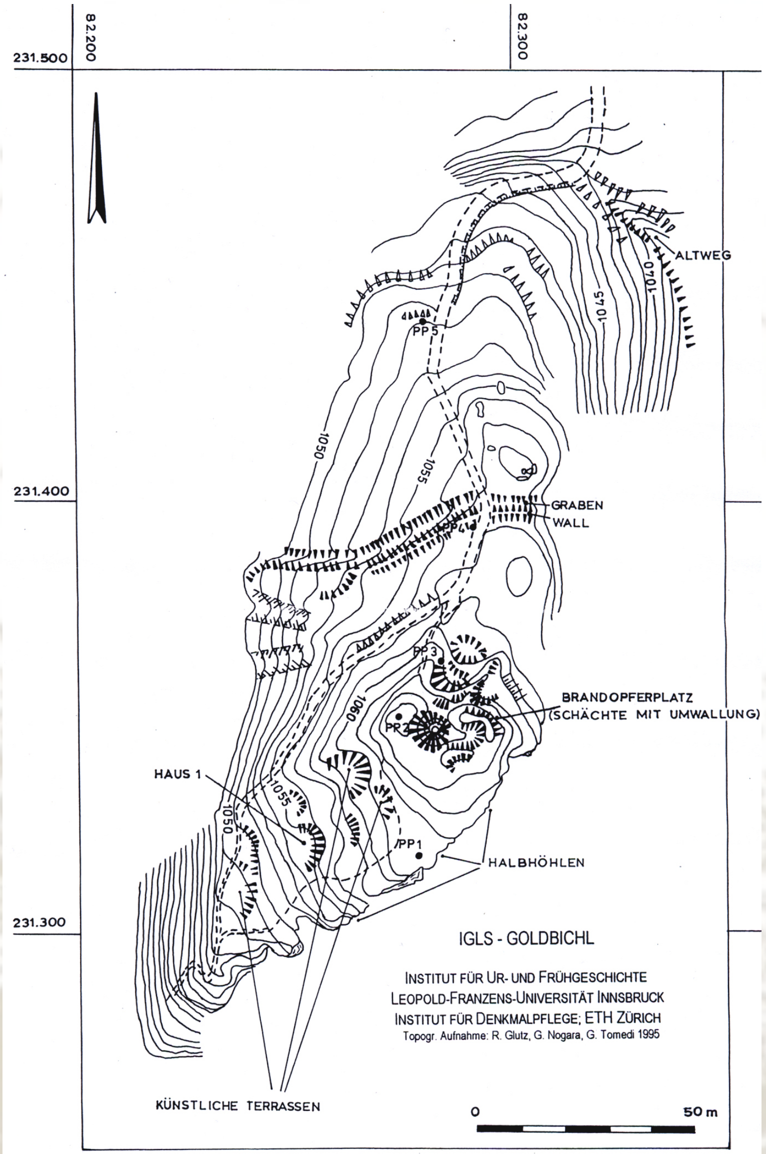
Part 2-2

Pyrometamorphic slags from the Goldbichl/Igls

Part 2-2

Highly **exposed position** near Innsbruck

Tomedi (2012)



Part 2-2

http://www.goldbichl.at/schule.html

This immolation site was active during the **Middle Bronze Age** (ca. 1900 - 1650 BC) and **the Late Iron Age** (ca. 500 - 15 BC).

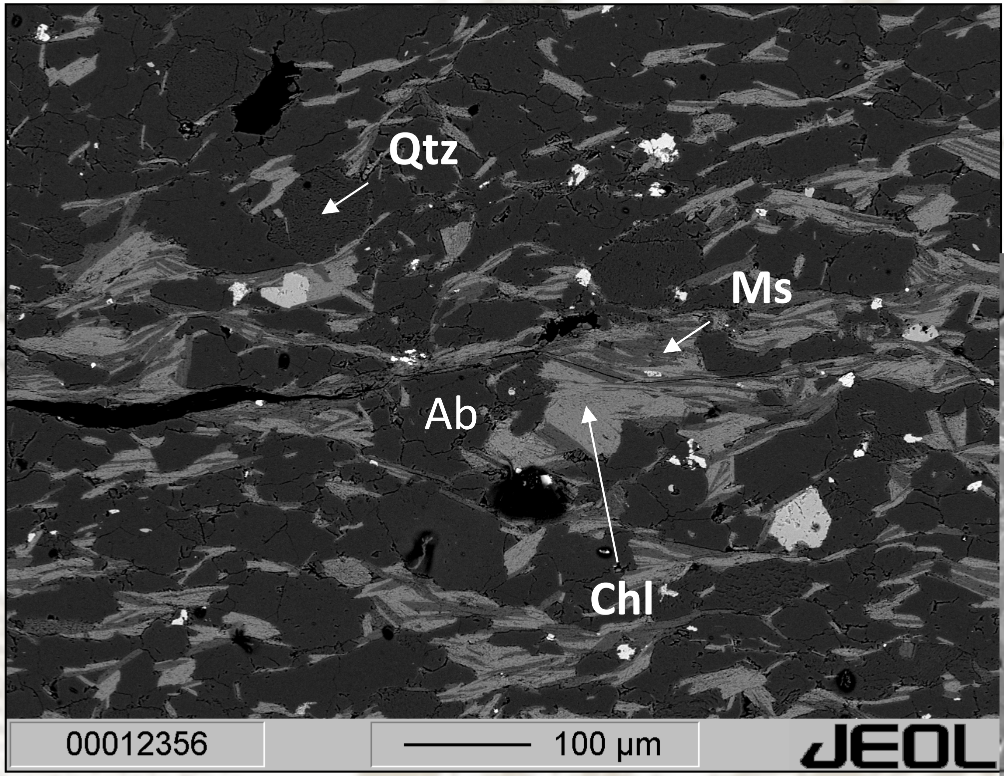
Abundant **bone and ceramic fragments** as well as **silex arrowheads** were found.

Part 2-2

Massive amounts of pyrometamorphic slags were found!

Part 2-2

During **pyrometamorphism** the rock changes its mineral assemblage:



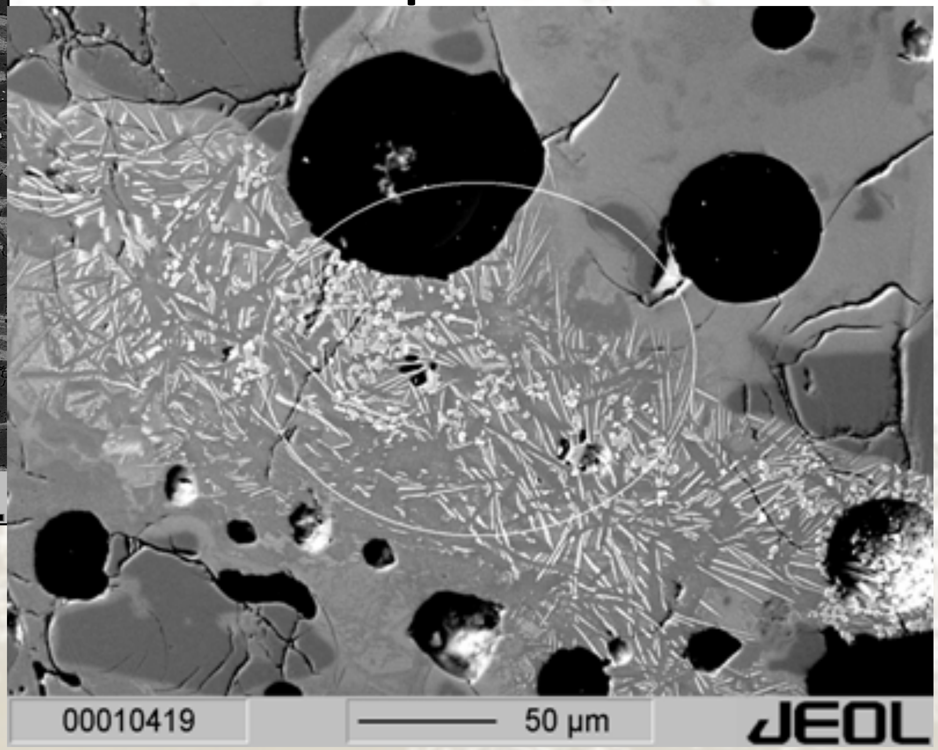
Protolith rock assemblage:

chlorite + muscovite + albite + quartz

Large degree of melting and mineral reactions occur! Rock changes texture and mineralogy.

Former chlorite domain:

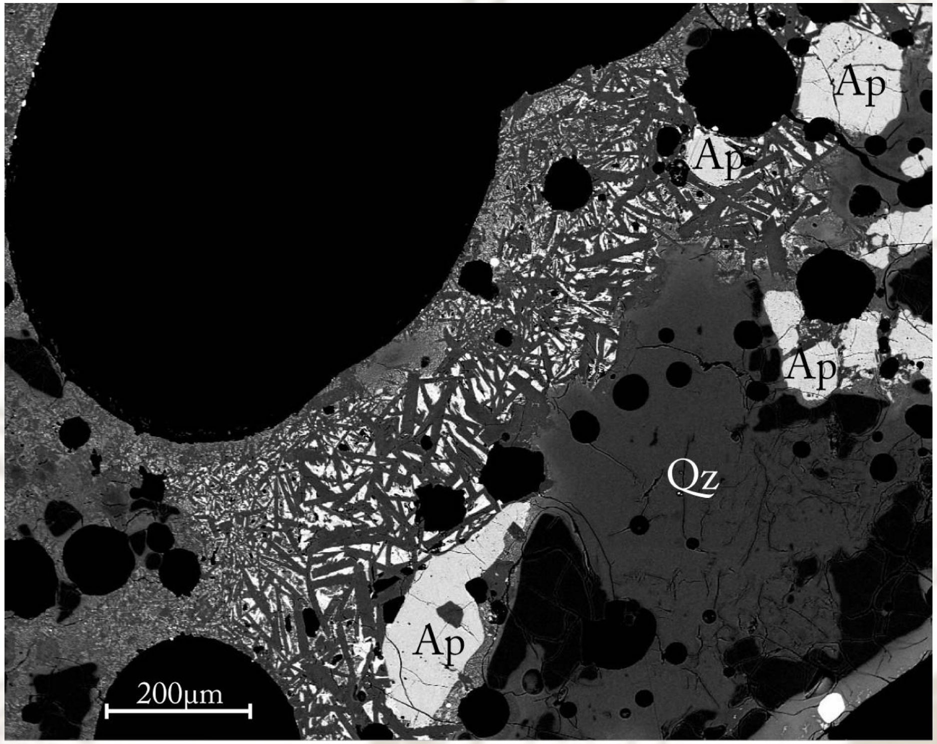
olivine + spinel + anorthite

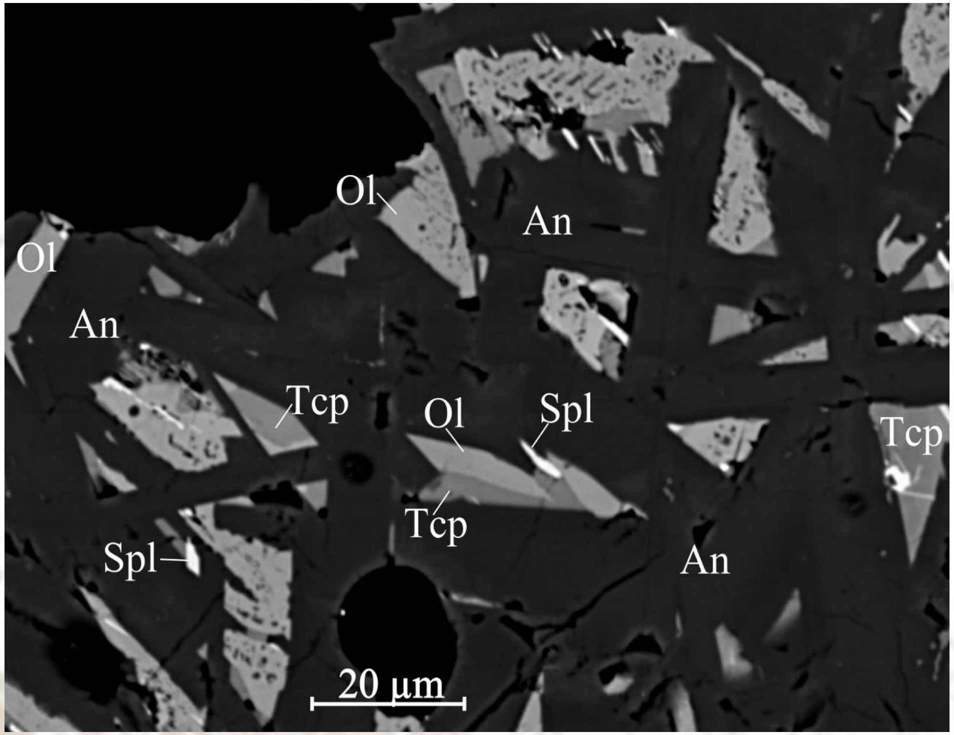


Schneider et al. (2013)

Part 2-2

In some localized areas **P-rich micro-domains** occur!





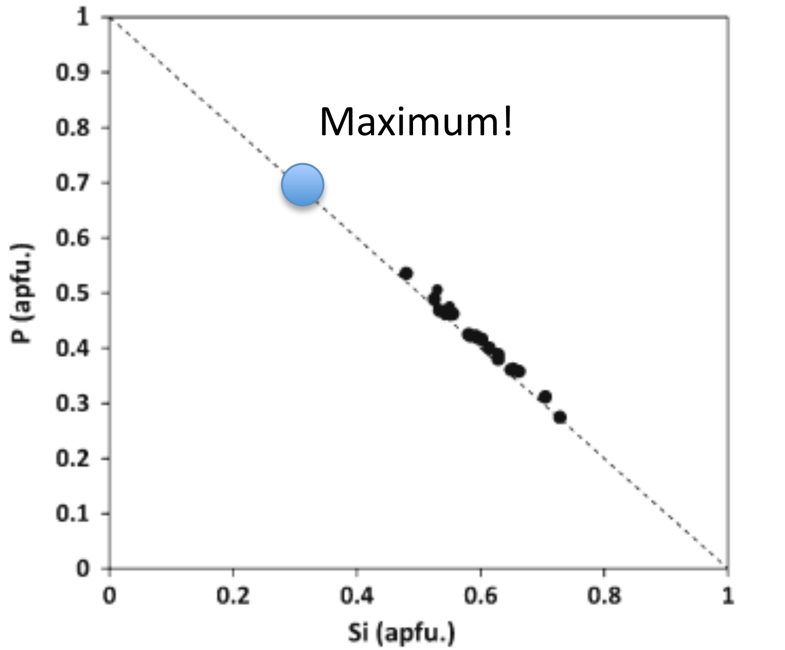
Schneider et al. (2013)

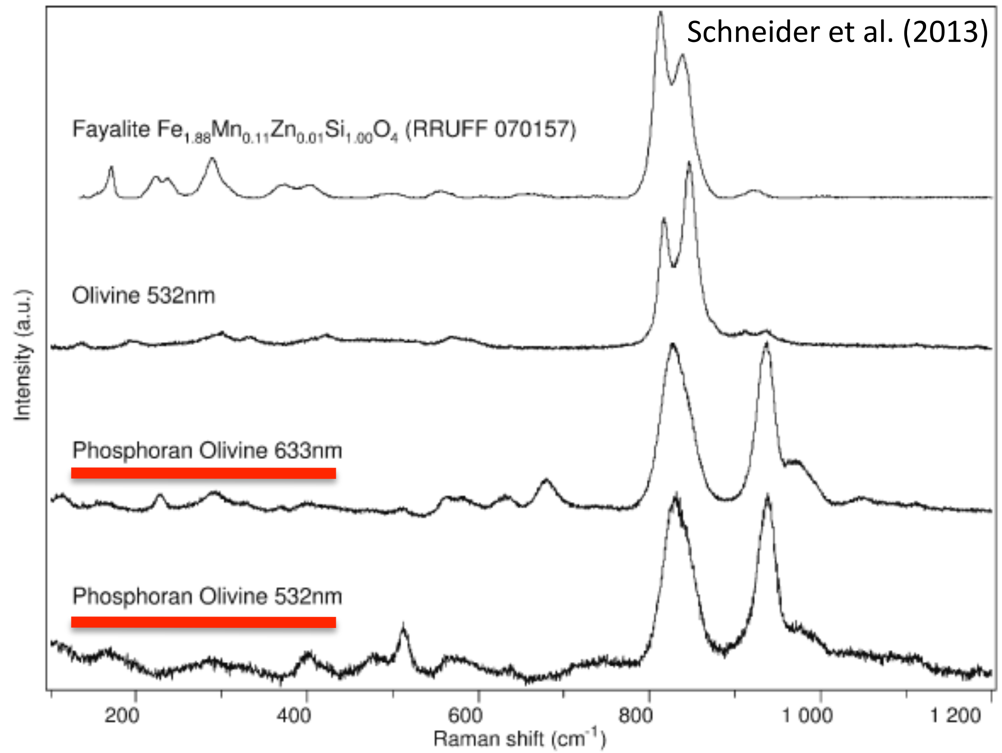
- In the **vicinity of apatite**.
- Olivine contains up to **23 wt.% P_2O_5**!
- **Stanfieldite** (TCP, $Ca_4Mg_5(PO_4)_6$) occurs.
- Anorthite contains up to **2 wt. % P_2O_5**!

This is also a highly unusual P-rich mineral assemblage!

Part 2-2

This P-rich olivine shows the **highest P-contents** found on Earth so far!



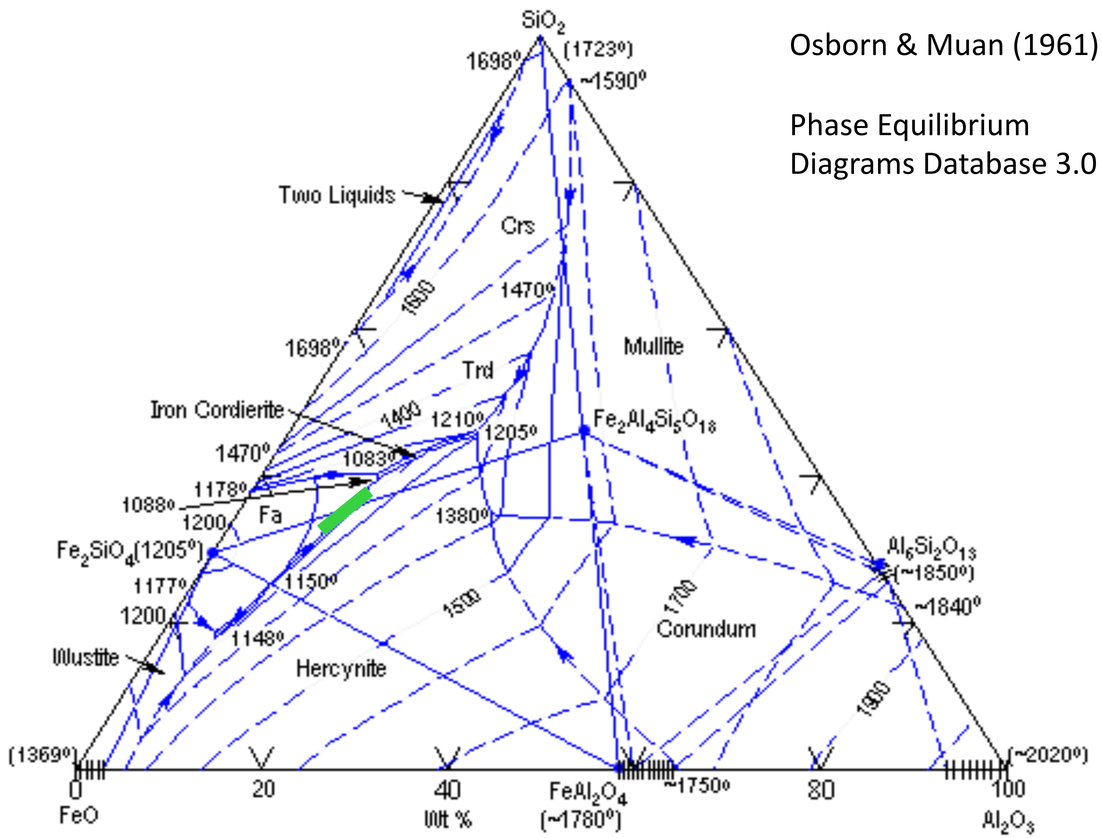


2P+ (□)$M_{1,2}$ ↔ 2Si + (Mg,Fe)$M_{1,2}$

Due to the high PO_4 contents, **significant changes** in the Raman spectra occur.

Part 2-2

Rough temperature constraints based on phase diagrams in the system SiO_2-FeO-Al_2O_3 only possible!



Osborn & Muan (1961)

Phase Equilibrium Diagrams Database 3.0

Coexisting **olivine + spinel** indicate at least ***T* ≥1000-1100°C**!

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Part 2-1 and 2-2 Conclusions

- Formation of **micro-domains** in the pyrometamorphic slags.
- **No textural and chemical equilibrium** in the slags!
- Temperature of formation **>1000-1100°C**.
- Extremely **high P-contents** of olivine.
- **P-phase occurrence** (whitlockite, stanfildite) is highly interesting!
- Petrological results now need to be **correlated with experimental and archaeological evidence**!

Questions to be answered:

- **What are the P-phases telling us?**
- **Can we verify these high temperatures experimentally?**
- **What do these high temperatures mean archaeologically?**

Part 2-3

What can be learned from calcinated bones?

Part 2-3

Calcination is a **thermal treatment process** in presence of air or oxygen applied to ores and other solid materials to bring about a **thermal decomposition**, phase transition, or removal of a volatile fraction.

The calcination process normally takes place **at temperatures below the melting point** of the product materials.

Calcinated bones form at fire temperatures of up to 600°C. Organic matter **(collagen)** burns off and anorganic materials such as **hydroxyl-apatite** remains.

In the course of this process the **color of the bones changes**.

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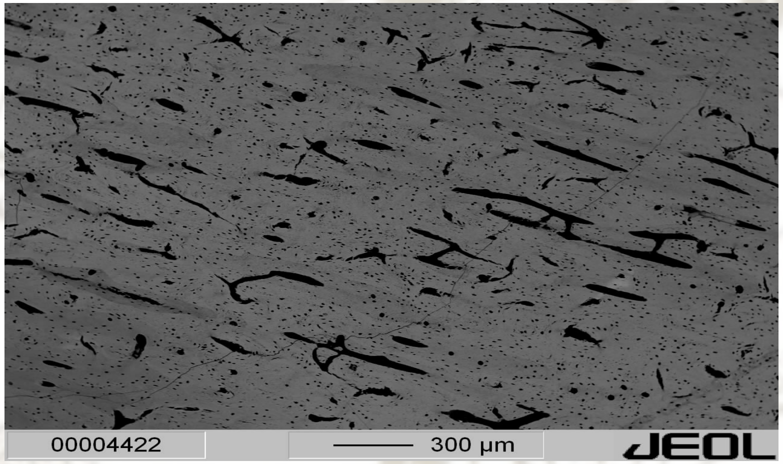
Part 2-3

Verbrennungsstufe	Färbung der Knochenreste		entsprechender Temperaturwert	Bemerkungen/Zustand der Knochenreste
I	gelblichweiß elfenbeinfarben glasig	**Yellow**	bis 200 °C um 250–300 °C	wie unverbrannter, frischer Knochen erste Schrumpfung durch Wasserverlust (ca. 2%)
II	braun	**Brown**	um 300 °C	Beginn des Austriebs organisch gebundenen Kohlenstoffs
	dunkelbraun schwarz	**Black**	um 400 °C	Verkohlung der organischen Knochensubstanz
III	grau blaugrau, taubenblau milchig hellgrau	**Grey**	um 550 °C	Kompakta manchmal innen noch schwarz
IV	milchig weiß mattweiß kreideartig	**White**	ab 650–700 °C	kreidig samtige, abreibbare Oberfläche (»kalziniert«) Kompakta innen manchmal noch grau ab ca. 750 °C kontinuierlich stärkere Schrumpfung
V	altweiß schmutzigweiß	**White**	ab ca. 800 °C	Knochen spröde, hart und fest (»versintert«) Auftreten typischer Hitzerisse je nach Bodenlagerung hellbeigefarben, weißlichgrau o. ä. maximale Schumpfung (25–30%), durchschnittlich 12% Spongiosa manchmal gelblich-ockerfarben

The color of bones changes!

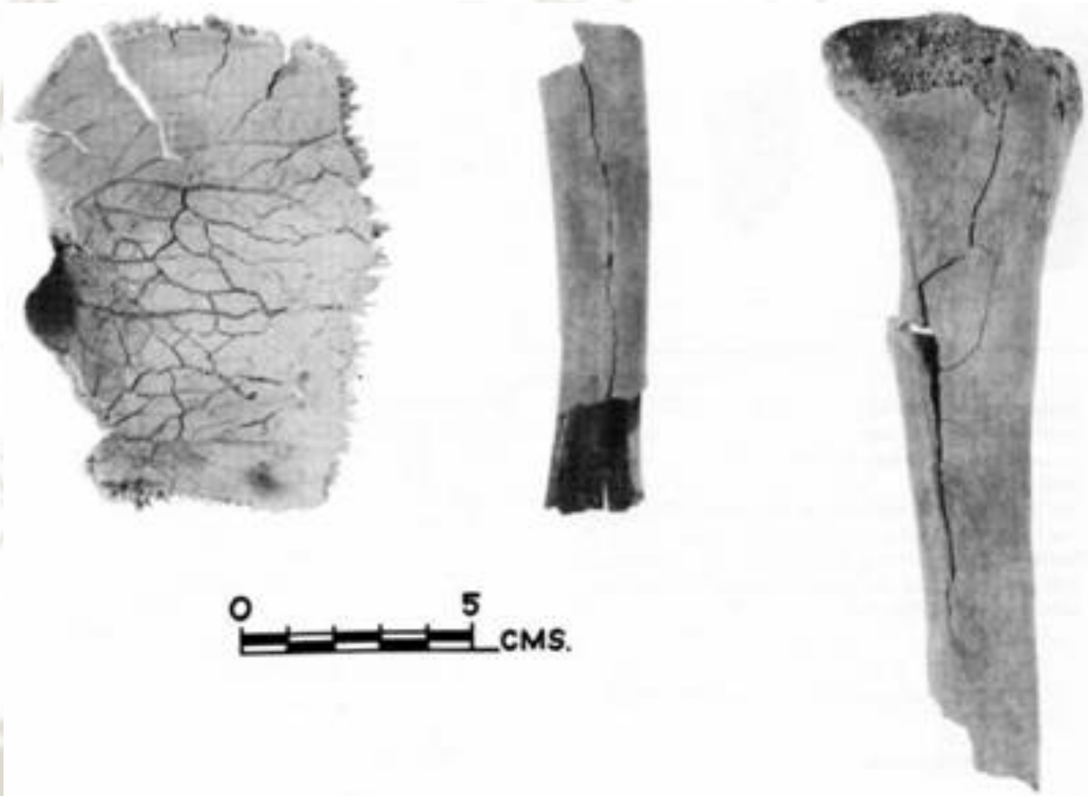
Wahl (1997)

Due to heating **shrinking in size** and **strong fragmentation of bones** occurs. Typical fractures form during the firing process.



Bitterlich (2012)

BSE image of fractures due to decrease in size.



International Journal of Medical Sciences (2012)

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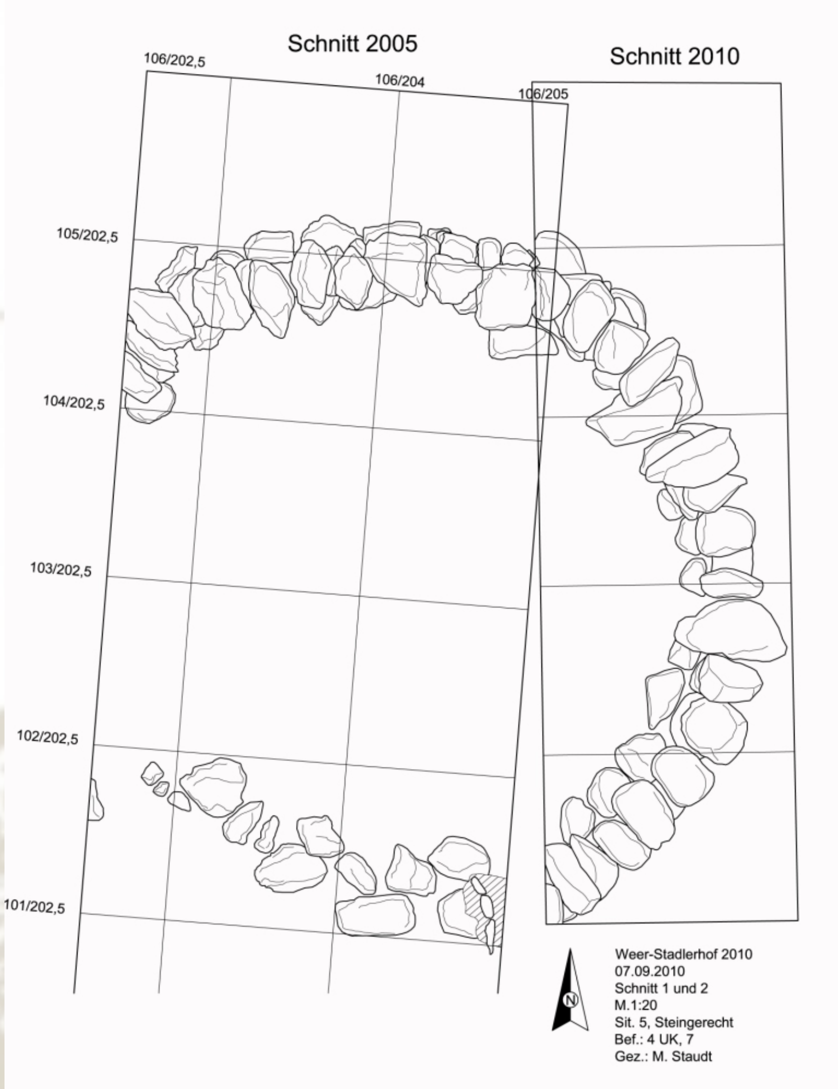
Part 2-3

Many bone fragments were retrieved from the **bone deposit Weer-Stadlerhof**.

Age: **1600-1250 BC**

One of the oldest bone deposits found so far!

The position of the **ritual immolation site** has **not been found** yet.



Töchterle (2012)

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Part 2-3

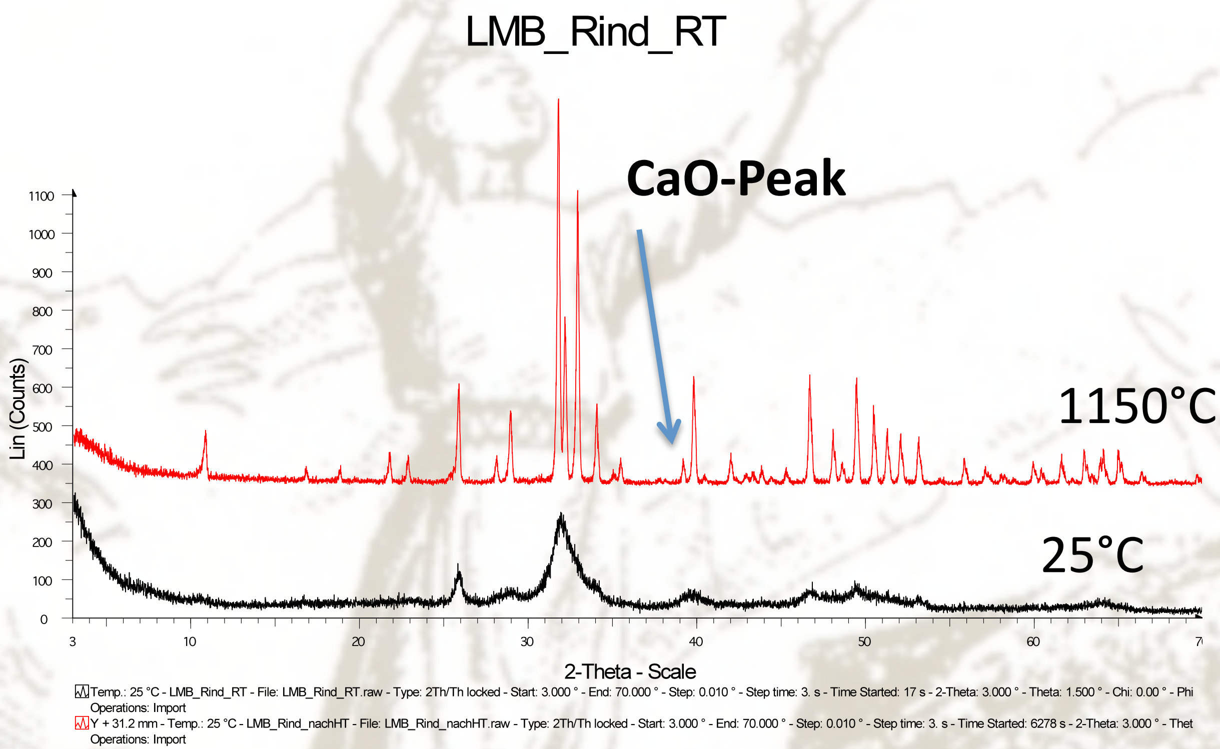
Archaeozoological results:

- **60740 sieved fragments**
- **3.4%** (ca. 2000 pieces) could be **attributed to animal species**
- **52% sheep/goat, 18% cow and 30% pig**
- Most bones from **skull as well as extremities**

Fotos Töchterle (2012)

Part 2-3

XRD investigations of calcinated bones: **high-*T* studies**

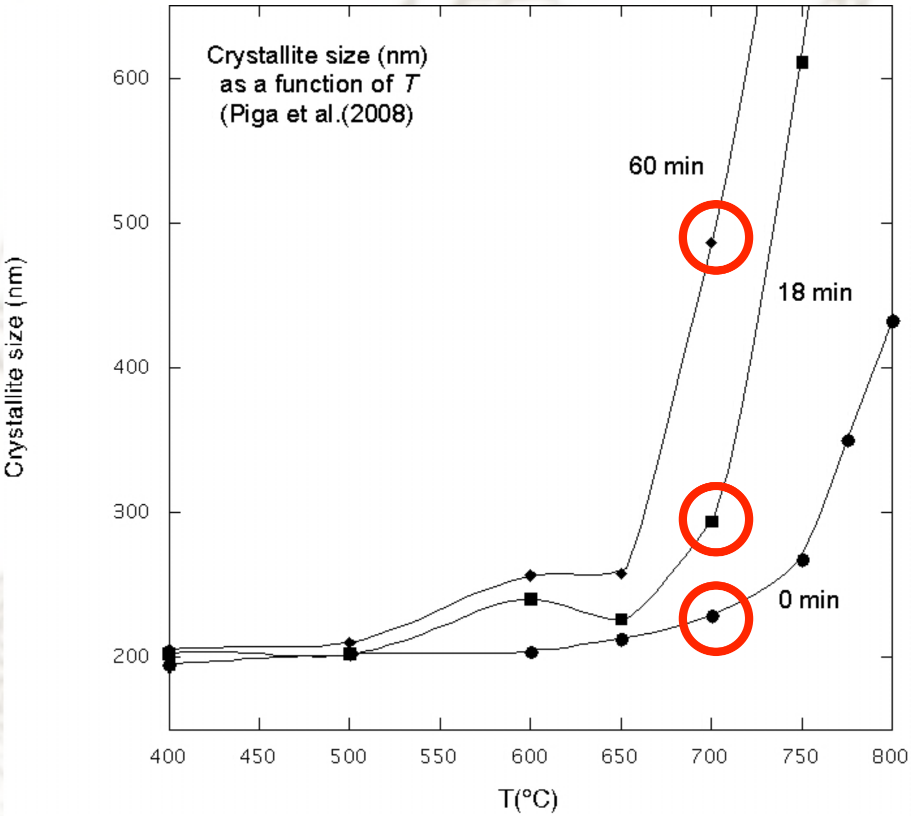


- At ca. **350°C** organic matter burns off.
- **Hydroxylapatite recrystallizes**
- At **>700°C** CaO forms (Haberko et al. 2006).

XRD patterns become **sharper with increasing temperature** due to better crystallization of apatite.

Part 2-3

XRD investigations of calcinated bones: **crystallite size measurements**



Piga et al. (2008)

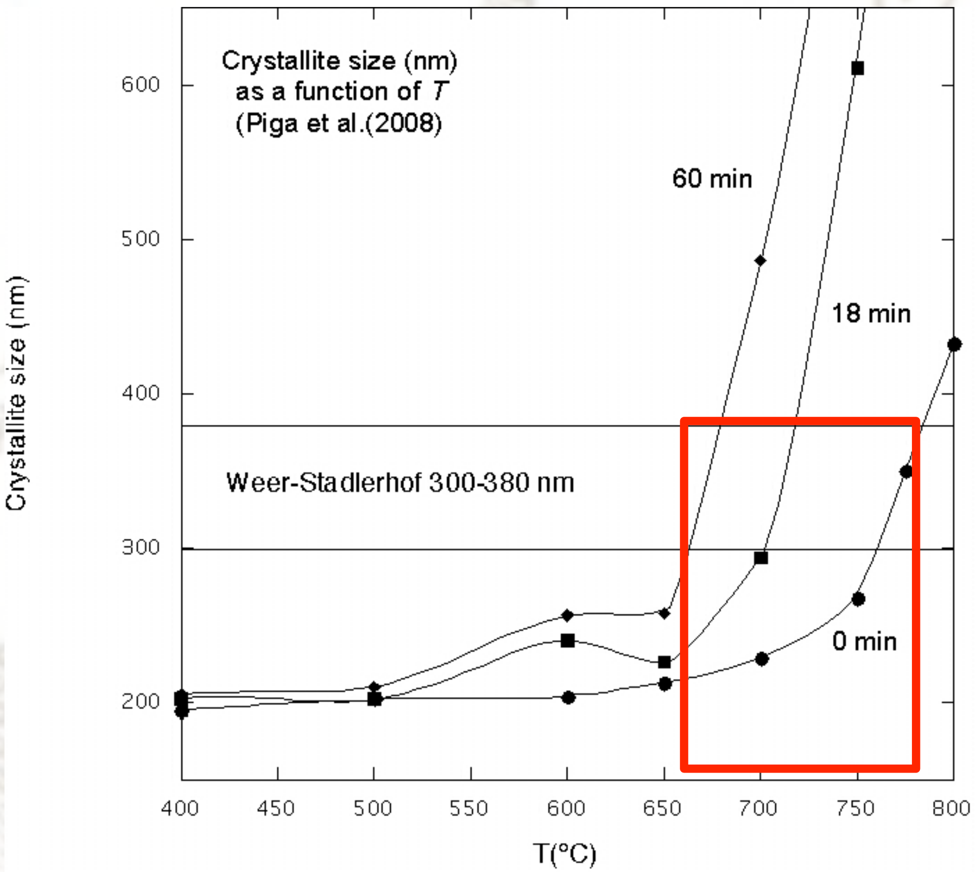
Average crystallite size of the hydroxylapatite mineral phase (1 Å = 10^{-10} m)

Temperature (°C)	0 min	18 min	60 min
Not burned	170		
200	175	175	175
300	180	184	188
400	195	203	205
500	202	202	210
600	204	240	256
650	213	226	258
700	229	294	486
750	268	611	800
775	350	836	920
800	432	1030	1200
825	732	1120	1254
850	923	1380	1500
900	1351	>1500 (1616)	>1500 (2621)
1000	>1500 (1569)	>1500 (2195)	>1500 (2950)

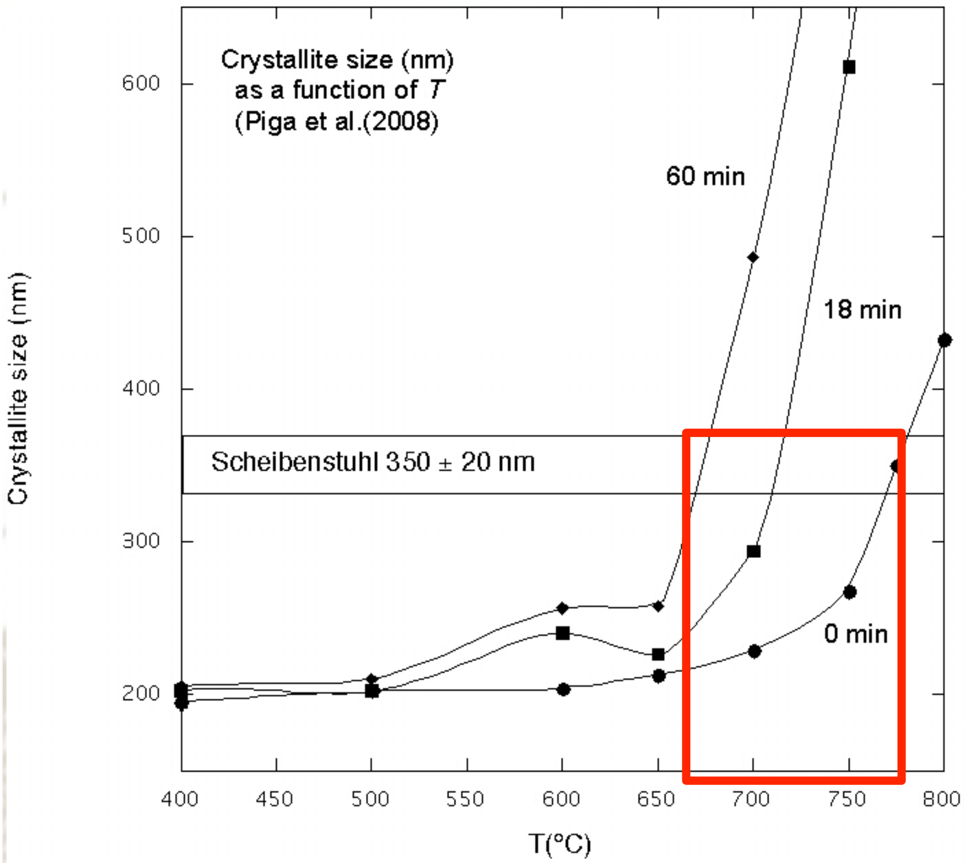
Calibration based **on cremated human remains**. Not only ***T*** is important, the **duration of firing** is important as well!

Part 2-3

XRD investigations of calcinated bones: **crystallite size measurements**



Weer/Stadlerhof



Scheibenstuhl/Nenzing

Part 2-3

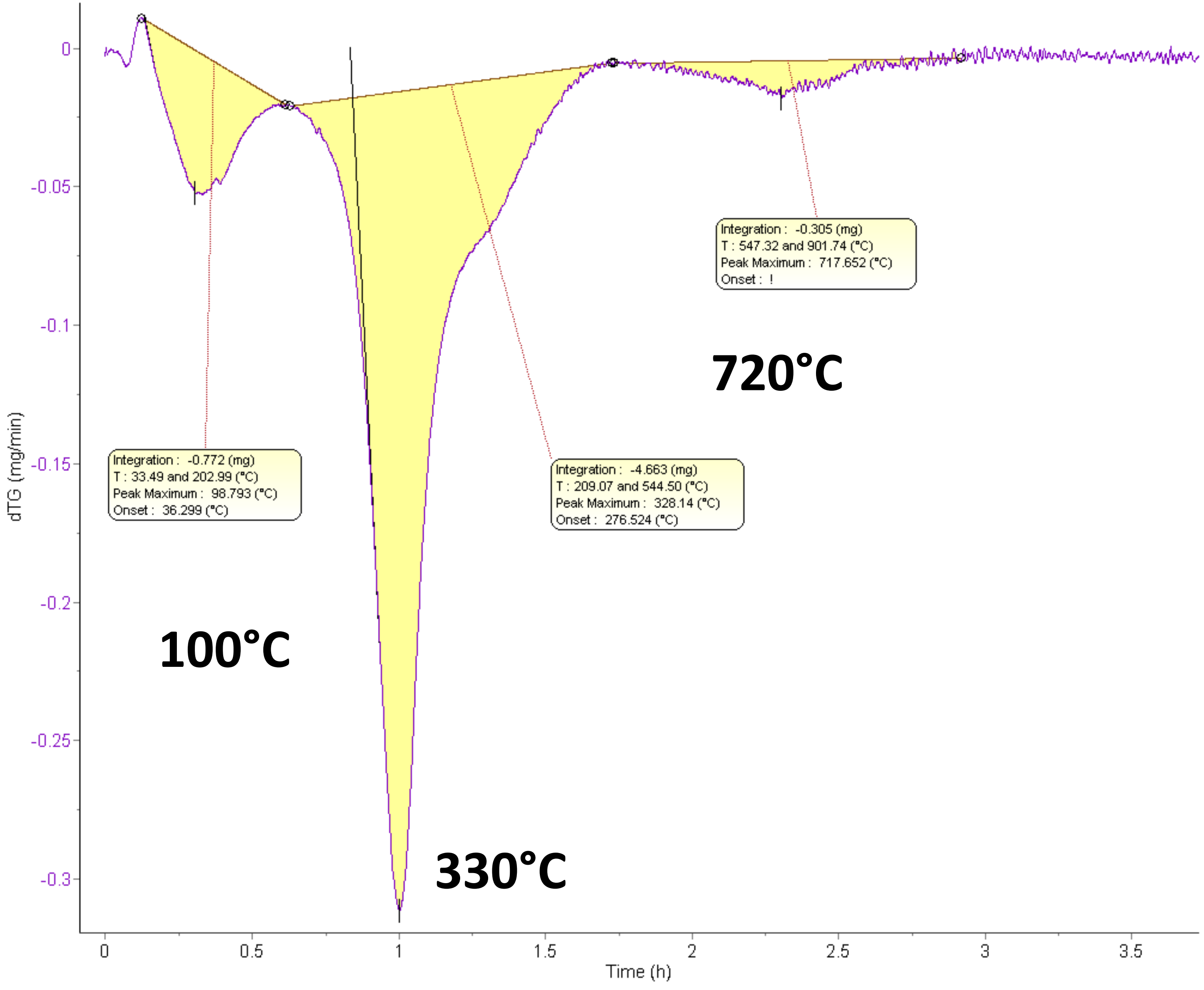
DTA-TG measurements

Loss of bone mass in three steps (maxima):

Ca. 100°C: H_2O loss

Ca. 330°C: decomposition of organic matter

Ca. 720°C: recrystallization of hydroxyl apatite



Bitterlich (2012)

Part 2-3 Conclusions

- Bone colour (white) indicates **high temperatures**.
- High temperature leads to **sharp diffraction patterns** due to **apatite recrystallization**.
- Firing of bones is a **multi-step process** (H_2O-loss, burning off organic matter, recrystallization) that can be easily monitored using DTA-TG.
- But calcinated bones **indicate lower temperatures (>650°C)** than the slags (1000-1100°C)!

Part 3

Experimental investigations of pyrometamorphic slags

Part 3-1

Fire temperatures

The temperature in a **large wood fire** is approximately **800°C**. By using **bellows or wind-driven air circulation** up to **1300°C** can be reached.

Pyrometamorphic processes lead to the formation of slags!

- **Can we reproduce the observed high-*T* mineral assemblages in the lab?**
- **Are there diagnostic mineral assemblages for immolation sites?**

Part 3: Conclusions

- The experimental investigations allow **inferences about firing temperatures and *f*O_2**. As starting materials **natural rocks** from the vicinity of the immolation sites are used: **1st set of experiments**

- By using **high-*T* XRD and differential thermal analysis (DTA-TG)** the high-*T* behavior of chlorite can be investigated and the **reaction products and textures** can be compared to the slags: **2nd set of experiments**

- In order to understand the occurrence of P-bearing minerals in the slags **bone-rock experiments** were conducted: **3rd set of experiments**

1^{st} set of experiments:
Experimental melting of natural rocks

Part 3-1

- **Quartzphyllites** heated up **to 1100°C** in a graphite crucible.

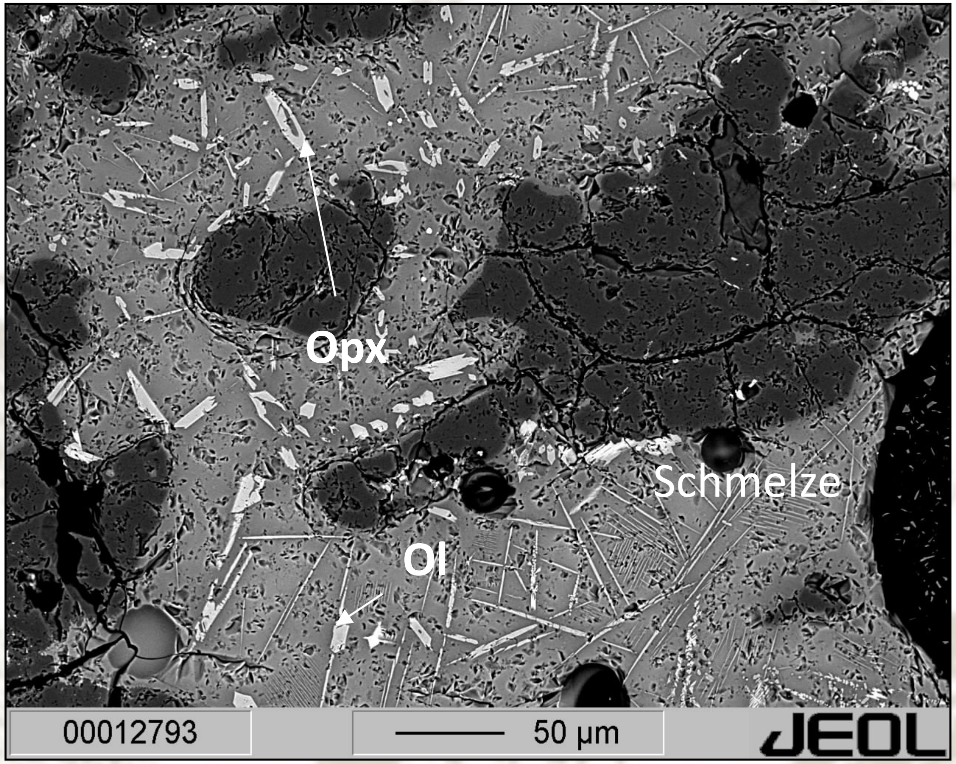
- Cooling with 100°C/h (t^{total} = 20h) down to 500°C.

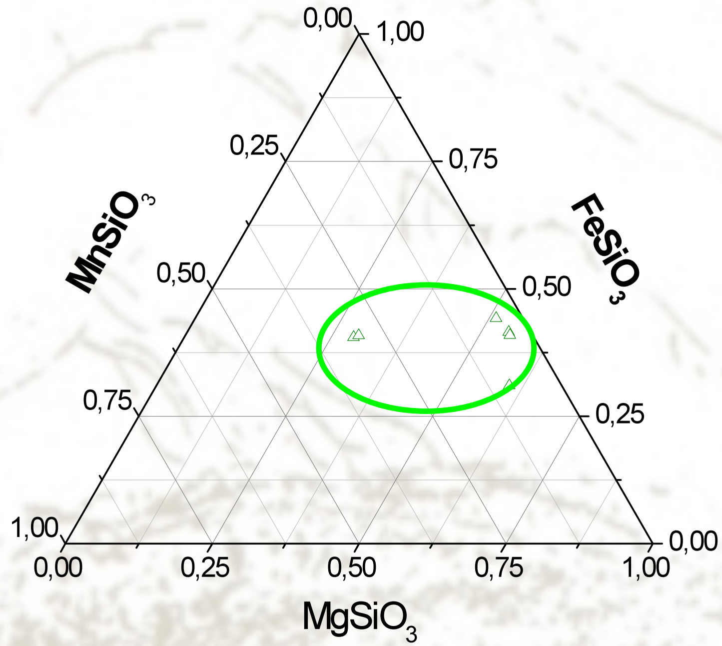
Graphite crucible and rock before the experiments.

Rock samples after the experiments.

Part 3-1

Observed **petrography and mineral chemistry**:





Orthopyroxene compositions.

Textural micro-domains and mineral chemical variations could be reproduced extremely well.

Part 3-1: Conclusions

- The use of **graphite crucibles** leads to highly efficient melting.
- The **textures** could be **well reproduced**.
- **Mineral chemical variations** could also be **well reproduced**.
- **Comparison with natural samples** indicates temperatures **>1100°C**!
- fO_2 must have been **highly reducing** (probably around QFM)!

2^{nd} set of experiments: Experimental investigations of the high-*T* behavior of chlorite

Part 3-2

***T*-dependent reaction history** of chlorite can be reconstructed.

Siemens D5005

- High-*T* XRD
- **Allows in-situ monitoring of mineral reactions as a function of temperature.**
  - 300-1200°C
  - Heating rate 0.5°C/s
  - Duration: 6 days 18 h.

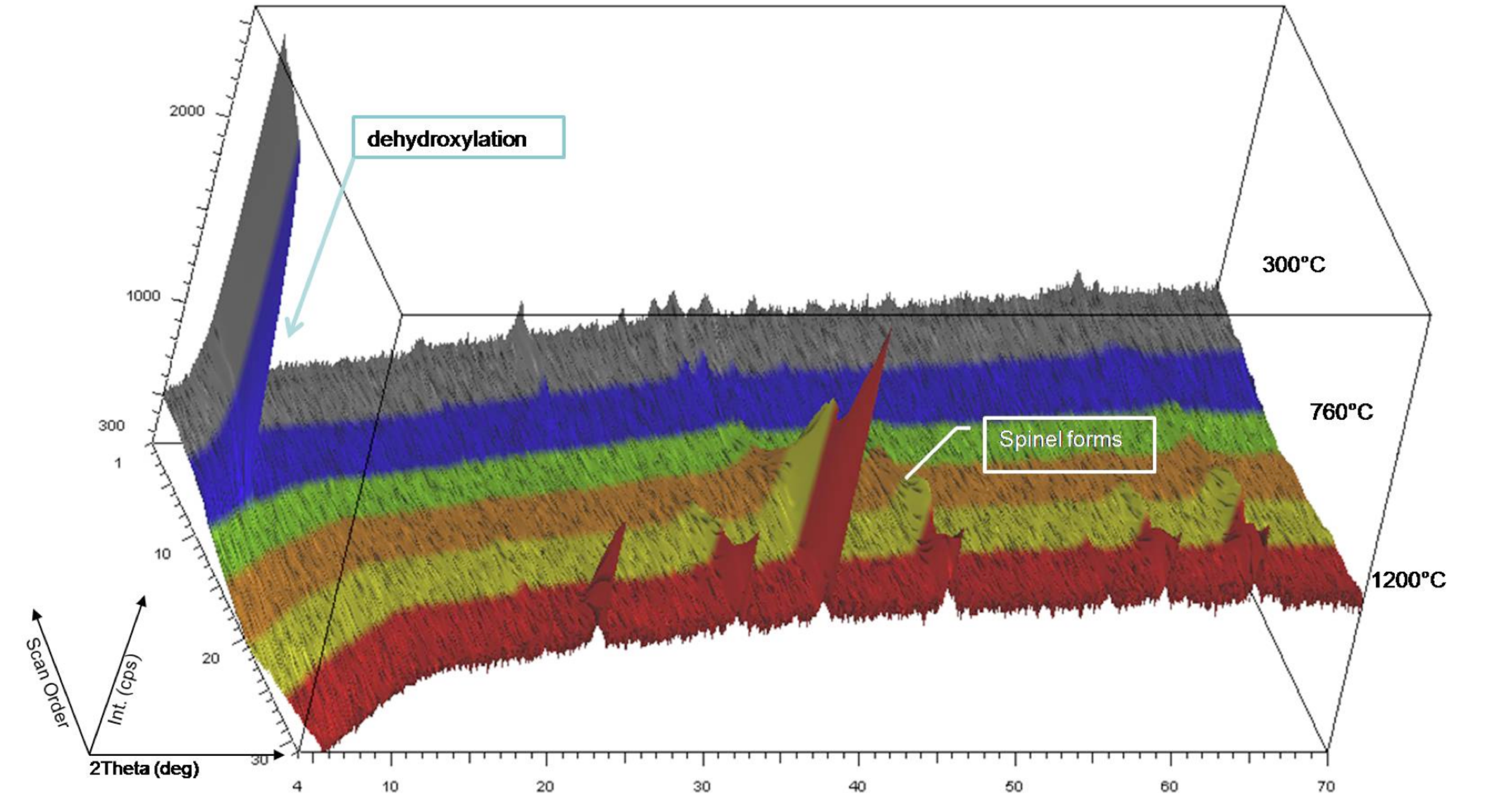
Use of chlorite with X_{Fe} = 0.46, similar to chlorite from the quartzphyllites.

Experiments were done **under oxidizing conditions!**

Part 3-2

High-*T* XRD

Chlorite: (X_{Fe}=0.46, 600-1200°C)

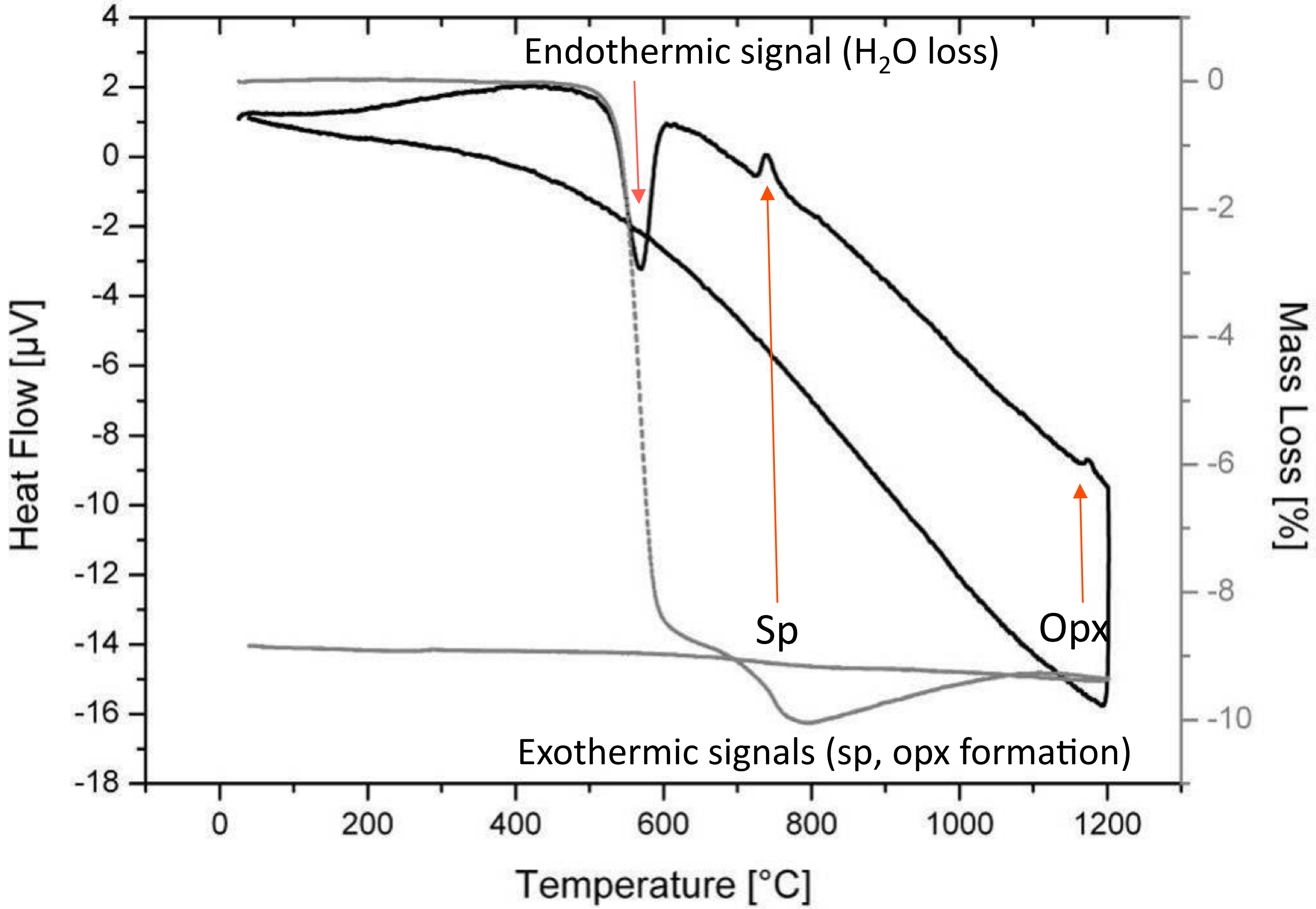


At 900°C **spinel** forms and around at 1120°C **sapphirine** appears which is followed by cristobalite around 1140-1160°C.

Part 3-2

DTA-TG: Chlorite

X_{Fe} = 0.46



Part 3-2

- **DTA-TG**
- **Energy changes** associated with mineral reactions as a function of temperature can be monitored in-situ (DTA).
- **Mass changes** as a function of temperature can be monitored (= TG).
- **Reducing He-atmosphere was used.**

Table 25: shows the different dehydroxylation temperatures, the DTA signals, the phase assemblage at the end of the DTA and the phase assemblage and their appearance under 1 atmosphere using HTXRD.
$T^{initial}$ – Dehyd.: Temperature of dehydroxylation of the brucite – interlayer
T^{im} – Dehyd.: Temperature of dehydroxylation of the talc – interlayer
T^{end} – Dehyd.: Temperature at which the dehydroxylation is completed

	$T^{initial}$ - Dehyd.	T^{im} - Dehyd.	T^{end} - Dehyd.	Endothermic Peaks	Exothermic Peaks	New phases (He-atm.)	New phases (1 atm. air) with HTXRD
CE, clinochlore X_{Fe}=0.11	497°C	726°C, 813°C	880°C	497°C 726°C	807°C	forsterite + spinel + enstatite	820°C forsterite 950°C spinel 1010°C enstatite
CD, X_{Fe}=0.46	507°C	740°C	812°C	507°C	725°C 1150°C	spinel + enstatite + cristobalite	900°C pleonaste 1120°C sapphirine 1140°C cristobalite
CC, X_{Fe}=0.62	493°C	623°C	765°C	493°C	719°C	spinel + enstatite + cordierite	
CA, chamosite X_{Fe}=0.89	360°C	472°C	700°C	400°C 483°C 1018°C 1088°C	707°C	melt / no phase analyses	900°C hematite 1100°C mullite 1160°C sapphirine + cristobalite

Schneider (2009)

Part 3-2

Both methods allow to infer the following ideal chlorite breakdown reaction:

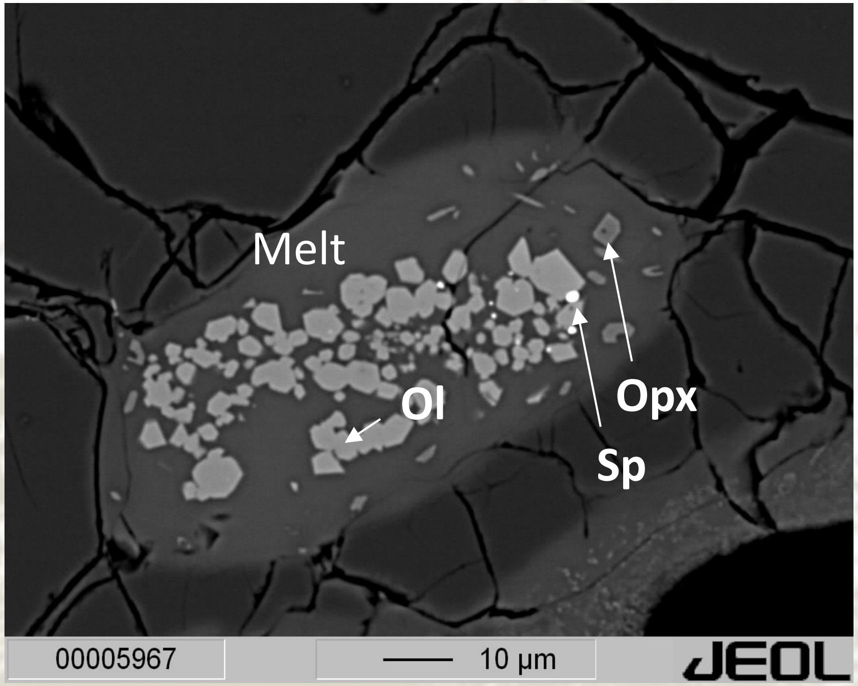
Mg-endmember clinochlor breakdown:

Clinochlore → Forsterite + Enstatite + Spinel + 4H_2O

$$Mg_5Al_2Si_3O_{10}(OH)_4 \rightarrow Mg_2SiO_4 + MgAl_2O_4 + 2MgSiO_3 + 4H_2O$$

Comparison with a chlorite domain in the slags from the Goldbichl.

Reducing experiments are correct!



Observed mineral assemblage: olivine + orthopyroxene + spinel + melt.

Part 3-2: Conclusions

- Mineral **breakdown reactions** can be monitored **in-situ**!
- **Dehydration behavior of chlorite** is complex (olivine → spinel → orthopyroxene).
- **Chlorite has a high thermal stability**. It completely disappears above 800°C.
- **The mineral assemblage from the reducing DTA (He-atmosphere) experiments at X_{Fe} = 0.46 can be observed in the slags.**
- The results also indicate **T> 1100°C at the Goldbichl site**.

3rd set of experiments: Experimental investigations of bone-rock interactions

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Part 4

- In the slags from Oetz and Goldbichl **P-bearing phases (olivine, clinopyroxene) as well as phosphates occur**.

- The most prominent phosphates are **whitlockite**, $Ca_9(Mg,Fe)[PO_3OH|(PO_4)_6]$, and **stanfieldite**, $Ca_4(Mg, Fe^{2+}, Mn^{2+})_5(PO_4)_6$.

- **Is it possible to create these phases experimentally?**

- In order to identify **diagnostic P-phases** bone-rock experiments were conducted.

Part 4

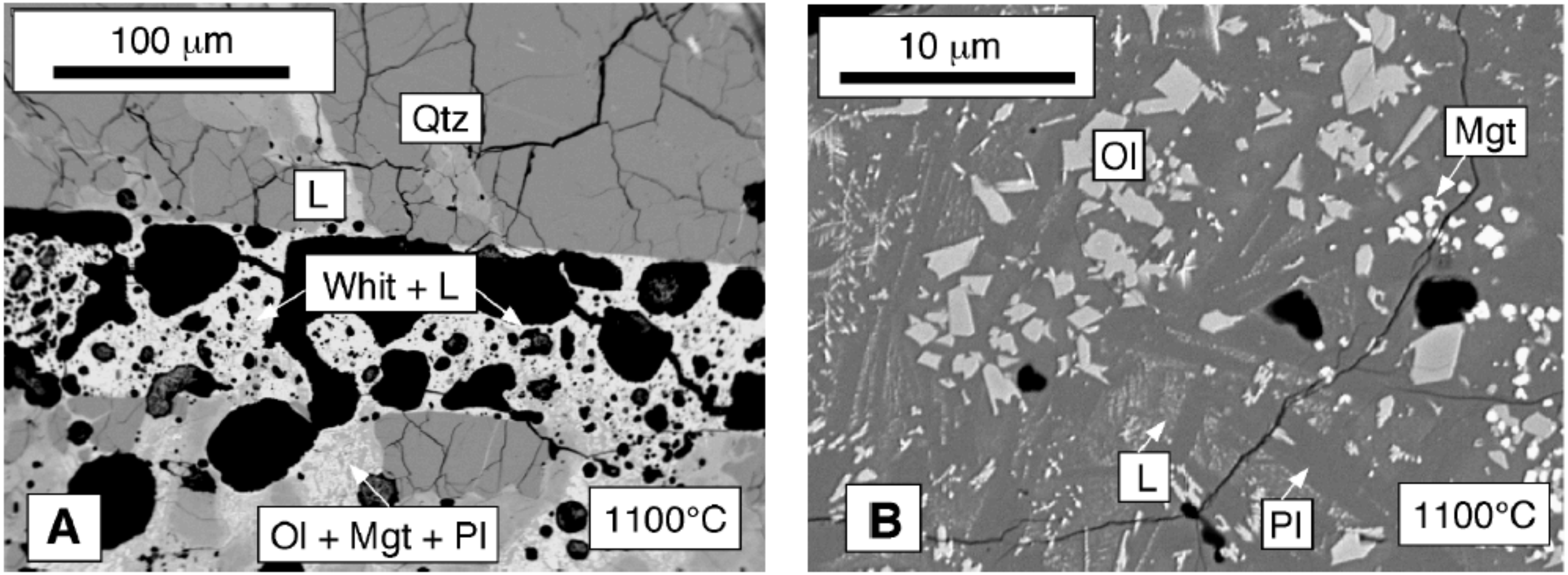
Tropper et al. (2006): **Bone-rock experiments** using orthogneisses from Oetz.

Chicken bone layer on top of an orthogneiss cube.

1100°C experiment in graphite crucible, cooling rate 60-120°C/h to 500°.

Part 4

Petrography of the bone-rock interface:



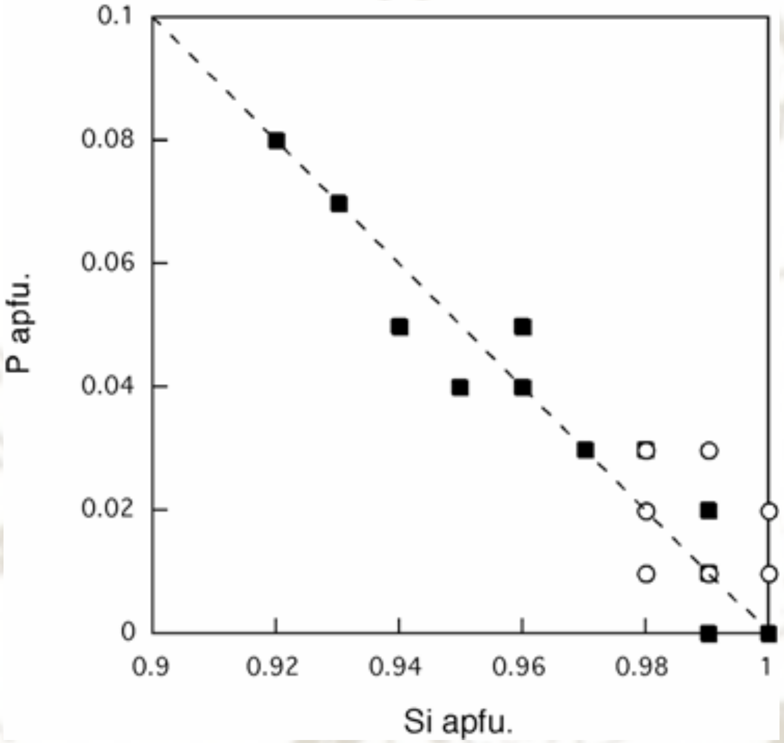
Tropper et al. (2006)

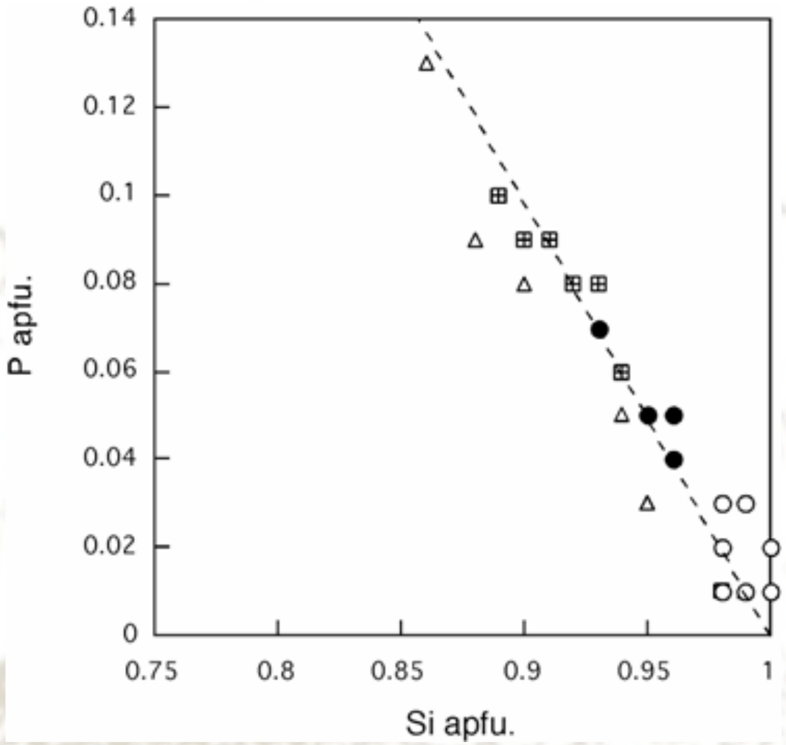
Olivine + Whitlockite + Anorthite + Spinel + Glass

Extremely **well reproduced** textures as well as mineral assemblages!

Part 4

Tropper et al. (2006): **Mineral chemistry of olivines**





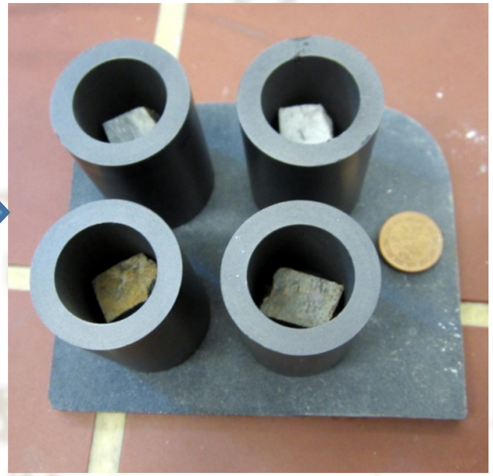
Olivine from the **experiments**. Olivine from the **slags**.

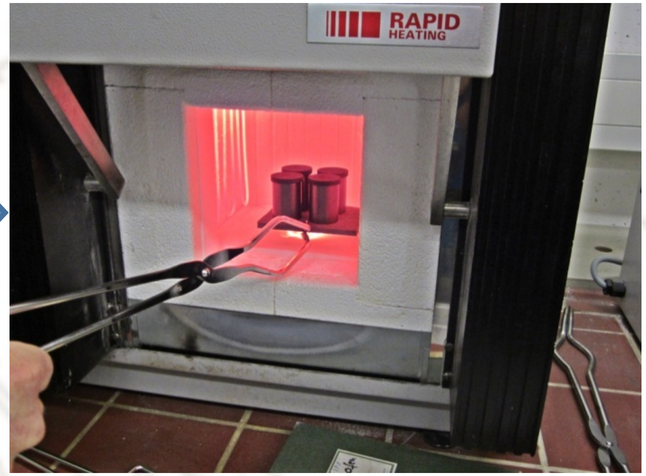
$$2P + (\square)M_{1,2} \leftrightarrow 2Si + (Mg,Fe)M_{1,2}$$

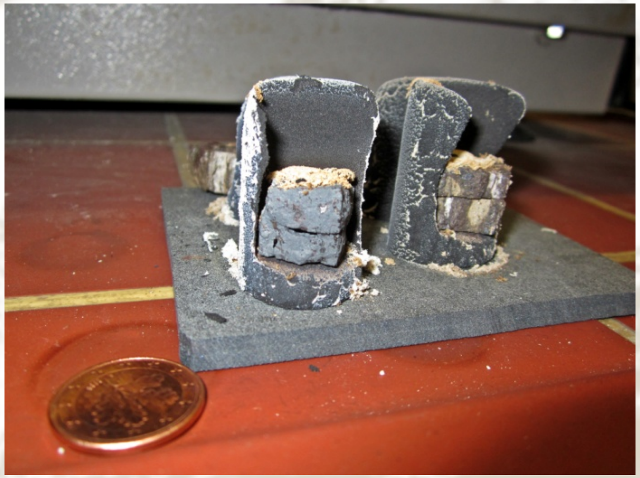
P-substitution in olivine could be reproduced but the extent is not the same!

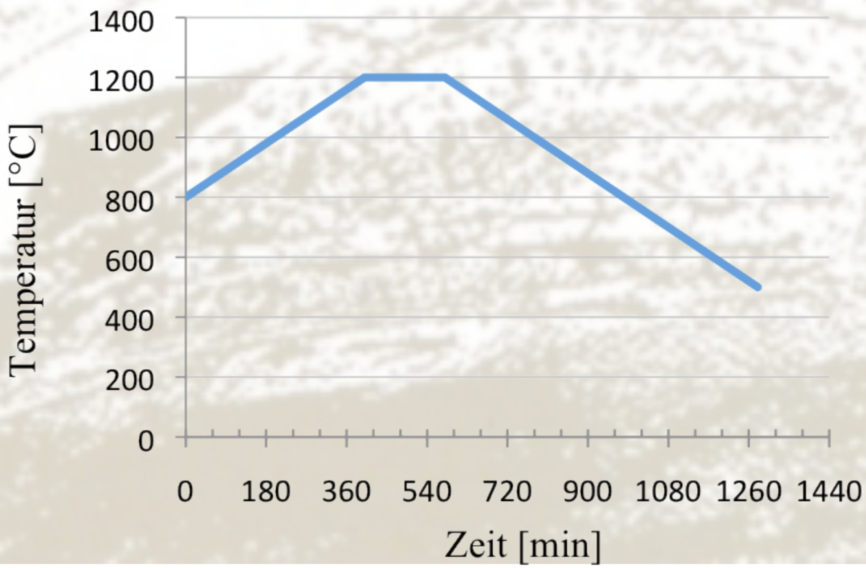
Part 4

Further bone-rock experiments were conducted at 1200°C using different rock types: **orthogneiss, quartzphyllite amphibolite and paragneiss**.







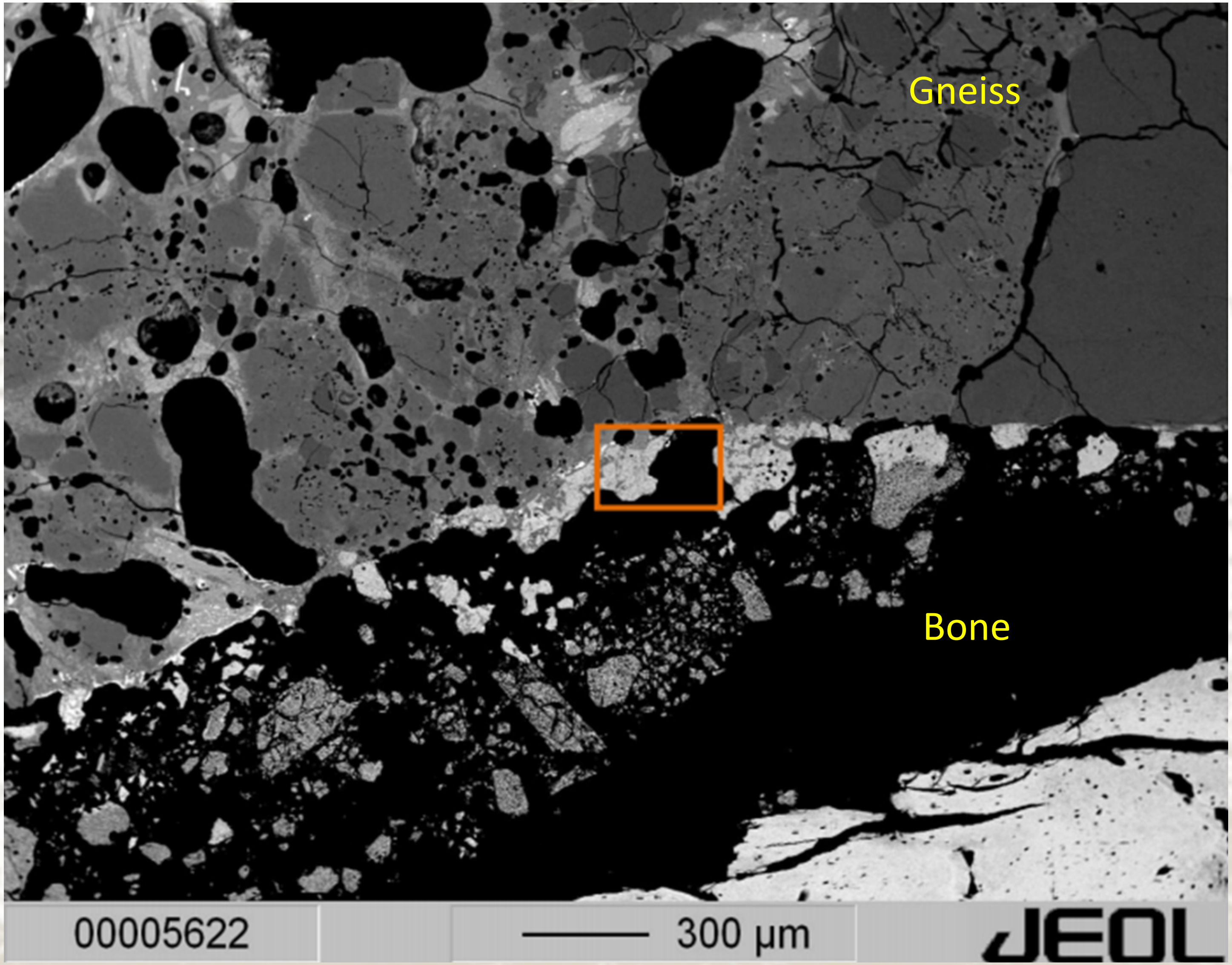


Spielmann (2013)

Part 4

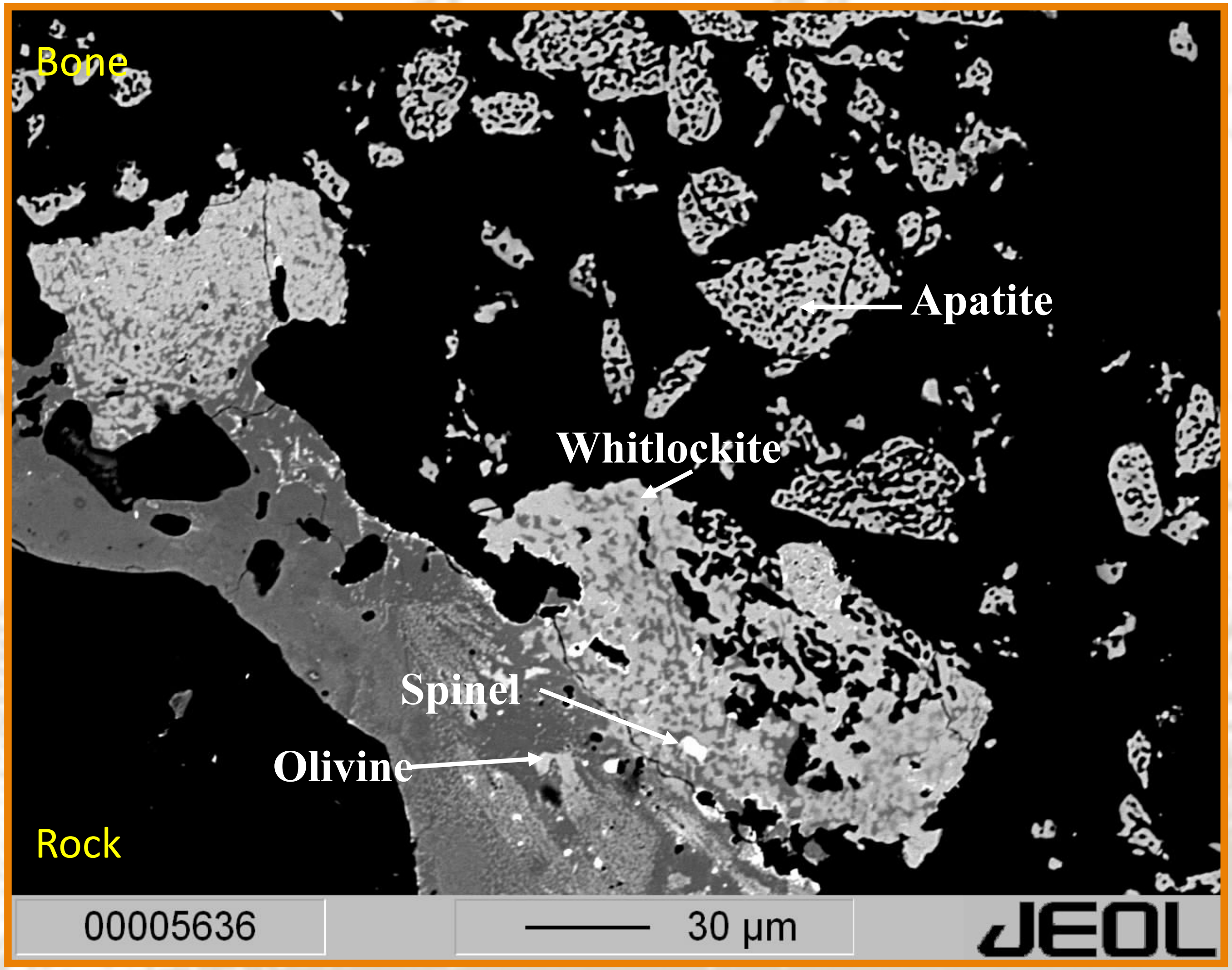
Paragneiss: overview

Spielmann (2013)



Part 4

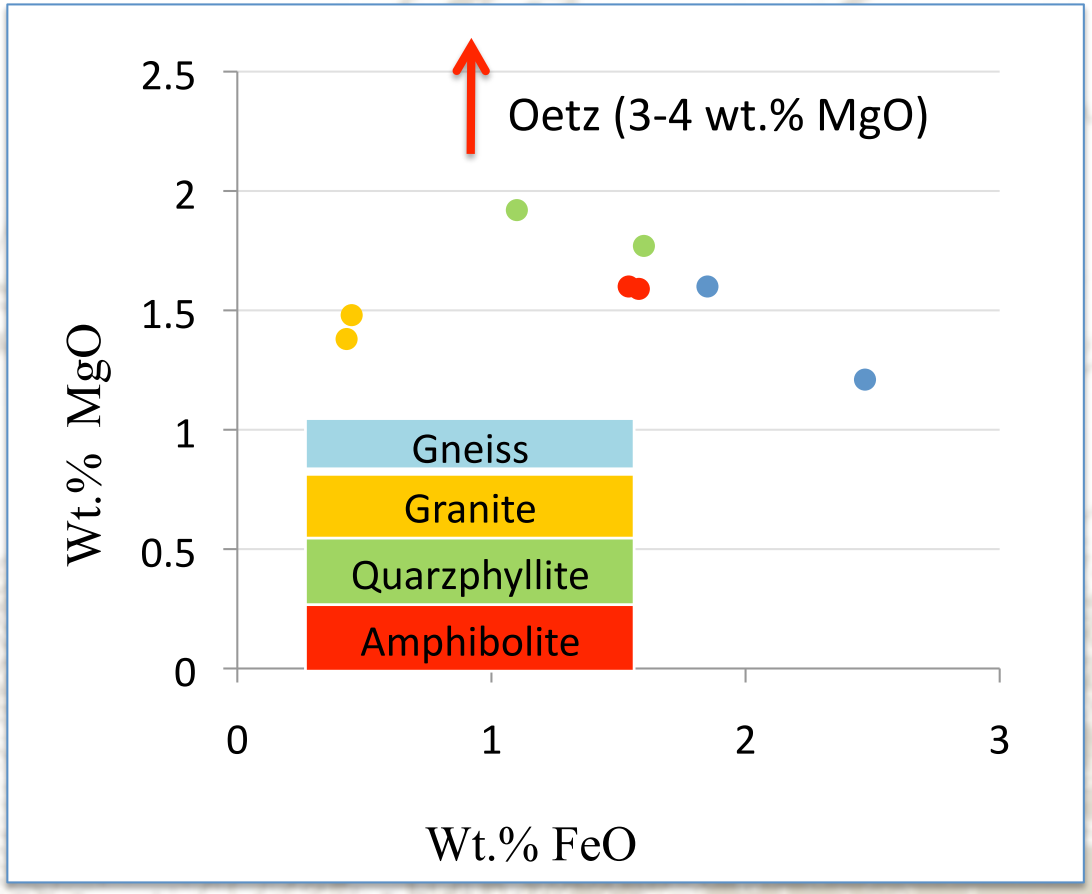
Quartzphyllite: overview



- Assemblage at the bone-rock interface:
- **Whitlockite + P-rich olivine + spinell + native Fe + glass**
- High degree of melting throughout the sample!

Part 4

Whitlockite: $(Ca_9(Mg,Fe)[PO_3OH|(PO_4)_6])$



Chemical composition of whitlockite **strongly depends on the nature** of the protolith rock composition.

Olivine

P-bearing olivines could also be reproduced. They show **up to 4.5 wt.% P_2O_5**.

Clinopyroxene

P-bearing clinopyroxenes also formed. They show **up to 15 wt.% P_2O_5!**

Part 4 Conclusions

- Bone-rock experiments **reproduce textures as well as mineralogy very well**.
- **P-bearing olivine and P-bearing clinopyroxene** formed in the experiments!
- **Whitlockite** forms at the bone-rock interface!
- **No stanfieldite** formed!

Discussion

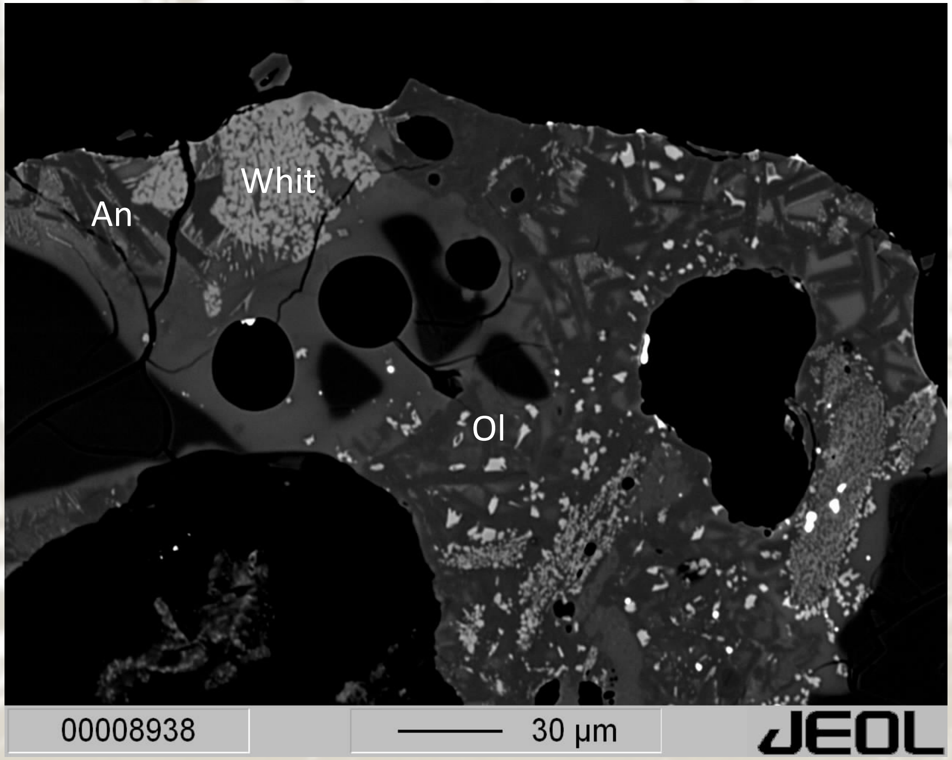
The relevance of P-bearing phases in pyrometamorphic slags

How can we form whitlockite?

It is possible to balance mineral reactions in the **chemical system CaO-FeO-SiO_2-P_2O_5-Al_2O_3-H_2O** between the phases **chamosite-quartz-fayalite-anorthite-whitlockite-H_2O**.

14 apatite + 7 chamosite + 7.5 quartz + 15.5 O_2 → **6 whitlockite + 7 anorthite + 14.5 fayalite + 8 H_2O**

Apatite
+
Chlorite
+
Quartz



Whitlockite
+
Plagioclase
+
Olivine

Part 5

How can we form P-bearing olivines?

In the **chemical system CaO-FeO-SiO_2-P_2O_5-Al_2O_3-H_2O** mineral reactions between the phases **chamosite-quartz-fayalite-anorthite-hercynite-apatite-sarcopside-H_2O** can be calculated:

The **phopshate sarcopside $Fe_3(PO_4)_2$** is structurally closely related to olivine (fayalite).

10 chamosite + 2 apatite + 10.5 quartz →
3 sarcopside + 10 anorthite + 20.5 fayalite + 41 H_2O

20 chamosite + 2 apatite →
3 sarcopside + 10 anorthite + 10 hercynite + 40.5 fayalit + 81H_2O

These reactions describe the formation of P-bearing olivine solid solutions very well!

Chlorite + Apatite ± Quartz = P-Olivine + Plagioclase + Spinel

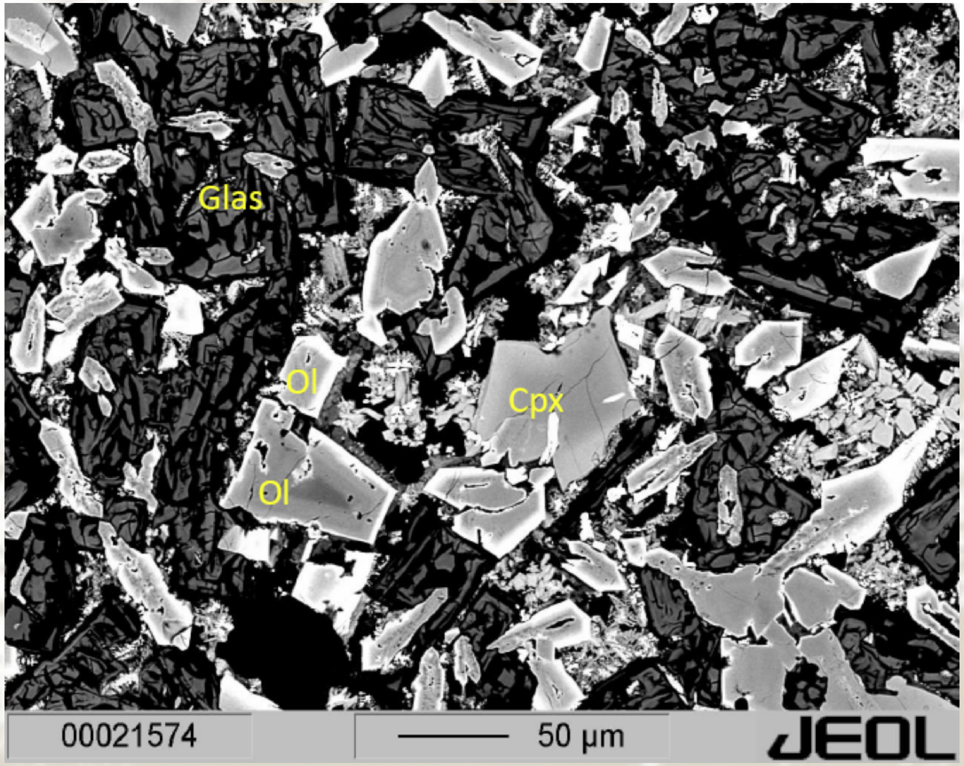
Part 5

Is bone apatite the only P-donor? **NO!**

Wood contains up to 0.001 wt.% P_2O_5!

Further P-donors are: **food (meat) or fertlizier**.....

Probe T005/013: **Slag-tempered ceramics from the Kiechlberg**. The mineral assemblage is olivine, clinopyroxene and glass. Glass (now altered) contains a lot of P_2O_5!



MgO	0.80
Al_2O_3	8.20
SiO_2	7.39
P_2O_5	**19.02**
K_2O	0.14
CaO	3.13
TiO_2	0.73
FeO	60.59
Total	100.00

Part 5

How do P-rich silicates form?

P-rich olivine and P-rich clinopyroxene form by:

1.) **Metastable growth:** agrees with observed microdomains

2.) **Extremely fast growth during cooling:** no equilibrium!

3.) According to Boesenberg et al. (2010) **mineral growth from a P-rich melt: in our samples** rather mineral reactions instead of melt!

4.) Bone-rock experiments have shown that **whitlockite and no stanfieldite forms**!

5.) Whitlockite could indeed be **a diagnostic phase**!

Conclusions

Part 6: Conclusions

- Although **200 ritual immolation sites** occur throughout the Eastern Alps **only** 2 have been investigated from a mineralogical/petrological point of view.
- The investigated sites (Oetz, Goldbichl/Igls) are **located on hill-tops** and show abundant **ceramic and bone fragments**.
- **Slags occur** (Oetz only little, Goldbichl, massive amounts)!
- Temperatures derived from the slags are **>1000-1100°C** under **highly reducing (QFM) conditions**.
- **Experimental investigations** verify these **temperatures** as well as the occurrence of **P-bearing olivine and whitlockte**.

Part 6: Conclusions

- P-rich minerals which indicate the presence of a P-source in the fire are the following:

whitlockite, P-rich olivine, P-rich clinopyroxene, stanfieldite

- The following mineral assemblage has experimentally shown to be associated with bone-rock interactions is:

P-rich olivine ± P-rich clinopyroxene ONLY when coexisting with whitlockite!

Part 6: Conclusions

- P-rich olivine, P-rich clinopyroxene and stanfieldite form by decomposition of detrital apatite in the slags of the Goldbichl.

No bone material is involved in their formation!

- P-rich olivine and whitlockite have been found in the slags from Oetz.

Bone material might be involved in their formation!

- But **bone apatite crystallinity of calcinated bones** yields much lower temperatures: might be due to their position **in "cooler" spots** of the fire (e.g. at the surface).

Part 6: Conclusions

- The high temperatures deduced from the slags are compatible with **core temperatures of large bone fires** with a possible wind-driven air circulation.

- **Archaeological implications for the Goldbichl site:** the massive slags probably represent the last firing event of the immolation site: the ritual „closing“ of the site by an enormous fire.

- **Archaeological implications for the Oetz site:** bone-rock interactions might have occurred. Only small amounts of slags have been found.

- **The occurrence of the mineral whitlockite could be diagnostic for bone-rock interactions only if one considers archaeological, petrological and experimental data!**

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