The Permian-Triassic of the Gartnerkofel-1 Core (Carnic Alps, Austria): Petrography and Geochemistry of an Anisian Ash-Flow Tuff

By JOHANNES H. OBENHOLZNER

With 10 Text-Figures, 4 Tables and 2 Plates


Zusammenfassung

The drilling project Gartnerkofel-I discovered between 30 and 34.5 m a layer of dacitic ash-flow tuff within a fluvial conglomerate sequence (Anisian Muschelkalk Conglomerate). The tuff is slightly to moderately welded and all glass shards are devitrified and altered. Bulk rock geochemistry of main, trace and RE elements show characteristic element contents and ratios of an "orogenic", calcalkaline magma.

1. Introduction

The Middle Triassic magmatism is an igneous event settled between Variscan and Alpine orogeny. In the Southern Alps this event is documented by intrusives, lavas, pyroclastic rocks and volcanogenic sediments from Scythian to Carnian times. The studied ash-flow tuff is the only pyroclastic deposit known from the Anisian. During the Ladinian, ignimbrites covered large areas in the eastern part of the Southern Alps, but nowadays these rocks are hardly exposed. So the drilling project Gartnerkofel-I enabled us for the first time
to examine a whole section of a Middle Triassic ash-flow tuff.

A 4-m drilling core and a small outcrop have been at our disposal to investigate this pyroclastic deposit, which is otherwise totally covered by sediments or hidden by Alpine tectonics. It is obvious that these poor possibilities of observation are not enough to solve all volcanological problems, so some of the results are hypothetical but help to elucidate the physiology of one of the ignimbrites in the Alpine area.

2. Geological Setting

(Text.Fig. 1)

The basal conglomerate, the ash-flow tuff (AFT, according to ash particle grain size) and the upper conglomerate are also exposed at an outcrop, where the AFT is only about 1 m thick and strongly tectonized (F. KAHLER & S. PREY, 1963). The core brought up rather fresh material and shows a section of 4 m through a macroscopically homogeneous layer, which is covered by a 10-cm-thick volcaniclastic bed. This reworked co-ignimbritic ash-fall deposit contains rare clasts of the AFT. The AFT at the outcrop and at the core, separated only about 30 m, represents the distal facies of a pyroclastic deposit. The decrease of thickness from E to W could be depositional due to morphology or perhaps indicates a flow direction (the massive Ladinian carbonate build up of the Gartnerkofel presently covers the possible source area).

The top of the lower conglomerate does not show any contact features (like reddening) at its boundary with the AFT, nor have fiamme structures been observed. The upper conglomerate contains boulders of the AFT as well as volcanic pebbles of different origin, indicating that the source area was eroded shortly after deposition of the pyroclastic cloud. No time equivalent, terrestrial sediments or volcanics are known in the entire area of the Carnic Alps, so it is not possible to correlate this pyroclastic event to an on-land volcanic terrain or to a caldera structure. The sediments below and above the conglomerate sequence are marine.

The core is slightly tectonized at its base and top. From 30 to 32 m the colour of this rock is red, from 32 to 33 m there is a transition zone from red to green and the base is gray-green (see Text-Fig. 2). This indicates differing oxidation and reduction conditions through the AFT. The famous ash-flow tuff of the Capel Curig Formation (Wales) shows similar features, which have been interpreted as a partially subaqueous, partially subaerial deposition and alteration (M.F. HOWELLS et al., 1979).

The whole sequence (fluvial conglomerates according to M. SCHMIDT (1987) and ash-flow tuff) documents an emersion phase of a hinterland in the Triassic (P. CROS, 1982), which is represented in the Austrian part of the Carnic Alps only by marine sediments (limestones, dolomites, shales). The Anisian conglomerates can be traced also to the Italian part of the Carnia, for instance to the Val Canale (Ugovizza Breccia: E. FARABEGOLI et al., 1985), but lacks any beds of pyroclastic rocks or lavas. Very rarely does the Ugovizza Breccia contain boulders of lava and tuffitic groundmass.

3. Petrography

All glass shards, constituting the matrix up to 60 % to 70 % of volume, are devitrified and altered to varying degrees. The shapes of the slightly elongated shards are outlined by iron oxides (Plate 2, Fig. 4). These features are best preserved in the upper, reddened part of the layer (rich in fine scattered iron oxides; greenish part is rich in chlorite). Below single crystals and microxenoliths, typical matrix deformation caused by load compaction of the AFT, can be observed. The shards consist of quartz and K-feldspar and are partially replaced by carbonate and/or clay minerals.
Text-Fig. 2.
Schematic section of the core between 25 and 35 m, showing uppermost top of lower conglomerate, ash-flow tuff layer, and ash-flow tuff boulder containing upper conglomerate.

Dot pattern signifies red color; line pattern gray-green. The vesicularity in thinsection is indicated by points per vacuole. Sample no. 6 shows one larger vacuole (diameter 2.5 cm).

<table>
<thead>
<tr>
<th>sample number</th>
<th>size of sample (cm)</th>
<th>vesicularity in thinsection</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

The tectonization and alteration at the base and at the top do not allow one to estimate the degree of welding relative to the central part (31.3–33.94 m), which is slightly to moderately welded. All shard textures in the tectonized parts of the core are either "ghost"-like, or destroyed.

The only partially fresh component is intermediate plagioclase (10%–15% of volume), which is often embayed and zoned (for mineral chemistry, see Table 2). In the Or-Ab-An triangle most of the analyses plot in the andesine field; a few crystals have oligoclase or labradorite composition. Sometimes crystal clots of plagioclase can be observed, but in general plagioclase occurs as individual pheno- or xenocrysts in the matrix (Plate 2, Fig. 3; Plate 2, Fig. 4).

A second type of plagioclase shows poikilitic inclusions of glass droplets (now chlorite as an alteration product of a basic to intermediate glass composition).

The association of poikilitic and inclusion-free plagioclases is also known from Upper Anisian andesitic and dacitic lavas from the Karawanken Mountains (J.H. OEBENHOLZNER, 1984). There the poikilitic ones are interpreted to be a petrographic indication for magma mixing. The example from the AFT (Plate 2, Fig. 2) shows a deep resorption embayment, significant for disequilibrium between crystal and melt. As we found no other indications for mixing, it is not provable; but magma mixing can be an important factor in triggering explosive eruptions (S.R.J. SPARKS et al., 1977).

The poikilitic plagioclases may also represent the product of an earlier eruption. These crystals might have been picked up during emplacement of the AFT.

Chlorite pseudomorphs after clinopyroxene(?) pumice fragments (0.3–1.2 mm) and microxenoliths of andesitic lava (Plate 2, Fig. 1), arenite (Werfen Formation?) and an older welded ash-flow tuff are rare and scattered in the core. It is very common to find lava fragments, of a composition more basic than the juvenile components, reworked in a pyroclastic deposit (C.S. Ross & R.L. Smith, 1961).

Accessories are altered Ti-magnetite, sometimes embayed, now consisting of an intergrowth of ilmenite and hematite (both in the red and green part), and apatite.

Two types of pumice fragments can be distinguished. One type is angular, white, with tubular, wormlike vesicles, sometimes containing larger ovoid vesicles. This pumice is considered to be a lithic or maybe more silicic component (Plate 1, Fig. 1). The other pumice type shows brownish colours, identical with the AFT but slightly deformed, with tubular vesicles only; representing a juvenile component (Plate 1, Fig. 2).

Irregularly shaped gas vacuoles with average diameter of 1 cm are common, but do not show a systematic distribution from base to top with lowest abundance in the central part as would be expected (C.S. Ross & R.L. Smith, 1961). This could be of restricted sampling by the core. The vacuoles are zonally filled with chlorite, carbonate minerals or quartz (Plate 1, Fig. 3).

X-ray diffractometry of the AFT boulders, which do not contain any primary minerals (except ore-phenocrysts and apatite), showed that polygorskite, a K-rich montmorillonite (?) and hematite build up this rock, which still exhibits the AFT texture in thin section. X-ray diffractometry had been done by E. KIRCHNER. A detailed study of alteration minerals is in preparation.
Table 1.  
Frequency of crystals and xenoliths.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>[%]</th>
<th>Size [mm]</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediate plagioclase</td>
<td>10–15</td>
<td>0.3–3</td>
<td>pheno- to xenocryst; often embayed</td>
</tr>
<tr>
<td>Pseudomorphs (CHL after CPX ?)</td>
<td>1</td>
<td>0.9–1</td>
<td>pheno- to xenocryst</td>
</tr>
<tr>
<td>Ore</td>
<td>1</td>
<td>0.15–0.5</td>
<td>pheno- to xenocryst</td>
</tr>
<tr>
<td>Vacuoles</td>
<td>1–2</td>
<td>0.5–20</td>
<td>irregular</td>
</tr>
<tr>
<td>Welded tuff fragments</td>
<td>2</td>
<td>0.12–0.3</td>
<td>lensoid to angular</td>
</tr>
<tr>
<td>Pumice</td>
<td>4–8</td>
<td>0.3–1.2</td>
<td>lensoid to angular</td>
</tr>
<tr>
<td>Andesitic lava fragments</td>
<td>2</td>
<td>0.9–1.5</td>
<td>subangular</td>
</tr>
<tr>
<td>Arenite</td>
<td>2</td>
<td>0.6–2.4</td>
<td>slightly rounded</td>
</tr>
<tr>
<td>Crystal clots</td>
<td>&lt;1</td>
<td>0.3–1.2</td>
<td>irregular</td>
</tr>
<tr>
<td>Carbonate xenolith</td>
<td>&lt;1</td>
<td>4.5</td>
<td>slightly rounded</td>
</tr>
<tr>
<td>Matrix (shards)</td>
<td>60–70</td>
<td>0.1–0.25</td>
<td>plate-, shred-like</td>
</tr>
</tbody>
</table>

The AFT boulder (Sample 9) includes a dolomite clast, which shows a 2-mm-thick, pale green contact rim of chloride and minor amounts of talc. This indicates that dolomitization – or at least an early phase of dolomitization – occurred prior to the eruption of the AFT.

4. Geochemistry

Bulk rock geochemistry was analyzed. Even such an analysis for ash-flow tuffs is rather unusual (R.A.F. Cas & J.V. Wright, p. 258–260, 1987). But the absence of fresh glass or magma characterizing minerals led us to test the chemical composition of several segments of the core that are macroscopically homogeneous, vesicle free and do not contain xenoliths larger than 1 mm. Eleven samples from the ash-flow tuff, 1 sample from the ash tuffite (clast-free, homogeneous material) and 4 boulders (2 AFT, 2 non-AFT boulders) of the upper conglomerate were analyzed to demonstrate alteration effects and to define a possible original magma composition.

The two non-AFT boulders are strongly altered ash-flow tuff clasts from the upper conglomerate outcrop near the drilling site, which do not correlate petrographically with the AFT event. They had been analyzed together with 4 Ladinian ash-flow tuff samples from Italy and Yugoslavia to figure out if there exists a geochemical relation or evolution between these Middle Triassic pyroclastic events.

Analyses were done by XRAL, Ontario for main and selected trace elements (Sr, Rb, Cr, Zr, Nb, Y, Ba) X-Ray Fluorescence Spectrometry and by C.J. Orth, Los Alamos for REE, Th, Ta, Hf and U by Neutron Activation Analysis.

Table 2.  
Mineral chemistry of plagioclases (selected microprobe analyses).  
Analyst: G. Neuhuber; Institute of Geosciences, Salzburg University.

<table>
<thead>
<tr>
<th>Sample No. 2</th>
<th>Sample No. 5</th>
<th>Sample No. 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pl 4.1c</td>
<td>Pl 5.1c</td>
<td>Pl 5.2r</td>
</tr>
<tr>
<td>SiO2</td>
<td>57.4</td>
<td>56.54</td>
</tr>
<tr>
<td>Al2O3</td>
<td>26.42</td>
<td>25.79</td>
</tr>
<tr>
<td>CaO</td>
<td>9.4</td>
<td>8.7</td>
</tr>
<tr>
<td>Na2O</td>
<td>6.25</td>
<td>6.31</td>
</tr>
<tr>
<td>K2O</td>
<td>0.62</td>
<td>0.73</td>
</tr>
<tr>
<td>BaO</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Σ</td>
<td>100.09</td>
<td>100.07</td>
</tr>
<tr>
<td>Si</td>
<td>10.316</td>
<td>10.489</td>
</tr>
<tr>
<td>Al</td>
<td>5.598</td>
<td>5.448</td>
</tr>
<tr>
<td>Ca</td>
<td>1.81</td>
<td>1.67</td>
</tr>
<tr>
<td>Na</td>
<td>2.178</td>
<td>2.192</td>
</tr>
<tr>
<td>K</td>
<td>0.142</td>
<td>0.167</td>
</tr>
<tr>
<td>Ba</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Or</td>
<td>3.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Ab</td>
<td>52.7</td>
<td>54.4</td>
</tr>
<tr>
<td>An</td>
<td>43.8</td>
<td>41.5</td>
</tr>
</tbody>
</table>
4.1. Main Element Geochemistry

The samples from the central part are of high-K-dacitic composition (Text-Fig. 3). The discrimination fields for andesites and dacites refer to A. EWART (1979). In the K2O-SiO2 diagram, an alteration trend (AT) is evident, showing for the samples from the base and the top and for the 2 AFT boulders strong K2O enrichment and SiO2 depletion. Reference samples of the non-AFT boulders and of lower Ladinian AFTs and ignimbrites from the eastern part of the Southern Alps (AFT-U, AFT-P, AFT-RS, AFT-RF) are clearly of even higher K2O contents and partially of higher SiO2 contents than typical AFT samples from the central part of the core.

It seems that the reference samples had also been affected by a secondary K influx, which can be seen for many Triassic volcanics of the Southern Alps. An enrichment factor up to 3 had been observed (P. SPADEA, 1970; F. LUCCHINI et al., 1980; G. DEVECCHI & V. DE ZANCHE, 1982; J.H. OBENHOLZNER, 1984). This kind of metasomatism often described from intracratonally erupted lavas is still problematical to explain (D. SAWYER et al., 1989). Most of the cited authors consider a hydrothermal activity to be responsible for this phenomenon.

It is interesting to remark that for all AFT samples the sum Na2O + K2O is nearly constant (6.6-7.5). This indicates a successive exchange of bulk rock Na by K, mostly effecting the plagioclase phases by replacing the albite component by orthoclase(?). Such hetero-
geneous feldspars are also known from other Triassic volcanic rocks in the Southern Alps (J.H. OBENHOLZNER, 1984; P.L. Rossi et al., 1979).

In the AFM diagram all samples of the AFT, including the two AFT boulders, plot within the area of calcalkaline rocks. The reference samples and the two non AFT boulders are more alkaline (Text-Fig. 4).

In the SiO₂-FeOtot/MgO diagram (A. MIYASHIRO, 1974; Text-Fig. 5) all samples plot within the field of calcalkaline rocks, except the two AFT boulders and AFT-RS and AFT-P (out of diagram range). The AFT boulders are strongly altered and enriched in FeOtot. Alteration effects are discussed below. The geochemical characterization of the reference samples outlines a higher FeOtot/MgO ratio than the AFT samples.

In the TiO₂-FeOtot/MgO diagram (J. BEBIEN, 1980; Text-Fig. 6) all samples plot within the field of orogenic rocks (AFT-P is out of diagram range).

### 4.2. Trace Element Geochemistry

The high-K-dacitic composition of the AFT is verified by the SiO₂-Nb/Y diagram (not shown; J.A. WINCHESTER & P.A. FLOYD, 1977). Only strongly altered samples and the rhyolitic AFT-RF plot outside the dacitic field.

The Nb-SiO₂ diagram (not shown; J.A. PEARCE & G.H. GALE, 1977) indicates that all samples are orogenic, except the two strongly altered AFT-boulders.

The plate tectonic interpretation of the cited diagrams is also in agreement with the Hf/3-Th-Ta plot (D.A. WOOD et al., 1979; Text-Fig. 7). This diagram, which was designed especially for basaltic and their differentiates from various tectonic settings, demonstrates that 3 of the AFT samples and the 2 AFT boulders plot within the field (D) of magmas from convergent plate margins. This diagram shows also the fields for Middle Triassic lavas from the Buda Mountains, Hungary (H: data from E. HORVATH & G. TARI, 1987) and the Dolomites, northern Italy (I: data from CASTELLARIN et al., 1988); which enclose the area of the AFT plots.

It is necessary to mention that the Hf and Th and to a lesser degree the Ta contents of the boulders are higher than the contents of the AFT samples.

<table>
<thead>
<tr>
<th>Table 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main and trace element data of AFT (no. 1-15); B1(8) = AFT boulder; B3(16), B4(17) = non-AFT boulders. Reference samples of Ladainian ash-flow tuffs from the eastern Southern Alps (RF = Rio Freddo (Italy); RS = Rio Salto (Italy); P = Podlog (Yugoslavia); U = Ugovizza (Italy).</td>
</tr>
</tbody>
</table>

| S.No. | Depth | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | MgO | CaO | Na₂O | K₂O | LOI | SUM | Cr | Nb | Sr | Y | Zr | Nb | Ba |
| 1 | 30.2 | 56.3 | 0.6 | 20.2 | 5.49 | 0.02 | 2.52 | 0.57 | 1.44 | 6.23 | 0.04 | 6.39 | 99.8 | 19 | 127 | 55 | 64 | 461 | 31 | 85 |
| 15 | 31.14 | 56.4 | 0.59 | 18.6 | 5.29 | 0.02 | 2.2 | 1.3 | 1.52 | 5.36 | 0.11 | 7.53 | 99.86 | 133 | 107 | 55 | 75 | 451 | 33 | 293 |
| 11 | 31.2 | 52.3 | 0.52 | 16.5 | 5.18 | 0.01 | 2.24 | 1.34 | 2.21 | 5.23 | 0.1 | 5.16 | 100.09 | 17 | 113 | 97 | 44 | 394 | 26 | 379 |
| 7 | 31.4 | 55.4 | 0.46 | 14.8 | 2.74 | 0.03 | 2 | 1.3 | 1.52 | 2.93 | 0.1 | 4.16 | 99.98 | 12 | 66 | 72 | 29 | 346 | 26 | 305 |
| 2 | 31.5 | 65.1 | 0.47 | 15.2 | 2.79 | 0.02 | 1.48 | 3 | 0.3 | 1.46 | 2.79 | 0.1 | 4.93 | 99.91 | 12 | 66 | 72 | 29 | 346 | 26 | 305 |
| 3 | 32.7 | 52.0 | 0.52 | 16.4 | 3.47 | 0.02 | 2.32 | 2.56 | 3.14 | 4.25 | 0.1 | 4.79 | 99.92 | 12 | 66 | 72 | 29 | 346 | 26 | 305 |
| 4 | 33.0 | 52.6 | 0.48 | 15.0 | 3.26 | 0.03 | 2.12 | 2.32 | 3.32 | 3.67 | 0.1 | 5.7 | 99.84 | 10 | 92 | 76 | 45 | 344 | 22 | 210 |
| 5 | 33.1 | 64.8 | 0.45 | 14.9 | 2.87 | 0.03 | 1.85 | 3.36 | 2.67 | 2.79 | 0.1 | 4.77 | 99.96 | 15 | 77 | 107 | 55 | 342 | 16 | 272 |
| 6 | 33.2 | 42.0 | 0.46 | 14.9 | 2.87 | 0.03 | 2 | 1.2 | 1.52 | 2.93 | 0.1 | 4.77 | 99.96 | 15 | 77 | 107 | 55 | 342 | 16 | 272 |
| 7 | 34.3 | 59.3 | 0.52 | 17.6 | 3.12 | 0.02 | 2.72 | 2.42 | 1.72 | 3.78 | 0.1 | 4.77 | 99.97 | 12 | 139 | 79 | 38 | 413 | 26 | 546 |
| 8 | 34.3 | 53.9 | 0.52 | 19.6 | 4.09 | 0.02 | 3.08 | 1.82 | 2.12 | 4.61 | 0.1 | 5.16 | 99.44 | 16 | 103 | 55 | 63 | 468 | 27 | 285 |

### Text-Fig. 7

Hf/3-Th-Ta Diagram.
A = N-type MORB; B = E-type MORB and tholeiitic within-plate basalts and their differentiates; C = Alkaline within-plate basalts and their differentiates; D = Convergent plate-margin basalts and their differentiates = calcalkaline rocks plot in the Th-rich part of field; D = Samples from Hungary; see text; I = Samples from Italy; see text.

---

42
that REE contents of glass separates and bulk rock analysis of pyroclastic-flow deposits are very close (except Eu contents), encouraged the author to test the REE contents of 7 AFT, 2 AFT boulder and 2 non-AFT boulder samples.

Text-Fig. 8 shows a rock/chondrite diagram (average chondrite after N. NAKAMURA, 1974) for 3 AFT samples from the central part and the 2 AFT boulders (4 AFT analyses from the base and the top show identical patterns; not drawn in Text-Fig. 8). The trace element variability for Rb, Sr, Y, Nb, Ba in relatively fresh samples from the central part (i.e., no. 5) do not show great variability. Smaller variabilities can be observed in those samples.

For estimating the natural element variability respectively secondary mobility. Text-Fig. 9 shows the ratio of rock to the least altered sample (no. 7) is observable.

The characteristic element variability of samples 7, 10 and 5 is rather large; only Cr, Zr contents show no variability, Sm and Eu anomaly, which is expected for samples more acidic than typical andesites (plagioclase fractionation?).

The pattern of the AFT boulders (Samples 8 and 9) is shifted downwards, without remarkable pattern change, indicating no selective REE mobility. Similar REE behaviour had been described for altered basalts (P.L. HELLMAN et al., 1979).

For comparison, an Andean dacite (R.S. THORPE et al., 1976; DA) is drawn, showing lower rock/chondrite ratios than the relatively fresh AFT samples and a smaller negative Eu anomaly. Two dacites (64.17% and 67.04% SiO₂) from the Rio Grande Rift (USA) have same light REE contents but steeper slopes and no Eu anomaly (data from M.A. DUNGAN et al., 1989; not drawn in Text-Fig. 8).

The La/Nb (2–5) and La/Th ratios (2–7) are typical for high-K-intermediate, orogenic rocks (J. GILL, 1981).

### 5. Alteration

For estimating the natural element variability respectively secondary mobility. Text-Fig. 9 shows the ratio of rock to the least altered sample (no. 7) is considered as a nearly relict domain: no carbonatization and clay mineral replacement of primary mineralphases is observed, less LOI). Most of the main elements in relatively fresh samples from the central part (i.e., no. 5) do not show great variability. Smaller variabilities can be seen for MgO, K₂O (both positive) and Na₂O (negative).

For the AFT boulders (no. 8, 9) a SiO₂, MnO, CaO, Na₂O depletion and a TiO₂, Al₂O₃, FeO, K₂O enrichment relative to the standard sample (no. 7) is observable (Text-Fig. 9). The ash tuffite (no. 1) follows the AFT boulder patterns at a lesser degree, except for P₂O₅, which is depleted relative to the standard.

The trace element variability for Rb, Sr, Y, Nb, Ba in relatively fresh samples from the central part (no. 5, 2 and 6) is rather large; only Cr, Zr contents show no variability (Text-Fig. 10).

The AFT boulders are enriched in Rb, Zr and Nb, de­pleted in Sr, Y and Ba. The ash tuff follows again the patterns of AFT boulders except in Y content, which is just a little outside the range of fresh samples.

Besides the described patterns it is necessary to point to Appendix 2, which shows clearly a depletion of SiO₂, CaO, Na₂O and Sr and an enrichment of Al₂O₃, TiO₂, Fe₂O₃, K₂O and Rb from the central part to the
top and to the base. Constant respectively in range of
natural variation are MnO, P₂O₅, Cr, Y, Nb and Ba.

The interpretation of these features cannot be sum­
marized under one model, so we try to figure out what
kind of processes could be responsible for the ob­
served element distribution.

The enrichment of Al₂O₃, TiO₂ and Fe₂O₃ and the loss
of SiO₂ indicates lateritic weathering conditions (H.
GINSBERG, 1982). The paleoclimatic environment for the
deposition of the Muschelkalk Conglomerate is deter­
mained as semiarid to arid, with periodically or season­
ally high rates of precipitation (M. SCHMIDT, 1987).
Such conditions would favour weathering. Also the
genesis of palygorskite as a weathering product of
basalts in this climate is well documented (M.K. HSNUD­
DIN SIDDIQUI, 1984). But compared with recent lateritic
weathering sections of volcanic rocks a basal altera­
tion is unknown.

The increase of K₂O and Rb, and the decrease of
Na₂O, CaO and Sr, are more typical for hydrothermal
alteration (C.D.A. SAWYER et al., 1989). But Zr, TiO₂ and
other major elements should vary only slightly. Al­
though we recognize such a pattern at the AFT and the
enrichment of Zr, TiO₂, Al₂O₃ and Fe₂O₃ is probably
caused by the loss of silica, we cannot accept this
model as it does not explain the loss of SiO₂.

Seawater alteration would strongly effect the less
welded base and top of the AFT, as water/rock ratios
in these parts are expected to be higher than in the
central part (W.E. SEYFRIED & J.L. BISCHOFF, 1979; W.E.
SEYFRIED & M.J. MOTTI, 1982). But neither low nor high
temperature alteration can produce the pattern of the
observed element mobility (i.e., the decrease of SiO₂
linked with the encrease of Al₂O₃).

Sample 14 was taken from the upper part of the AFT,
but below the ash tuffite. In this part, cm-large areas
consist of coarse grained calcite-quartz fabrics in
which still relics of the AFT occur. The quartz contains
a lot of very small fluid inclusions. Whether the precipi­
tation of quartz and calcite is related to the loss of
SiO₂ and CaO at the top and at the base of the AFT is
not yet determined.

At the present state of research a two-stage altera­
tion model is favoured. Lateritic weathering after de­
position followed by hydrothermal and/or seawater al­
teration could produce the described element distribu­
tion of the core samples. The two AFT boulders are at­
tached by this process at a higher degree than the
massive deposit, indicating that other parts of the AFT
are more altered than the core section or that the
hand-sized boulders had been easier to convert. Small
patches of quartz are ocurring in the carbonaceous
groundmass surrounding the boulders of the conglo­
merate, possibly reflecting SiO₂ migration.

6. Discussion

6.1. Geochemical Results

In general there is little information in literature about
Mesozoic ash-flow tuffs (C.S. Ross & R.L. SMITH,
1961). So the petrography and geochemistry of the AFT document that the natural inhomogeneities caused by microxenoliths, alteration, or loss of fines during transportation do not show significant influences on bulk rock geochemistry of the central AFT. Main, trace and RE elements of the central AFT give us a clear element distribution of an "orogenic", calcalkaline magma.

The alteration patterns of the AFT, although not well explained until now, are an important help to interpret other pyroclastic rocks of the Middle Triassic in the Southern Alps.

6.2. Plate Tectonic Setting

The geochemical composition of the AFT fits well with detailed studies of the massive lavas of the Southern Alps from Anisian to Carnian age. For the Karawanken Mountains (Austria) in the east (J.H. OBENHOLZNER, 1984, 1985; V. HOCK & J.H. OBENHOLZNER, 1987) and for the Dolomites (northern Italy) in the southwest (A. CASTELLARIN et al., 1988) tectonic setting of basaltic to intermediate volcanics is interpreted to be island-arc related.

Recent results in igneous petrology demonstrate that "orogenic", calcalkaline volcanics can also occur in intracontinental settings (D.G. BAILEY et al., 1989). These calcalkaline rocks are often associated with alkaline basalts, situated in an area of crustal extension. The author's investigations of basaltic rocks (Anisian–Ladinian) from the Carnic Alps (Italy), Dobratsch Mountain (Austria) and Orlica Mountains (Yugoslavia) suggest differentiation trends from mildly alkaline basalts to trachybasalts and to basaltic trachyandesites (J.H. OBENHOLZNER, unpubl. data).

The long known fact that an extensional tectonic regime created during Anisian and Ladinian times a facies differentiation according to basins and platforms, would support the hypothesis of an intracontinental magma genesis. The tectonic setting and the association of alkaline and "orogenic", calcalkaline rocks should initiate a reinterpretation of the Middle Triassic magmatism to diminish the paleogeographical problems in the Southern Alps linked to the assumption of a subduction zone during the Triassic.

It is necessary to keep in mind that time equivalent features of compressional tectonics which do not confirm crustal extension are also observable (A. CASTELLARIN et al., 1985).

Text-Fig. 9.
Rock/least altered sample diagram for main elements.
Sample numbers refer to Table 3.
For explanation see text.
6.3. Paleoenvironment

The fluvial deposition of the Muschelkalk Conglomerate is still under discussion (R. BRANDNER, pers. com.). For many volcanologists, ash-flow tuffs are an indicator for subaerial, explosive events. But S.R.J. SPARKS et al. (1980) demonstrated that welding could also occur under submarine conditions. So the AFT should not be used as an argument for fluvial or non-fluvial deposition of the Muschelkalk Conglomerate.

Acknowledgements

The author is grateful to Doz. Dr. H.P. SCHÖNLAUB and Dr. W. HOLSER for the opportunity to participate in the project and Dr. C.J. ORTH for analytical work. Thanks are also expressed to Prof. Dr. E. KIRCHNER (Institut für Geowissenschaften; Universität Salzburg) for clay mineral determination; G. NEUHUBER (Institut für Geowissenschaften; Universität Salzburg) for microprobe studies and Dr. W. HOLSER and Prof. Dr. W.J. SCHMIDT (Institut für Geowissenschaften; Montanuniversität Leoben) for critical reading of the manuscript.

Plate 1

Fig. 1: **White to greyish pumice fragment (P)**
- with tubular (t) and ovoid - lensoid (o) vesicles - lithic fragment.
- PPL.

Fig. 2: **Oxidized and slightly collapsed (small black arrows) pumice fragment**
- with tubular vesicles - juvenile component.
- Big black arrow points upward.
- PPL.

Fig. 3: **Filled vacuole.**
- Q = quartz; C = calcite.
- The shape of the vacuole is outlined by iron oxides (thin dark rim); the AFT-matrix (M) is bleached around the vacuole.
- PPL.

Fig. 4: **Typical shard texture of slightly to moderately welded central part of the AFT.**
- Sampled at 31.5 m.
- Shape of shards is shred-like; outlined by iron oxides. Shards consist of quartz and K-feldspar ± calcite.
- Black arrow points upward.
- PPL.
Plate 2

Fig. 1: Basaltic-andesitic (?) lithic fragment, slightly rounded. PPL.

Fig. 2: Poikilitic plagioclase with inclusions of devitrified glass droplets. Alien (?) component. Embayed at middle; left side of the crystal. PPL.

Fig. 3: Crystal clot of plagioclases (P) with inclusion of apatite (A) needles and altered Ti-magnetite (T). PPL.

Fig. 4: Strongly embayed andesine (A). Deformation of AFT-matrix can be seen below plagioclase 1 and 2. Black arrow points upward. PPL.