Chapter 2. Petrography and geochemistry of the Tepoztlán Formation

2.1. Petrography

Following the terminology for volcaniclastic rocks of McPhie et al. (1993), the Tepoztlán Formation is made up of tuffs and lavas, tuffaceous sandstones, conglomerates and breccias, originating from different transportational and depositional processes during or after volcanic eruptions (Fig. 2). In order to assign each depositional unit to a certain mode of transportation and deposition, their detailed petrography and lithologic description is given here. The modal proportions of phenocrysts were measured for nine representative samples of volcanic rocks (lava, blocks of block-and-ash flow deposits, lithoclasts of pyroclastic flow deposits) by point counting (Fig. 3; Table 1). Furthermore, first results on geochemical studies on the Tepoztlán Formation rocks are presented here. However, a detailed discussion on geochemical signatures and petrological features is found in Torres-Alvarado et al. (in prep.).

Lava

The lavas commonly have a blocky carapace and a dense core, being exposed either on the top of mountain ridges or intercalated between other depositional units. They are identified as a'a lavas. All analysed samples have a porphyritic to glomeroporphyritic texture. For the massive lavas, the total phenocryst contents are 2 - 60 vol.%. Plagioclase is the most abundant phase with subordinate K-feldspar, clinopyroxene and amphibole. Accessory phases consist of mica, abundant titanomagnetite and other accessories.

The plagioclase phenocrysts of anorthitic composition (~ 2500 µm) are euhedral to subhedral and show zonation. Clinopyroxene of augitic composition (~ 2000 µm) is the most abundant mafic phase and shows euhedral to subhedral habitus. Amphibole (magnesioriebeckite; ~ 2000 µm) occurs as a minor constituent.

The groundmass shows a hyalophylitic, sometimes trachytic texture, comprising plagioclase microlites and an ore phase (titanomagnetite). The whole rock SiO_2 content of the lavas ranges from 55.9 to 60.6 wt.%, identifying them as andesites or dacites. In regard to its chemical composition we can estimate depositional temperatures for the lava between 800 and 1200°C (Cas and Wright, 1987).

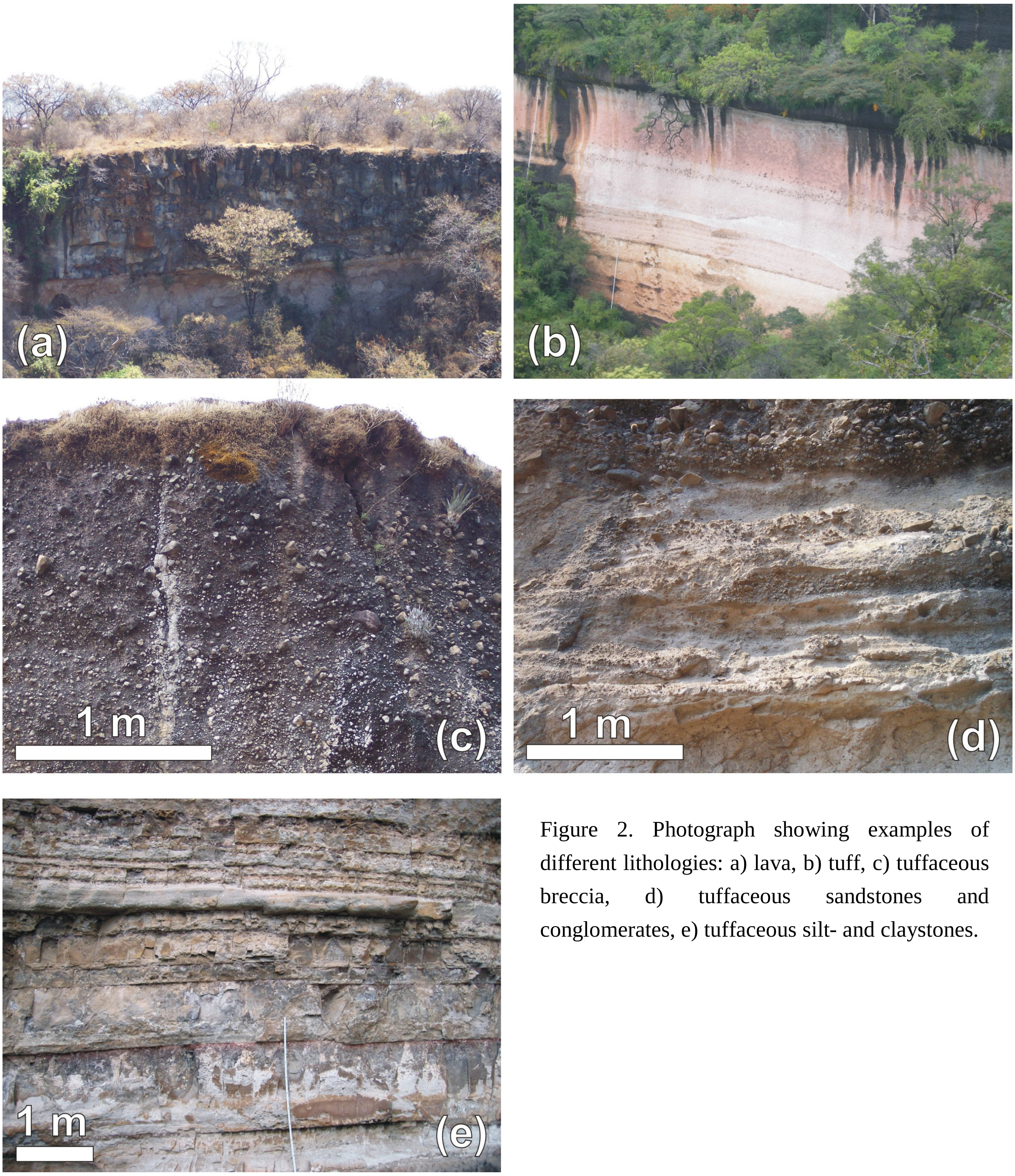

Figure 2. Photograph showing examples of different lithologies: a) lava, b) tuff, c) tuffaceous breccia, d) tuffaceous sandstones and conglomerates, e) tuffaceous silt- and claystones.

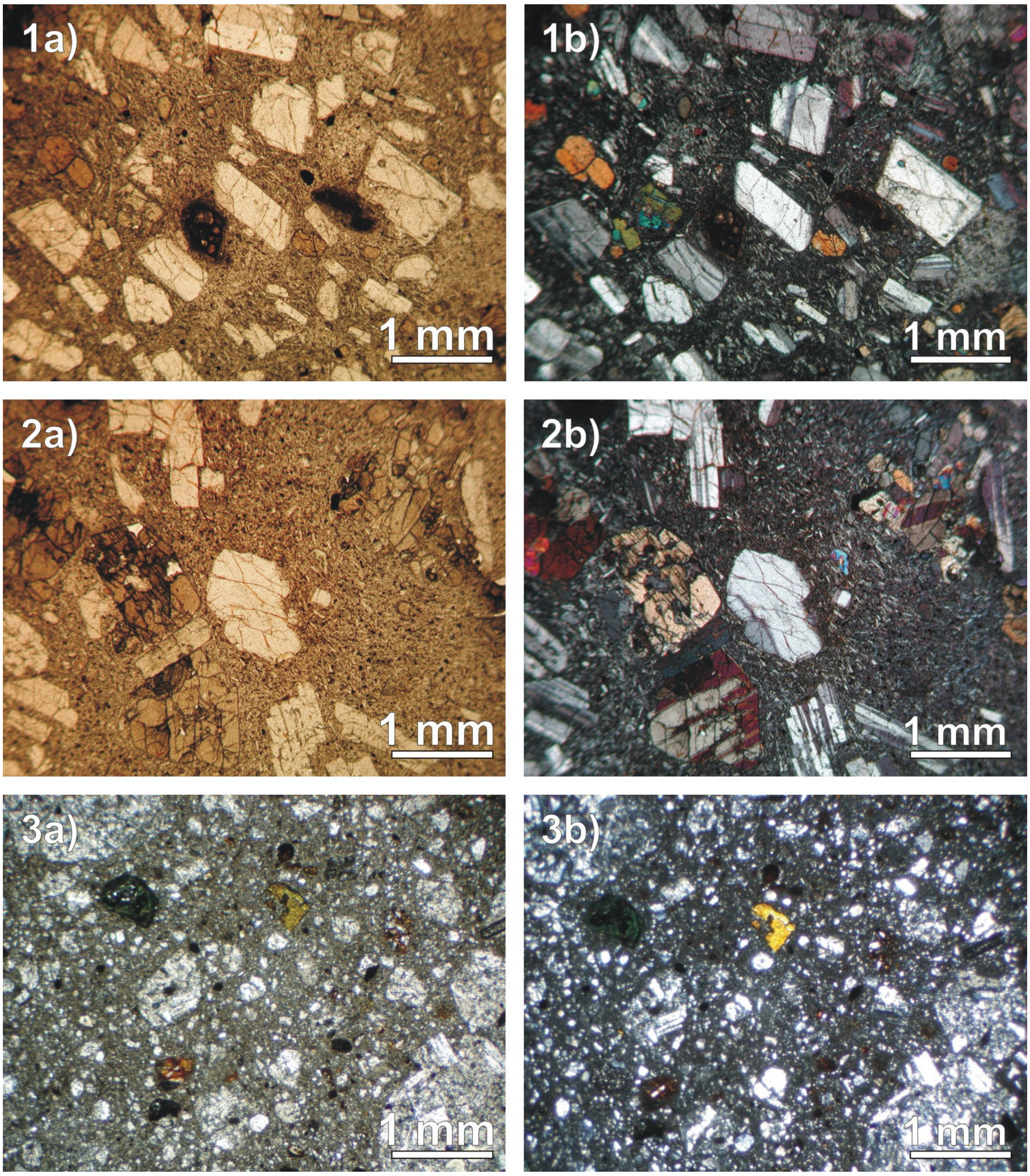

Figure 3. Photomicrographs of volcanic rocks of the Tepoztlán Formation. Scale bar is 1mm, 1) dense lava in the central part of a lava flow, 2) clasts in fluvial deposits, 3) Tuff. a) non-polarized and b) polarized light.

Tuff

Within the study area abundant tuff layers are exposed. Each unit consists of a massive to finely laminated or cross-bedded, varicoloured, poorly sorted mixture of medium to coarse ash horizons, sometimes rich in lapilli. Their thicknesses range from few centimetres to several meters. Based on texture and lithology we could distinguish fall and pyroclastic density current deposits. The petrographic composition of the tuffs indicates a purely magmatic activity, without any magma-water interaction.

The fall deposits reach thicknesses of a few centimetres, show mantle bedding and can be traced for several hundred meters throughout the outcrops. They consist of layers of coarse ash particles, showing either normal or inverse grading. The particles are composed of micropumice and pyroxene crystals.

The deposits of pyroclastic density currents could further be subdivided into units with stratification (ripples, cross-bedding, antidunes), massive pumice-rich units and blocky tuff breccias rich in dense lava blocks. The depositional temperatures for pyroclastic rocks are usually above 200°C (Fisher and Schmincke, 1984). The upper boundary of the depositional temperatures is estimated to be below 400°C, as the mineral content does not show any signs of modification due to welding (McArthur et al., 1998).

The stratified tuff layers range from 5 to 10 cm in thickness, are moderately sorted and are mostly composed of a coarse ash matrix with minor embedded pumice fragments. Locally, they show erosional bases and pinch-and-swell structures. They are interpreted as being deposited under surge-like depositional conditions from dilute gravity currents or during windy conditions (Allen et al., 1999).

The massive pumice-rich tuffs exhibit a wide range of grain-sizes, covering everything from fine ash to cobble-sized lithic and pumice clasts (max. 10 cm). The tuff matrix appears unwelded, comprising about 50% crystals, 2% lithics and 48% vitrics (average from 10 samples). Among the crystals, feldspars make up the dominant mineral phase. The mostly broken crystals of plagioclase and K-feldspar reach up to 2500 µm in size, subordinate pyroxene (augite) ranges from 400 to 2000 µm. Quartz crystals (200 µm) are a rare mineral phase but occur in 3 samples. Microcrysts reach sizes of 200-500 µm, however, plagioclase microcrystals commonly are 40-120 µm in size.

Cognate lithic clasts comprise grey to red porphyritic rocks of dacitic to andesitic composition (58.5 - 66.5 vol.% SiO_2). Plagioclase crystals (up to 2000 µm) form the dominant mineral phase, accompanied by K-feldspars (sanidine and microcline, ~2000 µm). Subordinate minerals are amphibole (up to 2000 µm) and clinopyroxene (augite, ~800 µm). Dark mica (biotite, ~1000 µm) is only present in few samples.

Pumice clasts range from creamy white to pale yellow in colour. They are relatively dense to finely vesicular and usually porphyritic, containing predominantly augite and plagioclase as phenocrystals. Within the matrix, pumice clasts usually do not exceed diameters of 6 mm. However, in pumice concentration zones on top of single units, clasts can reach up to 10 cm in diameter. Due to transportation and abrasion they appear subrounded to rounded. There are no macroscopic signs for fossil wood or other plant material. Microscopically there are nevertheless fragments of charcoal and various palynomorphs (see Chapter 5).

In some ignimbritic units, rare accessory clasts were found which were derived from the subvolcanic basement and brought to the surface during the eruption. They comprise red clay-/siltstones and grey carbonate rocks. Under the microscope, the red clay-/ siltstone shows a proportion of 15% crystals in a clayey, in parts still glassy matrix. The crystals consist of quartz, plagioclase and pyroxene as broken phenocrysts. Yellow, red and green particles suggest an alteration of pumice particles. The appearance of the rock fragments points to an origin from the underlying Balsas Group.

The carbonates range from a light- to darkgrey in colour. They are described as pack-/ or wackestones after Dunham (1962) with a calcitic-detritic matrix and are suggested to originate from the underlying Morelos Formation.

The poorly sorted blocky tuff breccia appears massive and matrix-supported. Grading patterns are absent. The angular, dense lava clasts are dominantly of block size and often show hexagonal shapes, derived from columnar jointing in lava flows. These deposits are interpreted as block-and-ash flow deposits.

The clasts are of andesitic composition (~ 59 vol.% SiO_2). The dominating mineral phase among the phenocrysts is plagioclase (500 - 7000 µm) with amphibole (100 - 4000 µm), augite (100 - 4000 µm) and rare K-feldspars (500 - 5000 µm) as subordinate minerals. The groundmass is composed of plagioclase, Fe-Ti magnetites and abundant glass.

The matrix of the tuff breccia possesses the same composition as the embodied lava clasts, pointing to a co-genetic origin. It is made up of glass shards, lava fragments and abundant phenocrystals resembling the crystal content of the clasts.

Tuffaceous breccias

Associated with the primary volcaniclastic deposits we find a wide variety of reworked products within the study area. Among them the mass flow deposits are characterised by tuffaceous breccias, originating from debris flows and hyperconcentrated flows, respectively. Debris flow deposits are sheet-like, show no signs of grading or sorting and reach thicknesses up to 10 m. The hyperconcentrated flow deposits however show erosional basal surfaces, normal or inverse grading and occasional diffuse sedimentary structures. These deposits reach about 4 m in thickness within the study area.

The mass flow deposits are composed of angular to subangular clasts in a pinkish red matrix of fine to medium sand. The clast size usually is in the range of pebbles and cobbles, not exceeding diameters of 20 cm; however, single outsized clasts of 2 m in diameter have been observed. The clasts within the mass flow deposits have similar characteristics and compositions as the primary deposits described above for which reason an origin due to reworking of the latter is evident. The prevalence of angular to subangular intermediate volcanic clasts implies a local source, and thus contemporaneous volcanism and sedimentation. The matrix of the mass flow deposits is commonly composed of 30% lithic and pumice fragments (up to 1.2 mm), 10% crystals and 60% glass shards showing significant alteration to clay minerals. The fragments do not show any alignment within the matrix. Plagioclase (600 µm) and amphibole (800 µm) phenocrysts are subhedral and commonly broken while amphiboles show signs of alteration. The rare quartz phenocrysts reach sizes of 800 µm. The tuffaceous breccias were deposited under ambient air temperature conditions.

Tuffaceous sandstones and conglomerates

The grey, cross-bedded, fine to medium grained sandstones and pebbly to bouldery conglomerates within the study area are interpreted as fluvial deposits. They appear in sheets and lentils as manifested in channels and gravel bars or as fillings of scours, respectively. The matrix dominantly consists of sand grains, resembling small clasts of lava, pumice or reworked ash-particles. Based on the composition, the presence of crystals and the absence of basement material, the original fragmentation process and components support an initial pyroclastic origin. However, the sedimentary structures indicate significant reworking of either primary pyroclastic material or material that had already previously been reworked by lahars. Clast abrasion in streams was rather inefficient as shown by the subangular to subrounded shapes. The tuffaceous sandstones and conglomerates were deposited under ambient air temperature conditions.

Tuffaceous silt- and claystones

Several thin strata of red to purple tuffaceous silt- and claystones are recognized within the study area. They appear massive or laminated and rarely exceed thicknesses of more than one or two cm. However, at some locations such as near Malinalco silt- and claystones reach thicknesses of several meters. Thin sheet- or lentil-like deposits are interpreted as waning flood sediments. The purple colour probably represents subaerial alteration. However, no paleosoils could be found throughout the whole sequence. Near Malinalco and in the east of the village Santo Domingo in the State of Morelos (19.00°N, 99.03°W), several meters thick, coarsening-upward clay- and siltstones are interpreted as lacustrine deposits. The finest sediments show a varve-like texture with lamination and pumice drop stones. The coarsening-upward is interpreted as deposition near the lake-shore with steady accumulation of sediment in a progradational setting. The tuffaceous silt- and claystones were deposited under ambient air temperature conditions.

Table 1: modal abundance of representative samples of Tepoztlán Formation volcanic rocks in per cent.

Lithology	**Lava**				**Blocks of Block-and-Ash Flow**		**Lithoclasts**		
Sample No.	M210	TL250-1	TL233-12P	TE5	TL233-HO	TL250-5P	SL1	SL2	SL3a
Plag.	40,40	0,68	15,74	0,36	2,52	5,84	1,12	4,08	17,10
K-fspar	0,00	0,18	1,19	0,14	0,00	0,59	0,58	0,20	9,63
Amph	5,94	0,00	0,00	0,02	0,15	1,58	0,98	1,29	0,55
Cpx	13,07	0,88	11,88	1,47	0,30	1,88	0,00	0,20	2,45
Mica	0,00	0,12	0,00	0,00	0,00	0,00	2,28	4,18	0,00
Quartz	0,00	0,12	0,59	0,00	0,00	0,00	0,00	0,00	0,00
Fe-Ti	0,59	0,02	0,59	0,02	0,03	0,10	0,04	0,05	0,27
Ground-mass	40	98	70	98	97	90	95	90	70

Plag.=Plagioclase; K-fspar.=K-feldspar; Amph.=Amphibole; Cpx=Clinopyroxene

2.2. Geochemistry

A total of 56 samples was collected in sections MA, SA, TEP, SO, TO and TL, comprising all types of volcanic material of the Tepoztlán Formation (pyroclastic flow, lava and dyke samples, clast components). All samples were carefully cleaned and further pulverized using an achat mill for geochemical and isotopic analyses. Major and trace elements were analysed by the commercial laboratories Actlabs, Canada, following the “4LithoResearch” methodology. The samples were fused using a lithium metaborate/tetraborate mixture and the glass pellets were then completely dissolved with 5% HNO_3. Major elements, as well as Ba, Sr, Sc, Zr, V, and Be were analysed using inductively coupled plasma (ICP) with an analytical precision better than 2%. Trace element (including rare-earth elements, REE) analyses were done by inductively coupled plasma-mass spectrometry (ICPMS), with analytical errors between 5 and 12%. Isotopic analyses were performed at Geochemical Laboratory of the University of Tübingen by Dr. Muharrem Satir. All data are listed in Appendix 1 and the results are presented in Torres-Alvarado et al. (in prep.).

The Tepoztlán Formation is composed of subalkaline and hy-normative volcanic and sedimentary rocks. The volcanic rocks range in composition from basaltic andesite to rhyolite; however, andesites and dacites are clearly dominating (Fig. 4). Distinct geochemical provinces or temporal trends cannot be observed within these rocks.

Torres-Alvarado et al. (in prep.) propose that contents of LILE, REE and HFSE are very similar among the different areas of the Tepoztlán Formation and follow similar trends to those of Quaternary volcanic rocks from the Sierra Chichinautzin Volcanic Field. Major and trace element concentrations show that assimilation of heterogeneous continental crust and fractional crystallization were important processes in the evolution of the Tepoztlán Formation magmas.

The isotopic composition of the samples ranges from $^{87}Sr/^{86}Sr$ = 0.703760 to 0.704436 and $^{143}Nd/^{144}Nd$ = 0.512794 to 0.512913 (Torres-Alvarado et al., in prep.). All analysed samples fall within the mantle array. Their isotopic composition is interpreted to indicate simple mixing between mafic magma and the upper crust. The source of these magmas is probably a heterogeneous mantle. They evolved by assimilation of country rock and further fractional crystallization in the upper crust (Torres-Alvarado et al., in prep.).

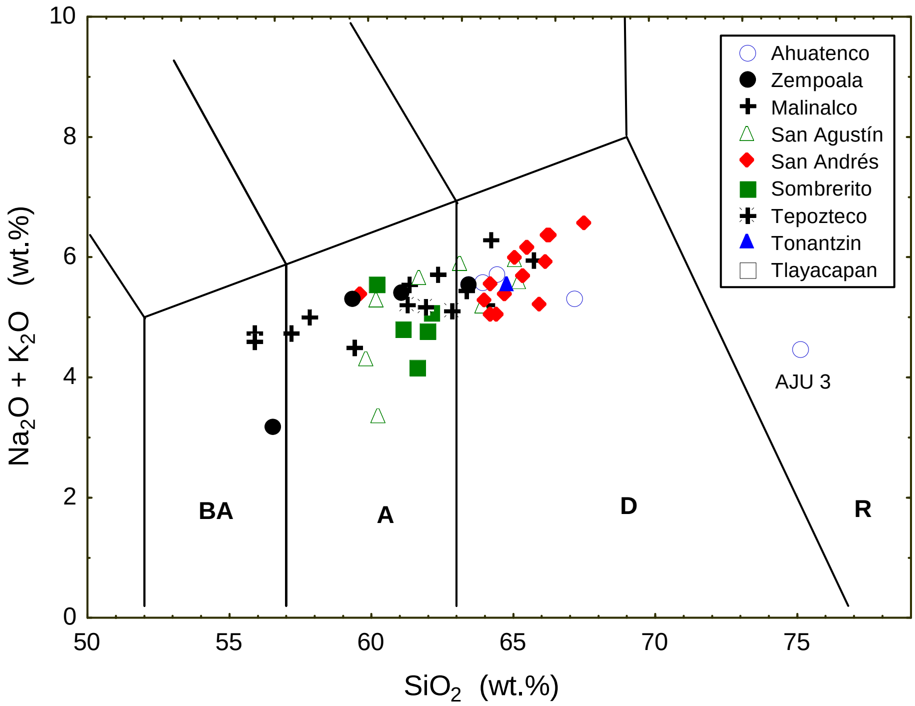

Figure 4. Rock classification of the Tepoztlán Formation based on the total alkali-silica (TAS) scheme (Le Bas et al., 1986; Le Bas, 1989, 2000). BA, basaltic andesite; A, andesite; D, dacite; R, rhyolite.