Mineralogical Magazine, February 1999, Vol. 63(1), pp. 131–141

A scanning electron microscope study of post-depositional changes in the northeast Niğde ignimbrites, South Central Anatolia, Turkey

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ABSTRACT

The ignimbrites of the northeast Niğde area, which are subdivided into the Lower, Middle and Upper ignimbrites on the basis of their compositional and stratigraphical characteristics, display textural variations from the base to the top. A large proportion of these ignimbrites have been altered and recrystallized by the processes of compaction, welding and devitrification, and as a result of volatile movement. The alteration and recrystallization processes include four stages: hydration, glassy and spherulitic stages accompanied by vapour-phase crystallisation. In the early phases of devitrification, detailed shard shapes are easily recognisable with the scanning electron microscope, but as alteration proceeds clarity of detail disappears because compaction results in collapse of the structure of the rock. Spherulitic and vapour-phase crystallisation usually involves the growth of alkali feldspar and cristobalite. These later stages are more common in the Upper Ignimbrite than the Middle and Lower ignimbrites.

Keywords: ignimbrite, Niğde, compaction, welding, devitrification, hydration, glassy, spherulitic, vapour-phase.

Introduction

The Pliocene pyroclastic deposits exposed to the northeast of Niğde in south central Anatolia (Fig. 1) belong to the K-rich calc-alkaline series and show a continuous compositional sequence from basaltic andesite to rhyolite. There is a good stratigraphical and petrographical zonation in the main ignimbrite bodies, and therefore, they are classified as Lower (Unit 1), Middle (Unit 2) and Upper (Unit 3) ignimbrites (Fig. 2). The Lower Ignimbrite is of andesitic or rhyolitic composition; the Middle Ignimbrite is dacitic or rhyodacitic; and the Upper Ignimbrite is rhyodacitic and rhyolitic. These ignimbrite units are separated from each other by an andesitic ash flow and reworked deposits respectively (Fig. 2).

Phenocrysts (in order of decreasing abundance) are plagioclase, quartz, biotite, titano-magnetite, hornblende, clino- and orthopyroxene together with traces of apatite (Table 1). The total phenocryst content is less than 20% by volume for the Upper and Lower ignimbrites but it is slightly higher in the Middle Ignimbrite reaching up to 24% by volume. Lithic fragments rarely exceed 8% by volume and they generally constitute less than 10% in all units (Fig. 3). The groundmass is composed of small glass shards and pumice particles (72–90% by volume of the rock; Fig. 3).

These ignimbrite units show both welded and non-welded characteristics and they have been altered by devitrification, compaction and to a lesser extent by vapour phase crystallisation

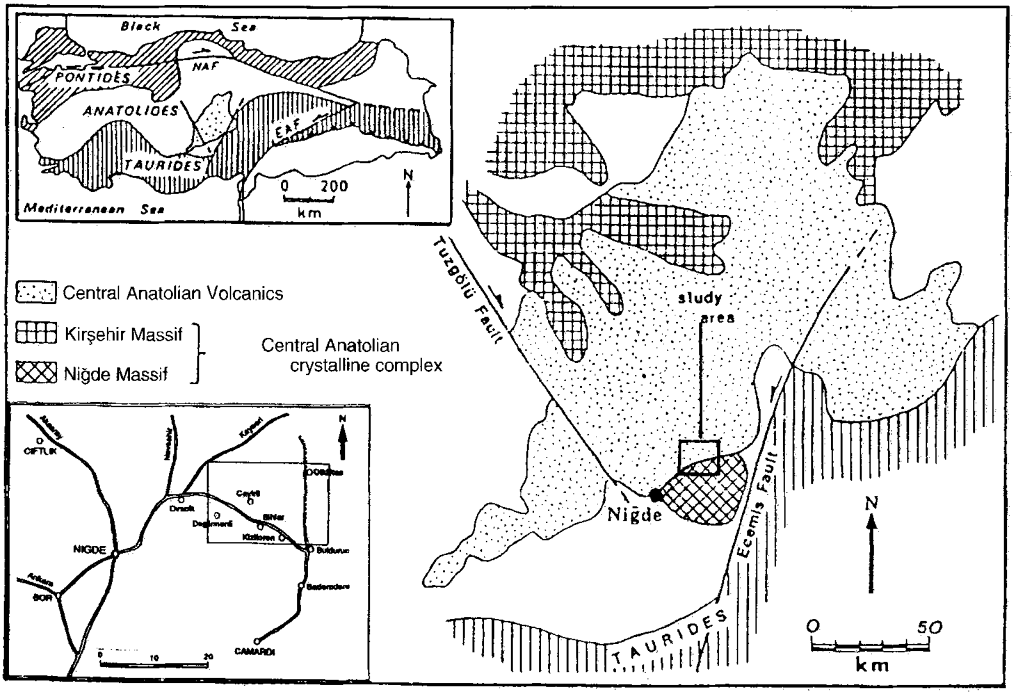

FIG. 1. Location map of the study area, NAF: North Anatolian Fault; EAF: East Anatolian Fault (After Toprak and Göncüoğlu, 1993).

processes to a fine-grained mixture of alkali feldspar and cristobalite. Welding, compaction and crystallisation are processes of major importance in changing pyroclastic rocks after deposition (Carr, 1981). The physical variations which occur within the main ignimbrite bodies have been studied by the scanning electron microscope and are reported in this paper.

Textural variations

The northeast Niğde ignimbrites have been subdivided into zones defined by their degree of welding, devitrification and their compositional differences (Yurtmen, 1993). The stratigraphically oldest Lower Ignimbrite (Fig. 2) has low-grade ignimbrite characteristics (Branney and

TABLE 1. Phenocryst assemblage of the northeast Niğde volcanics

Units	Plg	Qz	Bt	Cpx	Opx	Hb	Mt	Ap
Upper Ign.	+	+	+	±	±	±	+	±
Pumice-fall	+	+	+	±	±	±	+	
Rewrk. dep.	+	±	+	+		+	+	
Mddle Ign.	+		+	+	±	±	+	±
Grey ash	+	±	+	+		+	+	
Lower Ign.	+	±	+	±		+	+	

Notes: Plagioclase phenocrysts (about 30% by volume) are always present.
Abbreviations: Plg – plagioclase, Qz = quartz, Bt – biotite, Cpx – clinopyroxene, Opx– orthopyroxene, Hb = Hornblende, Mt = titanomagnetite, Ap = apatite, + = always present, ± = sometimes present.

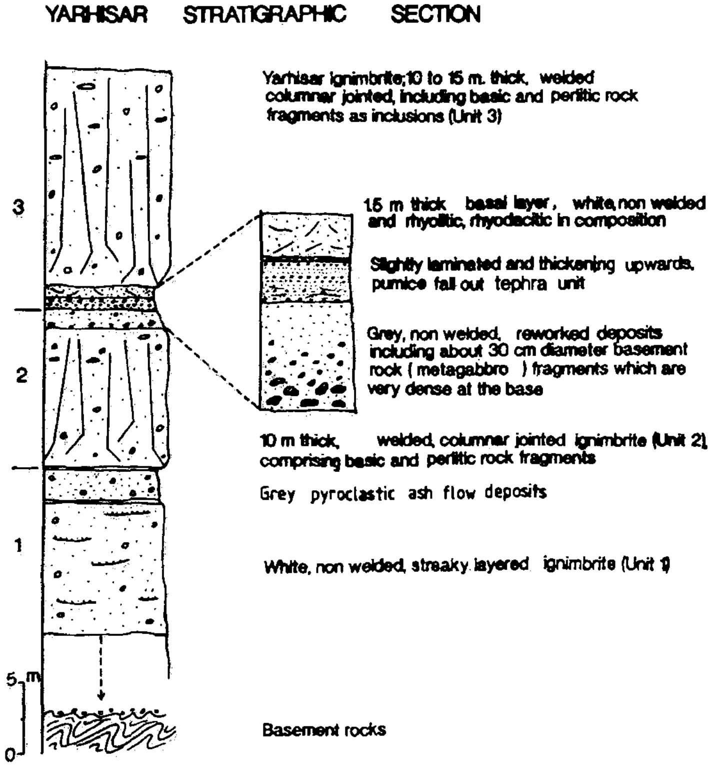

FIG. 2. A stratigraphical section of the ignimbrites in Yarhisar.

Kokelaar, 1992) with no welding; these are overlain by the moderate-graded Middle and Upper Ignimbrites (Fig. 2) displaying both non-welded and slightly welded, devitrified zones.

The principal stages of crystallisation have been identified which may take place during the cooling history of the silicic glass. In order of frequency of occurrence, these are devitrification which involves hydration, followed by a glassy stage and a growth of spherulite, vapour-phase crystallisation and granophyric crystallisation (Smith, 1960; Lofgren, 1970, 1971*a*). Textural variations observed in the Niğde volcanics suggest that these rocks have undergone recrystallisation which includes the hydration stage, the glassy stage and the spherulitic stage accompanied by vapour-phase crystallisation.

The hydration stage

This stage of devitrification is common in the Lower Ignimbrite and the basal layer of the Upper Ignimbrite (Fig. 2).

The non-welded Lower Ignimbrite is a generally massive unit forming the base of the eruption products and is composed of a white, somewhat friable pumice flow deposit which is clearly controlled by the underlying topography. This unit consists of extremely rich pale-brown glass shards and pumice, crystals and poor lithic fragments. The shards are very fresh with little or no welding and they are fibrous, elongated and circular. Y-shaped particles are also common.

The Upper Ignimbrite unit (Fig. 2) is composed of two different zones as layer 2a or basal layer and layer 2b or main body distinguished by their depositional characteristics (Sparks *et al.*, 1973). These two layers occur immediately above the pyroclastic fall unit (Fig. 2) which is composed of varied proportions of pumice, crystals and lithic fragments. Glass shards are very rare in the pumice fall and the groundmass consists entirely of small angular pumice shards and they have a characteristically elongated, fibrous and cellular

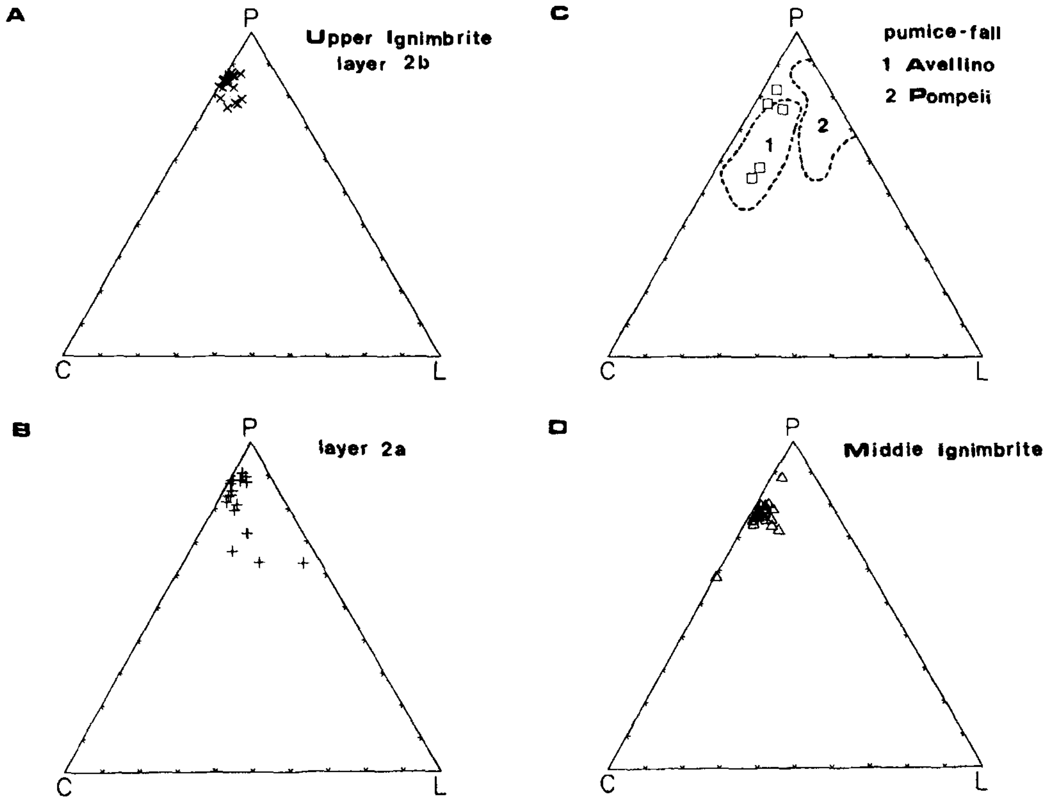

FIG. 3. Plot of weight percentages of pumice (P), crystals (C), and lithic fragments (L) for whole samples collected from the Upper Ignimbrite main body (a) and basal layer (b), the pumice-fall (c), and the Middle Ignimbrite (d) of the Northeast Niğde volcanics. The fields of the Pompeii and Avellino pumice are also indicated in the pumice-fall PCL diagram for comparison (after Lirer *et al.*, 1973).

structure together with some pale-brown glass shards.

The basal layer is made up of loose tephra containing pumice and lithic fragments ranging in size between 0.5 cm and 10 cm in diameter. Characteristically broken bubble-wall shaped particles (pumice and glass shards) are also preserved in this unit and indicate primary non-welding of tephra. At the very bottom of the basal layer, the shards are predominantly block- to plate-like (Fig. 4*a–f*). Y-shaped fragments are rare. There are small glassy particles on the surface of all shards and sometimes on the vesicle surfaces within the pumice (Fig. 5*a–d*). Above the base, the pumice has irregularly shaped vesicles ranging from pipes to pods (Fig. 5*e,f*). Towards the top of the unit deformation becomes significant and shards are modestly welded. Y-shaped, cuspate or lunate glass shards are deformed and thin bubble shard walls have collapsed more than thick ones (Fig. 6*a–d*).

Glassy and spherulitic stage

The Middle Ignimbrite and the Upper Ignimbrite main body show glassy and spherulitic stages of devitrification. The glassy stage is marked by a felsitic texture with minor spherulites whereas the spherulitic stage is marked by an abundance of spherulites and micropoikilitic quartz.

The creamy white Middle Ignimbrite (Fig. 2) is columnar jointed and moderately welded. There is a small amount of field evidence presented by some fragments which are imbricated parallel to the depositional surface (Bates and Jackson, 1980; Branney and Kokelaar, 1992). Characteristically

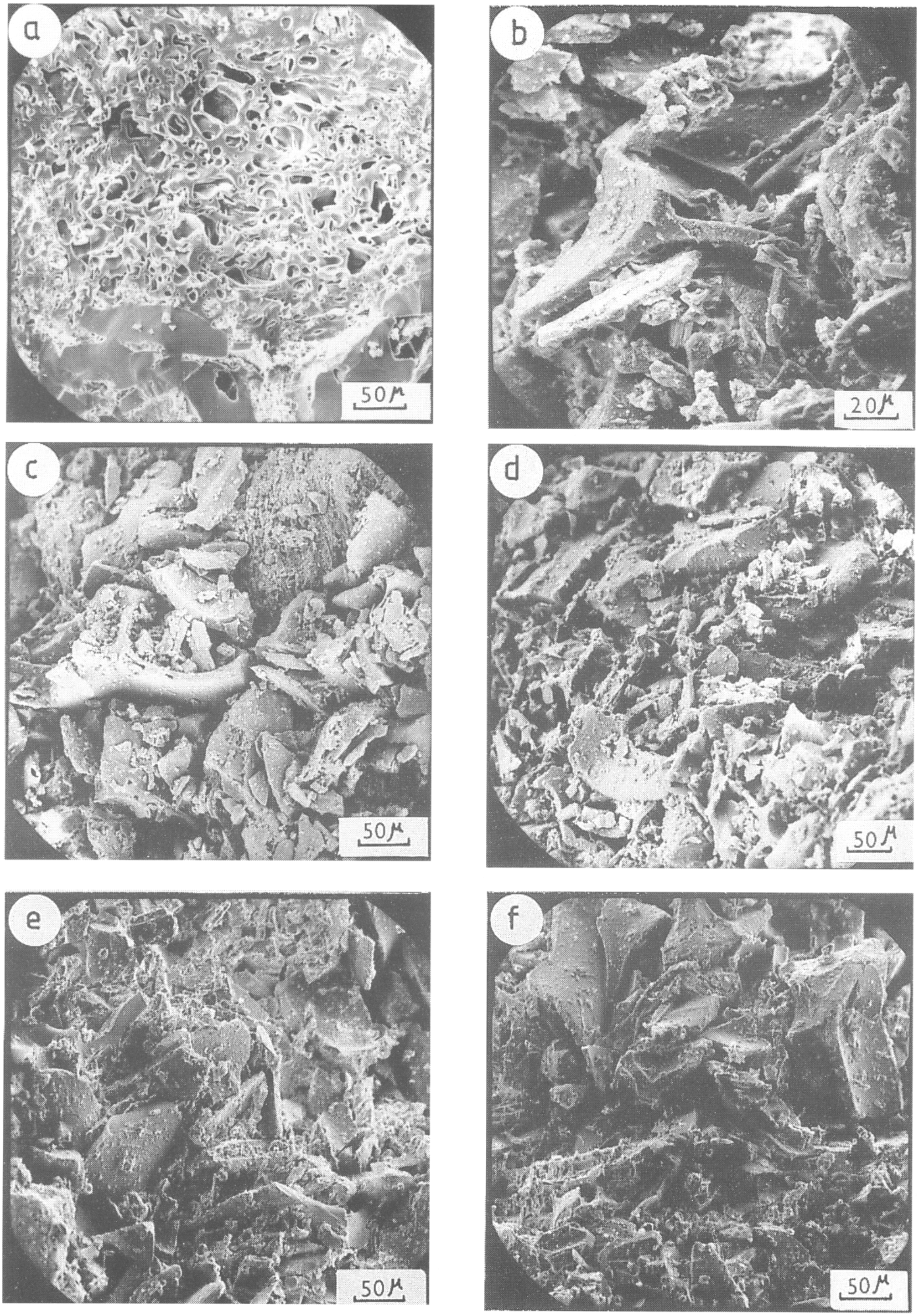

FIG. 4. (*a*) SEM photomicrograph of the slightly collapsed pumice and fresh glass. (*b–f*) SEM image of the block to plate like rhyolitic glass shards at the base of the basal layer.

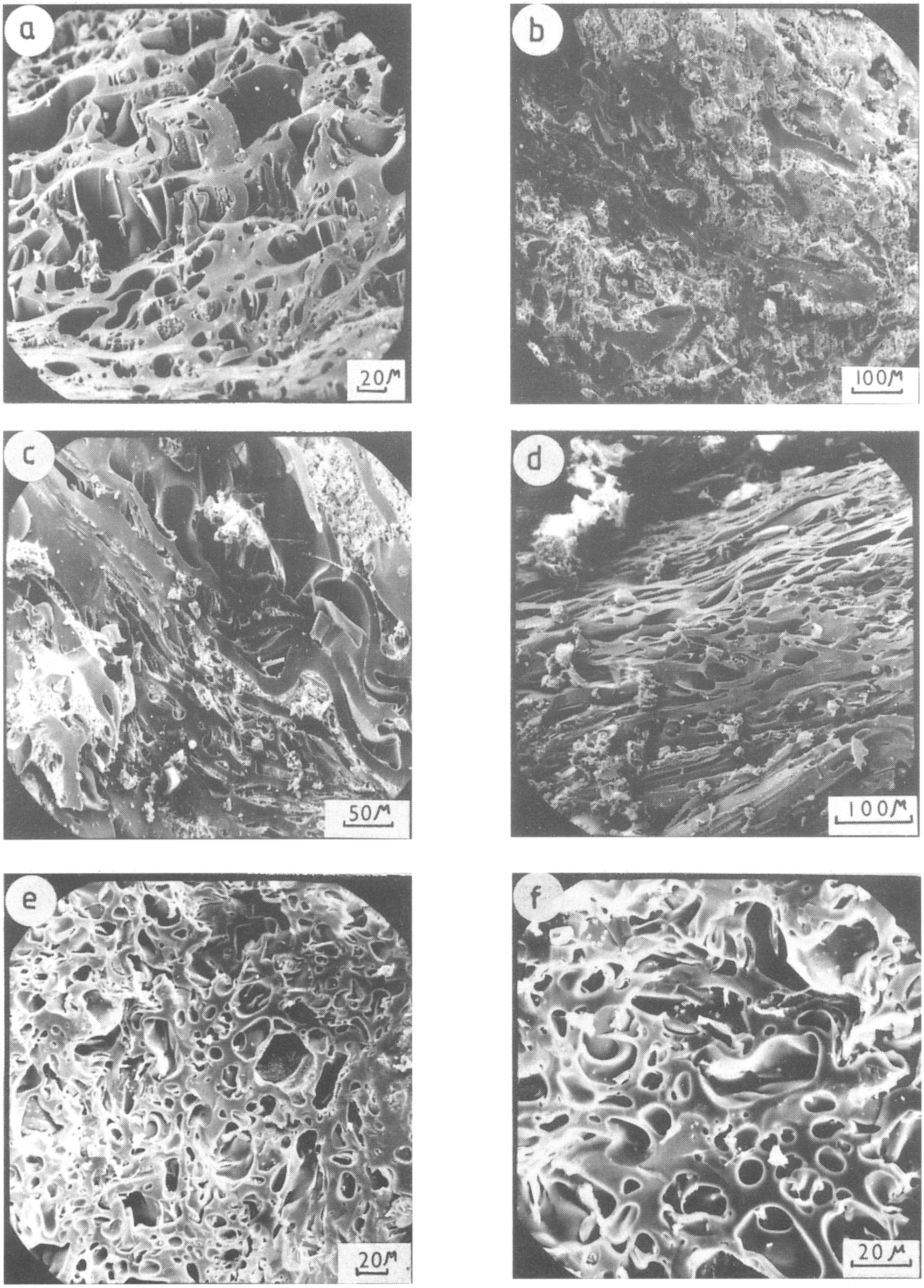

FIG. 5. (*a*) SEM photomicrograph of the vesiculated fresh glass in the basal layer. (*b*) SEM image of the bubble junction shards in the finer grained glassy matrix. (*c*) SEM image of the vesiculated and incompletely collapsed fresh glass. (*d*) SEM of the fibrous structured pumice with elongated vesicles. (*e*) and (*f*) SEM image of the slightly collapsed pumice fragments showing irregular vesicle shapes from pipes to pods.

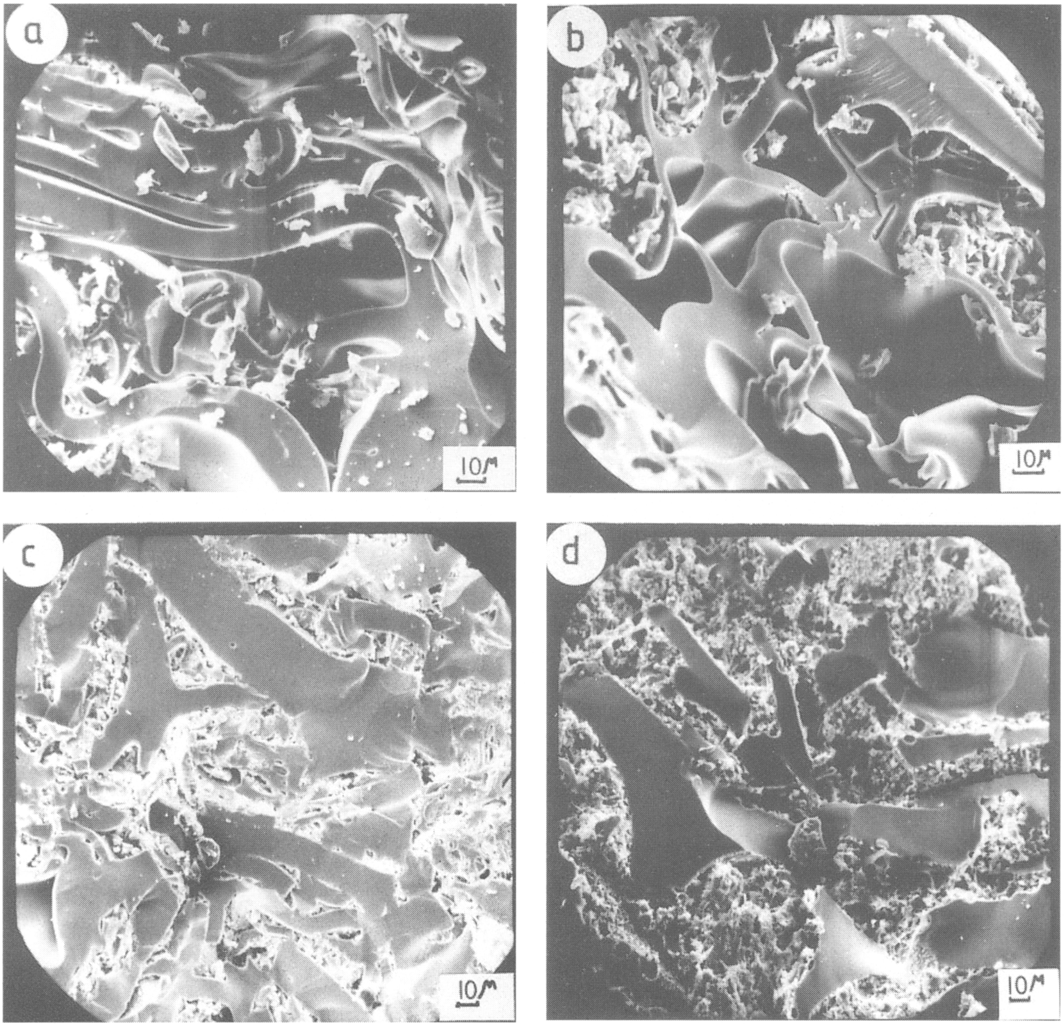

FIG. 6. (*a*) and (*b*) Scanning electron photomicrograph of vesiculated glass shards in the basal layer of the Upper Ignimbrite. Vesicle walls are collapsed and deformed. (*c*) and (*d*) SEM photomicrograph of fresh shards emplaced in the smaller grained glassy matrix.

it contains both scattered lithic and pumice fragments ranging from 1 to 30 cm in diameter. The maximum thickness of the unit is 15 m around Çayirli (Fig. 1) where it is best exposed. The groundmass is formed completely of small devitrified and highly vesiculated glass shards accompanied by smaller amounts of pumice particles. Devitrified glass displays axiolitic intergrowths chiefly of cristobalite and feldspar. Spherulites can be seen only in pumice inclusions and pore spaces which can be clearly seen with the petrographic microscope (Fig. 7*a*). These pore spaces sometimes contain abundant iron ores and newly formed minute crystals.

The Upper Ignimbrite main body shows well developed columnar jointing and contains gas cavities (lenticules) towards the top of the unit. The groundmass of this unit is also vitrophyric and entirely constituted from devitrified bubble wall shards forming an axiolitic structure with parallel intergrowth of alkali feldspar and cristobalite in the original forms of the shards. This can be clearly seen with both the scanning-electron microscope and the petrographic micro-

FIG. 7. (*a*) Photomicrograph showing the spherulitic texture developed in the pore spaces in the Middle Ignimbrite, CPL. (*b*) Spherulitic texture in the Upper Ignimbrite, CPL. (*c*) Photomicrograph of devitrified glass displaying axiolitic texture in the Upper Ignimbrite.

scope in this moderately welded unit (Fig. 7*c*; Fig. 8*a,b*). Also many shards form large spherulites consisting of radially disposed fibrous crystals probably of alkali feldspar and cristobalite in porous patches which were formerly pumice (Fig. 7*b*).

Vapour-phase crystallisation

This stage of devitrification is observed only in the Upper Ignimbrite main body and within the gas cavities located towards the top of this unit. These cavities can be seen especially on recently broken surfaces of the rocks and contain vapour-phase (cristobalite, alkali feldspar) crystals (Fig. 8(*c*–*f*). This crystallisation results from the percolation of hot gases through the ignimbrites during cooling. The most important gas sources are probably diffusion from juvenile vitric particles and trapped groundwater (Sheridan, 1970; Chapin and Lowell, 1979).

Chemical composition of the fresh and devitrified glass

Fresh and devitrified glasses from the Upper and devitrified glass from the Middle Ignimbrite have been analysed for their major element compositions by electron microprobe. Fresh and slightly devitrified glass indicating the first and second stages of devitrification are dominant in the basal layer and have also been analysed. When the third and fourth stages of devitrification are observed, the beam size of the electron microprobe is too small to obtain an average result and then crystals which have developed were analysed, i.e. tridymite/cristobalite and sanidine. Normative compositions of the fresh and devitrified glass are plotted in the Ab(P)-Or(A)-Qz(Q) granite system (Fig. 9). Fresh glass plots close to the 1 kbar (P_{H_2O}) ternary minimum but devitrified glass analyses are more scattered as explained above.

Discussion

Ignimbrites are emplaced at high temperatures (600–750°C) and welding, crystallisation and alteration may occur during the initial period of cooling. Devitrification in them, however, can be more complex. The essential devitrification stages (hydration, glassy, spherulitic and granophyric) can all occur. However, because of the variation and zonation in welding, different degrees of devitrification can develop at different levels (Smith, 1960*b*) and it is thought to be controlled by the following factors: chemical composition of the tuff and accessory volatiles, rate of cooling,

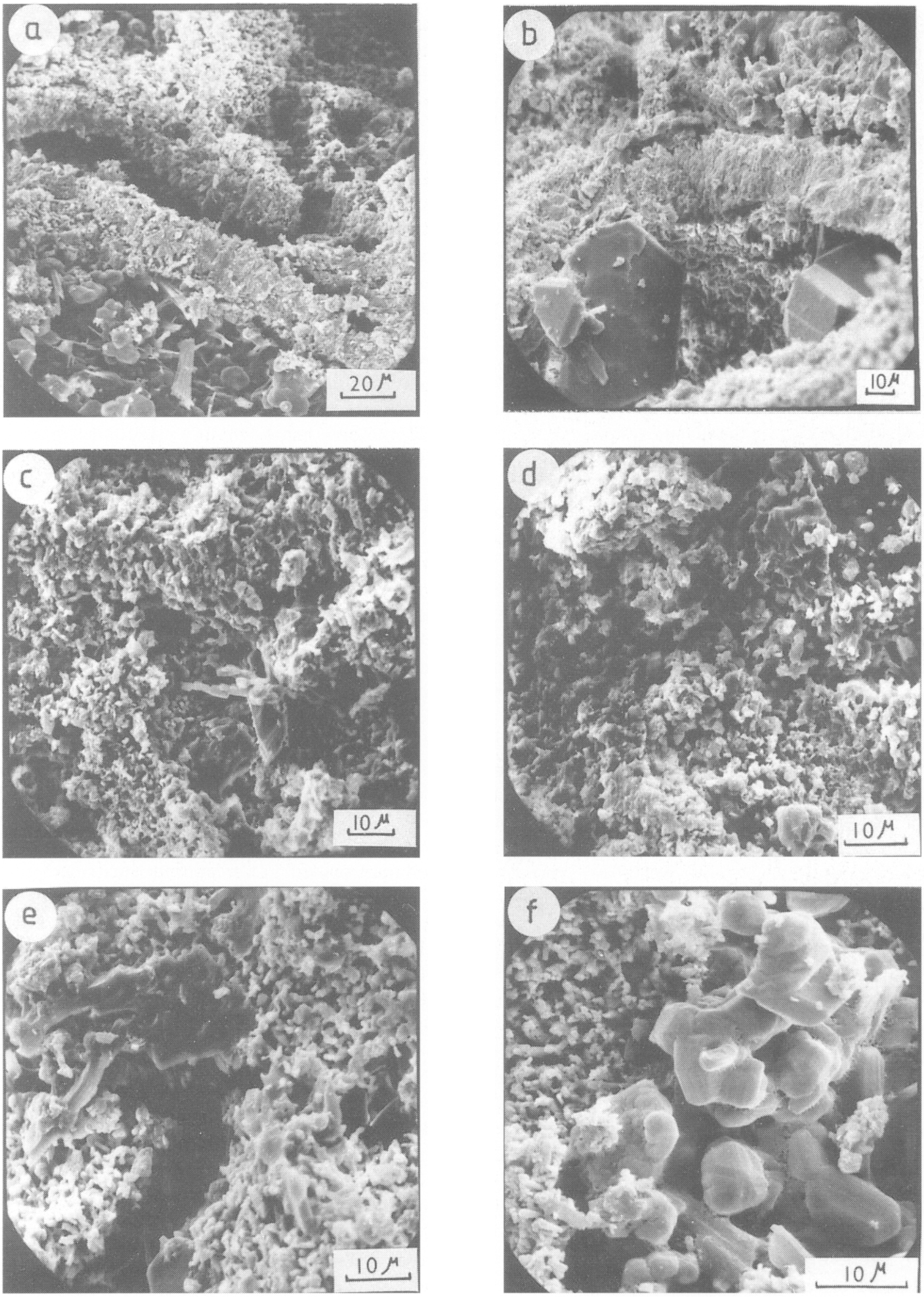

FIG. 8. (*a*) SEM photomicrograph of the devitrified glass showing newly formed minerals in axiolitic texture and in the pore space. (*b*) Same as (*a*) with a plagioclase and a biotite crystal in the lower part of the micrograph. (*c–f*) SEM photomicrograph of the small aggregates of vapour-phase minerals, probably alkali feldspar and cristobalite.

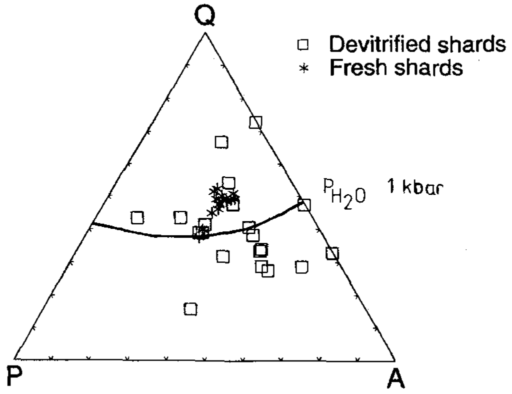

FIG. 9. Normative compositions of the residual glass at 1 kbar P_{H_2O} in the granite system.

temperature of devitrification, identity of the minerals formed and their stability relations (Ross and Smith, 1961).

Welding of shards to one another requires the formation of chemical adhesion (Doremus, 1973, in Carr, 1981) and is enhanced by factors that lower the viscosity of glass, including the emplacement temperature, the thickness of the deposit and the composition and physical properties of the residual volatiles (Sparks *et al.*, 1978). Chapin and Lowell (1979) have explained that the emplacement temperature is the dominant factor in determining whether a tuff undergoes primary or secondary welding. If the temperature is well above the softening point, the glassy particles agglutinate and collapse during deposition in the laminar boundary layer, and the tuff develops megascopic laminar flow structures (primary welding). However, if the temperature is below the softening point, deposition occurs as loose ash and welding is a post emplacement process (secondary welding). In the first case the resultant tuff will have a primary foliation and lineation and may contain lenticules representing pockets of gases trapped during welding. In the second case, the glassy particles will fail to adhere and deposition will occur as loose ash in a laminar flow regime. Collapse and welding occur after deposition and the resulting tuff is not lineated and any therefore any foliation which is apparent is a result of secondary compaction. The tuff lacks conspicuous gas cavities, because most of the entrained gases escaped during welding (Chapin and Lowell, 1979). Only the grain-size distribution (Sparks, 1976) and preferred orientation of solid particles remain as evidence of the laminar flow regime during deposition (Elston and Smith, 1970). However, all the northeast Niğde volcanics display post-emplacement depositional characteristics with their massive appearance, lack of lineation, localized imbrication of solid particles, and the content of gas cavities in the top part of the Upper Ignimbrite. These cavities are replaced by a vapour-phase crystallisation. The occurrence of gas cavities in the ignimbrites can be interpreted as rapid deposition of the tuff which allowed gases to be trapped (Chapin and Lowell, 1979).

Devitrification depends on the rate of diffusion of elements such as Na through the glass, which in turn depends on the viscosity of the glass. Therefore, welding and devitrification are probably more rapid in low-viscosity glasses (Schminke, 1974).

Devitrification in the northeast Niğde ignimbrites involves hydration, a glassy stage, and a spherulitic stage accompanied by vapour phase crystallisation. The hydration stage is identified by the colourless or pale brown glass shards and could have been formed as a result of the chemical changes during compaction. This process depends on the viscosity of the glass and the thickness of the deposit. The glassy stage is characterized by the formation of an axiolitic structure revealed by a radial crystallisation of fibrous aggregates of intergrown feldspar and cristobalite which have been identified by XRD analysis. This crystallisation is interpreted to have occurred after the pyroclastic flow had come to rest and cooled to the appropriate temperature. This stage of devitrification is very common throughout the whole area. Some small spherulites can also be seen to have developed at this stage. The spherulitic stage of devitrification appears to be quite restricted in these ignimbrites. Spherulites can be seen only in pumice inclusions and pore spaces. As suggested by Carr (1981), devitrified pumice seems to host spherulite growth more than the glassy welded matrix. Spherulites consist of radiating clusters of fibres, together with a concentric zoning made visible by slight changes of colour and vary in size from 0.1 to 0.5 mm.

Another phase of devitrification — vapour-phase crystallisation is also observed in the ignimbrites. Coarse-grained feldspar and silica polymorphs appear to have been emplaced into the axiolitic-textured devitrified matrix.

Cas and Wright (1987) explained that vapour-phase crystallisation usually involves the growth of tridymite, but less commonly cristobalite. Both these minerals readily invert to the stable polymorph quartz. The other main mineral which grows during this phase is alkali feldspar (sanidine) and more rarely hematite, biotite, amphiboles and zeolites in open pore spaces (e.g. between uncompacted shards and pumice, and in the vesicles of uncollapsed pumice). Cristobalite and alkali feldspar found in the devitrified matrix are also observed widely (e.g. Central Volcanic Region, New Zealand) and seem to be generally characteristic of devitrified welded tuffs (Ross and Smith, 1961; Ewart, 1965).

Vapour-phase crystallisation occurs contemporaneously with, or after, devitrification, and at least the early vapours, from which these secondary mineral species are precipitated, are derived from trapped volatiles. These vapours continue to exsolve or diffuse, or both, from juvenile glassy fragments and heated groundwater, which percolates through the ignimbrite shortly after its emplacement and during cooling (Smith, 1960*b*; Ross and Smith, 1961; Chapin and Lowell, 1979). These fluids escape and move upwards during compaction and welding. After emplacement of an ignimbrite, downward percolation of rain water leaches elements out of the porous, glassy top of the ignimbrites, and may also lead to secondary mineral precipitation in open pore spaces (Cas and Wright, 1987). The vapour-phase crystallisation phenomenon is much more common in the Upper Ignimbrite than the Middle and Lower Ignimbrite.

Acknowledgements

This study is part of the PhD thesis of S. Yurtmen and was supported by Çukurova University. This is very gratefully acknowledged. Special thanks are due to David Emley for his help and training for the scanning electron microscope studies.

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[*Manuscript received 1 December 1995: revised 10 March 1998*]