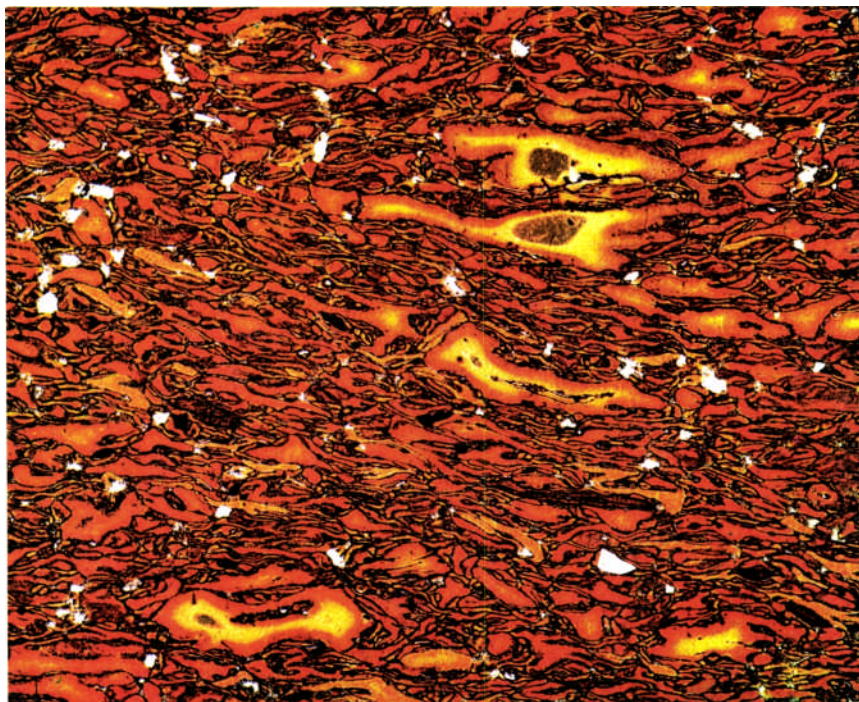


Thin section showing oxidation and later partial reduction of the iron in a glassy welded tuff. Iddings (1899, pl. 50, fig. B) shows the same section in black and white. His belief that this was all originally red and that bleaching took place after deposition is confirmed by the presence of very fine grained microlites of magnetite in the light-colored area. From Yellowstone National Park.



The dull brown cores of the large shards near the middle of this photomicrograph of glassy welded tuff represent the original character of the glass, and the red areas are a result of oxidation. The horizontal alignment of shards indicates marked compaction. USNM specimen 38771 from Rio Blanco, 10 miles north-northwest of Guadalajara, Mexico.

Ash-Flow Tuffs: Their Origin,
Geologic Relations and Identification
and
Zones and Zonal Variations in
Welded Ash Flows

with Foreword by
ROBERT L. SMITH

Reprinted from U.S. Geological Survey
Professional Papers 354-F and 366

Managing Editor
JONATHAN F. CALLENDER

NEW MEXICO GEOLOGICAL SOCIETY
SPECIAL PUBLICATION NO. 9

1980

CONTENTS

Publications of New Mexico Geological Society	Inside Front Cover
Foreword	<i>Robert L. Smith</i> iii
Preface	<i>James M. Robertson</i> iv
Ash-flow Tuffs: Their Origin, Geologic Relations and Identification (Reprint of U.S. Geological Survey Professional Paper 366) <i>Clarence S. Ross and Robert L. Smith</i> 1-I	
Contents	1-111
Illustrations	1-IV
References	50
Figures 16-98	55
Zones and Zonal Variations in Welded Ash Flows (Reprint of U.S. Geological Survey Professional Paper 354-F) <i>Robert L. Smith</i> 2-I	
Contents	2-III
Illustrations	2-111
References	158
Plate 20	At end of text
Plate 21	Following P. 152

FOREWORD

by
Robert L. Smith

Twenty years have passed since publication of U.S. Geological Survey Professional Papers 366, *Ash-flow tuffs: Their origin, geologic relations and identification*, by C. S. Ross and R. L. Smith (1961), and 354-F, *Zones and zonal variations in ash-flows*, by R. L. Smith (1960). As these papers are now being re-published, perhaps a few words are appropriate to clarify their historical evolution and to view them in the context of the present time.

Clarence Ross and I began an intensive general study of microscopic and field characteristics of "welded tuffs" in 1948, in the hope that such a study would aid our interpretation of the Bandelier Tuff, Jemez Mountains, New Mexico. The study led to a general overview which became Professional Paper 366. Professional Paper 366 was written during the late 1940's and early 1950's. The paper was virtually complete in its present form in 1954 and should have been published in 1955 or 1956. For various reasons the paper with but minor updates to about 1956, did not go to press until 1960, and we feared that it would be obsolete before it was published. Moreover, the first printing of PP366 in 1960 was contracted out by the Government Printing Office and the reproduction of the plates was unacceptable and reprinting was required. This reprinting by GPO delayed the publication date until 1961 *after* the publication of PP 354-F and my review paper "Ash Flows" (1960). For the specialist in welded tuffs Professional Paper 366 probably was obsolete when published, but fortunately specialists were few and the paper has long been popular and useful to students, teachers and to geologists not specialized in the geology of silicic volcanic rocks. Professional Paper 354-F was conceived during the mid-1950's, written in 1958, and published in June of 1960, the same month that "Ash Flows" appeared in the Geological Society of America Bulletin. This latter paper was written in 1959 and, although it was labeled a review paper, it actually represented a five-year conceptual advance beyond Professional Paper 366, and contained much additional data. However, the main value of Professional Paper 366 is in the many photomicrographs depicting variations in ash-flow tuffs, and in the historical summary that attempts to outline the evolution of thought leading to modern concepts. These sections are probably of most value to students and have not yet been superseded.

Professional Paper 354-F introduces the concept of the "cooling unit" and provides some genetic and descriptive order to the many lithological variations found in welded tuffs. The cooling unit was conceived by the author as a device to provide genetic meaning to map units, as well as an aid to mapping, and had its origin in the very complex units of the Bandelier Tuff. The fact that no Bandelier-type units are depicted in Professional Paper 354-F, has puzzled several observant students of these rocks, and on several occasions I have been asked "why?"

Professional Paper 354-F deals primarily with zonal variations in what I termed "simple cooling units" and although concepts of more complex units were introduced they were not illustrated. The more complex units were to have been the subjects of a sequel to the paper. Illustrations, an oral presentation and an abstract were prepared for an International Association of Volcanology and Chemistry of the Earth's Interior symposium in 1962 in Italy, but alas! the paper was never written.

The cooling-unit concept was built around the premise that the two major variables controlling the lithologic variations in welded tuffs are emplacement temperature of the ash flows and the thickness of the resulting deposit. As originally planned, Professional Paper 354-F was to have been written around a thickness-temperature hierarchy of examples of actual cooling units, but this proved to be impractical at the time. Instead, the model was developed from the then existing fragments of cooling units whose properties could be reasonably extrapolated from one deposit to another.

The sources for the illustrations in plate 20 of the original PP354-F may now be of historical interest. Figure A was patterned after the Battleship Rock Tuff, Jemez Mountains, New Mexico; figure B was patterned after the Walcott Tuff of Idaho; figures C and D are hypothetical composites based on observations of a large number of vertical sections of devitrified units seen over a period of years in the western United States. A detailed listing of these units, even if they could all be recalled, is impractical here, but the welded tuffs of the San Juan Mountains, Yellowstone, and southeastern Utah, certainly played a dominant role.

Once these "simple" patterns of plate 20 were rationalized in a temperature-thickness context, the

"compound" nature of the Bandelier Tuff units could then be recognized and understood in terms of a cumulative series of ash flows of systematically increasing emplacement temperatures and, ultimately, of changing compositions. Much of this reminiscence now seems trivial but in the 1940's and 1950's there were major problems. For years we were puzzled as to why "vitrophyre zones," so common under many welded tuff sheets, are absent in the Bandelier Tuff outside the caldera, but present inside. This can now be explained by the compound nature of the Bandelier cooling units. Such an explanation gives insight into eruption mechanics.

The "zone of granophyric crystallization" was postulated on the basis of observations made on a very thick cooling unit in the Chiricahua Mountains, Arizona (Member 6 of Enlows, 1955) and on the Superior Dacite (now Apache Leap Tuff of Peterson, 1969), Arizona. The "zone of fumarolic alteration" was largely speculative and, although eroded off in most tuffs, probably exists only as a discontinuous zone in most tuff sheets. In 1975 I encountered for the first time a continuous "zone of fumarolic alteration" on the ash flows surrounding Okmok caldera on Umnak Island, Aleutian Islands, Alaska. This zone was nearly everywhere present and ranged in thickness from about 0.1 to about 3 meters.

Professional Papers 366 and 354-F should be updated, amplified and recast into a simple quantitative synthesis of those rocks that we know as ash-flow tuffs. I have toyed with the idea for some years, butto

date have only outlined the problem. The completion of such a complex task would be professionally rewarding and of interest to advanced students, but would destroy the simplicity that makes these publications useful to beginning students.

Modern studies of ash-flow tuffs are becoming strongly focused in two directions: 1) Mathematical modeling of eruption mechanics and 2) quantitative evaluation of chemical and mineralogical evolution. Of the two main areas of study, I think that eruption mechanics is fascinating and particularly significant if extended to problems of magma generation, magma rise in the crust, and plate tectonics. However, I also think that studies that relate to the chemical evolution of magmas, volcano periodicity and prediction, crustal evolution, ore deposits and their reserves, and certain energy resources will form a major wave of future research in earth science. Riding the crest of the wave will be in-depth studies of pyroclastic rocks, particularly ash-flow tuffs. We have only just begun to tap the real wealth of knowledge stored in these rocks.

REFERENCES

- Enlows, H. E., 1955, Welded tuffs of Chiricahua National Monument, Arizona: Geological Society of America Bulletin, v. 66, p. 1215-1246.
- Peterson, D. W., 1969, Geologic map of the Superior Quadrangle, Pinal County, Arizona: U.S. Geological Survey Geological Quadrangle Map GS-818.
- Smith, R. L., 1960, Ash flows: Geological Society of America Bulletin, v. 71, p. 795-842.

PREFACE

Both of these papers have been out-of-print for a number of years, much to the dismay of an ever-growing number of geologists who by choice or necessity find themselves working with volcanic rocks. Because much of the pioneering work on ash-flow tuffs described in both papers was done in New Mexico and because New Mexico, as well as the rest of the southwestern United States and northern Mexico, contains widespread accumulations of ash-flow tuffs that are currently under intensive study, the New Mexico Geological Society felt it was both appropriate and timely to re-issue these two classic contributions to modern volcanology. The actual reprinting effort would not have been realized, however, without the enthusiastic support and full cooperation of the U.S. Geological Survey's Office of Scientific Publications which supplied all of the original photographic plates.

Just to keep the record straight, the original inspiration to reprint the two papers also stems, in no small part, from a long, frustrating and ultimately unsuccessful search for an original copy of Professional Paper 366 for my own library.

James M. Robertson, Past President,
New Mexico Geological Society

Ash-Flow Tuffs: Their Origin Geologic Relations and Identification

By CLARENCE S. ROSS *and* ROBERT L. SMITH

GEOLOGICAL SURVEY PROFESSIONAL PAPER 366

A study of the emplacement, by flowage, of hot gas-emitting volcanic ash; its induration by welding and crystallization, and criteria for recognizing the resulting rock



UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

First printing 1961
Second printing 1964
Third printing 1968

CONTENTS

	Page		Page
Abstract -----	1	Recognition of ash-flow tuffs—Continued	
Introduction -----	1	Microscopic characteristics	31
Acknowledgments	2	Pyroclastic character-----	32
Nomenclature ----	2	Pumice fragments -----	33
Glossary of terms --	3	Welding distortion and stretching-----	33
Development of concepts	8	Phenocrysts and foreign materials -----	35
Historic eruptions of ash-flow tuffs-----	15	Devitrification -----	36
Pelee	15	Physical chemistry	38
Valley of Ten Thousand Smokes-----	16	Heat -----	39
Cotopaxi -----	16	Viscosity -----	40
Source vents for ash-flow tuffs -----	16	Volatile components-----	40
Recognition of ash-flow tuffs-----	18	Welding -----	41
Field characteristics -----	18	Devitrification	44
Pyroclastic character-----	18	Physical properties	45
Degree of sorting -----	19	Indices of refraction	45
Thickness ----	20	Specific gravity	46
Layering -----	20	Porosity -----	46
Areal extent-----	22	Ash-flow materials of intermediate composition	47
Gentle dips -----	23	Andesitic ash flows of Costa Rica	48
Welding and deformation of pumice -----	24	Distribution in time	48
Fused tuffs contrasted with welded tuffs -----	26	Mesozoic	49
Devitrification and vapor-phase minerals-----	26	Paleozoic ---	49
Jointing -----	28	Precambrian -----	49
Erosion forms-----	29	Selected references-----	50
Fossil fumaroles-----	30	Index -----	79

ILLUSTRATIONS

	Page
FRONTISPIECE. Oxidation and reduction in glassy welded tuffs.	
FIGURE 1. Welded tuff from Battleship Rock, Jemez Springs quadrangle, New Mexico-----	4
2. A "small typical nuee ardente" of Feb. 8, 1930, at Pelee -----	6
3. Battleship Rock, Valles Mountains, N.Mex., showing columnar structure characteristic of many ash-flow tuffs-----	19
4. Tuff section on the eastern wall of Colle Callon, near its junction with Peralta Canyon, Valles Mountains, N.Mex. -----	19
5. Welded-tuff scarp in Callon Media Dia, Valles Mountains, N.Mex., showing columnar joining in thoroughly welded tuffs	20
6. Ash-flow tuff scarp below the Puye Pueblo ruins, Valles Mountains, N.Mex-----	20
7. Ash-flow tuff scarp of Capulin Canyon, Valles Mountains, N.Mex-----	23
8. Ash-flow tuff scarp, Valles Mountains, N.Mex., showing level surface of an ash flow and even bedding in a series of ash flows ---	24
9. Hand specimen of welded tuff with conchoidal fracture, superficially resembling a typical obsidian	25
10. Photomicrograph of thin section of same obsidianlike welded tuff of figure 9 showing very complete welding	25
11. Ash-flow tuff from 4 miles north of Thumb Ranger Station, Yellowstone National Park -----	27
12. Hand specimen collected from a 10- to 20-meter thick layer of glassy welded tuff, Guerrero, Mexico-----	29
13. Reverse side of the specimen shown in figure 12, showing pyroclastic (eutaxitic) structure-----	29
14. Scarp in Wildcat Canyon, Valles Mountains, N.Mex., representing slightly welded to nonwelded part of a single ash flow -----	30
15. Porosity of Battleship Rock ash-flow tuff, Valles Mountains, N.Mex. -----	47
16. Photomicrograph of glassy ash-flow tuff from South Sumatra-----	56
17. Photomicrograph of ash-flow tuff from the Ammon quadrangle, southeastern Idaho -----	56
18. Photomicrograph of glassy ash-flow tuff from the Ammon quadrangle, southeastern Idaho, showing slight warping of the shards-----	56
19. Photomicrograph of ash-flow tuff from Iceland, showing no distortion of the structures -----	56
20. Photomicrograph of ash-flow tuff showing alinement of shards due to orientation during emplacement by flowage -----	57
21. Photomicrograph of fragment of an older welded tuff enclosed in a younger tuff material -----	57
22. Photomicrograph of glassy welded tuff from South Sumatra showing sharply angular shard fragments	57
23. Photomicrograph of glassy ash-flow tuff from Barley Canyon, Valles Mountains, N.Mex., showing only slight welding ----	57
24. Photomicrograph of glassy ash-flow tuff from Arequipa region, Peru, showing wide range in the size of the shards-----	58
25. Photomicrograph of glassy welded tuff from Arequipa region, Peru, showing lack of characteristic shard forms due to disruption during flowage or explosive violence-----	58
26. Photomicrograph of glassy welded tuff from Lake Toba region, North Sumatra, with compressed shards molded against the phenocrysts-----	58
27. Photomicrograph of glassy ash-flow tuff from Lake Toba region, North Sumatra, with only slight welding and no distortion of the shards-----	58
28. Photomicrograph of welded tuff from Saguache County, Colo., showing incipient devitrification -----	59
29. Photomicrograph of welded tuff of the Rattlesnake formation from central Oregon, showing only slight distortion, and partial devitrification -----	59
30. Photomicrograph of obsidianlike welded tuff from the Valles Mountains, N.Mex., showing vague retention of tuff structure -----	60
31. Photomicrograph of glassy welded tuff from the Valles Mountains, N.Mex., showing evidence of plasticity of the glass during welding and extreme distortion -----	60

32.	Photomicrograph of welded tuff from the Iron Springs area, Utah, showing slightly impaired shard structure due to thorough welding and strong compression followed by devitrification -----	60
33.	Photomicrograph of welded tuff from the Iron Springs area, Utah, which has remained glassy following distortion -----	60
34.	Photomicrograph of fine-grained glassy welded tuff showing extreme compression and molding against a phenocryst, simulating flow structure of an extrusive rhyolite -----	61
35.	Photomicrograph of glassy welded tuff from southeastern Idaho, with compressed shards but good retention of the structure -----	61
36.	Photomicrograph of glassy welded tuff showing marked simulation of flow structure due to molding of the shards against the phenocrysts -----	61
37.	Photomicrograph of glassy flow-banded rock from an intrusive dike, Lake County, Colo -----	61
38.	Photomicrograph of welded tuff from the Valles Mountains, N.Mex., showing well-developed parallel arrangement of the shards	62
39.	Photomicrograph of glassy welded tuff from Lake Toba, northern Sumatra, showing collapse of pumice fragments with a retention of pumice structure -----	62
40.	Photomicrograph of devitrified welded tuff from Iron Springs, Utah, that has undergone very marked compression, but retains recognizable shard structure -----	62
41.	Photomicrograph of glassy welded tuff from same unit as specimen shown in figure 40, showing elimination, by stretching, of all recognizable shard structure -----	62
42.	Hand specimen from Battleship Rock, N.Mex., shown in figure 3, showing nonwelded, uncollapsed pumice fragments that stand in relief on the weathered surface -----	63
43.	Photomicrograph of thin section from specimen shown in figure 42, showing several noncollapsed glassy pumice fragments -----	63
44.	Photomicrograph of glassy welded tuff from the Western United States, showing thoroughly welded shard structure and complete collapse of pumice -----	63
45.	Photomicrograph of welded tuff from the Valles Mountains, N.Mex., showing complete collapse of pumice, but retention of pumice structure -----	64
46.	Photomicrograph of glassy welded tuff from Kuinimi, Kaga, Japan, showing collapse of pumice structure and development of perlitic fractures -----	64
47.	Photomicrograph of welded tuff from the Valles Mountains, N.Mex., showing distortion and molding of plastic pumice fragments -----	64
48.	Photomicrograph of welded tuff from the Valles Mountains, N.Mex., showing great distortion and molding of pumice against phenocrysts -----	64
49.	Hand specimen from the Ammon quadrangle, southeastern Idaho, showing lithophysal cavities that developed after complete welding and distortion of the shard structure -----	65
50.	Photomicrograph of thin section from specimen shown in figure 49, showing distortion of tuff structure -----	65
51.	Photomicrograph of thin section from specimen taken from same horizon as that shown in figure 49, but collected 8 or 10 miles farther southeast -----	65
52.	Hand specimen of welded tuff from southeastern Idaho showing vesicular cavities which developed after deposition and complete welding of the tuff -----	66
53.	Photomicrograph of thin section from specimen shown in figure 52, showing a spherulite that has grown out from a plagioclase phenocryst acting as a nucleus -----	66
54.	Photomicrograph of part of a very large spherulite developed in welded tuff showing three concentric zones -----	66
55.	Photomicrograph of specimen from the Jemez Springs quadrangle, Valles Mountains, N.Mex., showing complete destruction of shard structure by crystallization -----	67
56.	Same area shown in figure 55 but under crossed nicols, illustrating coarse-grained intergrowth of feldspar and cristobalite --	67
57.	Photomicrograph of specimen from the Valles Mountains, N.Mex., showing devitrification of pumice and destruction of structure -----	67
58.	Same area shown in figure 57, illustrating tendency for coarse-grained devitrification products to develop in the pumice fragments -----	67
59.	Photomicrograph of welded tuff that has undergone welding, extreme distortion, and devitrification of the shard structures -----	68
60.	Same area as illustrated in figure 59, showing a coarse-grained radial aggregate of feldspar and cristobalite laths developed independently of the original shard structure -----	68
61.	Photomicrograph of welded tuff from southeastern Idaho, showing devitrified shards and partial destruction of pumice structure -----	68
62.	Photomicrograph of welded tuff from the Jemez Springs quadrangle, Valles Mountains, N.Mex., showing complete destruction of original structure by development of coarse-grained devitrification products....	68
63.	Photomicrograph of welded tuff from the Valles Mountains, N.Mex., showing a very large spherulite in which radial aggregates of feldspar and cristobalite are well represented-----	69

	Page
64. Photomicrograph of welded tuff from the Valles Mountains, N.Mex., showing the development of groups of spherulites -----	69
65. Photomicrograph of welded tuff from the Lake Toba region, Sumatra, showing spherulitic areas -----	69
66. Photomicrograph of welded tuff from the Valles Mountains, N.Mex., showing an open cavity in which platelike crystals of tridymite have developed -----	69
67. Polished section through a so-called thunder egg, a type of hollow spherulite which commonly develops in glassy volcanic rocks -----	70
68. Photomicrograph of the outer rim material of figure 67, showing section perpendicular to the plane of deposition -----	70
69. Photomicrograph of the outer rim material of figure 67, showing section parallel to the plane of deposition -----	70
70. Photomicrograph of welded tuff from southeastern Idaho, showing parallel structure produced by molding of shards against each other -----	70
71. Photomicrograph of tuff from the Valles Mountains, N.Mex., showing welding and devitrification, but without distortion of the shard structure -----	71
72. Photomicrograph of specimen shown in figure 71, and ----- er higher magnification, illustrating axiolitic struc	71
73. Photomicrograph of devitrified welded tuff from the shards around a feldspar phenocryst ----- Valles Mountains, N.Mex., showing molding of the	71
74. Photomicrograph of devitrified welded tuff from the feet axiolitic structure ----- Western United States showing uncommonly per-	71
75. Photomicrograph of welded tuff from Australia, showing partial loss of structure by devitrification	72
76. Photomicrograph of devitrified welded tuff from Hungary, showing obscured shard structures	72
77. Photomicrograph of devitrified welded tuff from Korea, showing dim retention of shard structure..._	72
78. Photomicrograph of welded tuff from Sweden, showing local preservation of shard structure	72
79. Photomicrograph of a welded tuff of intermediate composition from Russian Armenia, showing slight welding but distortion of pumice	73
80. Photomicrograph of a welded tuff of intermediate composition from Russian Armenia, showing moderate welding and warping of shards	73
81. Photomicrograph of andesitic welded tuff from Japan, showing lineation produced by thorough compaction -----	73
82. Photomicrograph of welded tuff from Calaveras County, Calif., illustrating the type biotite-augite latite described by Ransome	73
83. Photomicrograph of welded tuff from Argentina described by Bonorino as andesite, showing section parallel to the plane of deposition -----	74
84. Photomicrograph of same specimen shown in figure 83, showing section perpendicular to the plane of deposition -----	74
85. Hand specimen of andesitic welded tuff from Costa Rica -----	74
86. Photomicrograph of section from specimen shown in figure 85, showing destruction of pumice structure by welding -----	74
87. Photographic reproduction of a colored drawing by Iddings_-----	75
88. Photomicrograph of one of Iddings' thin sections of rocks from Yellowstone National Park	75
89. Copy of a photomicrograph of Iddings' "welded pumice with axiolites"	75
90. Photomicrograph of specimen from the Valles Mountains, N.Mex., studied by Iddings	75
91. Photomicrograph of welded tuff from Yellowstone National Park studied by Iddings, showing typical large inclusion of andesite	76
92. Photomicrograph of welded tuff from Yellowstone National Park, studied by Iddings, showing incipient devitrification and thorough welding	76
93. Photomicrograph of glassy welded tuff from Wadsworth, Nev., studied by Zirkel, showing section diagonal to the plane of deposition	76
94. Photomicrograph of welded tuff from West Humbolt, Nev., studied by Zirkel, showing extreme flattening and stretching of shard structures	76
95. Photographic reproduction of a drawing presented by Zirkel, showing axiolitic structure -----	77
96. Photomicrograph of ash-flow tuff from the Valley of Ten Thousand Smokes, showing little induration. _	77
97. Photomicrograph of welded tuff from New Zealand, representing materials which were the basis for Marshall's outstanding contribution to an understanding of ash-tuffs	77
98. Photomicrograph of welded tuff from Morocco, described by Bouladon and Joura ^v sky	77