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CAN NORTHERN HEMISPHERE HOLOCENE VOLCANIC EVENTS BE RECORDED IN POLLEN DATA?

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ABSTRACT - *Can Northern Hemisphere Holocene volcanic events be recorded in pollen data?* - Il Quaternario, **6**(1), 1993, 119-138 - A number of major volcanic events are documented as having taken place during the post-glacial Holocene. Recent evidence suggests a link between short-term episodes of climate change and the effects of volcanic dust veils and aerosols moving in the atmosphere. Increased atmospheric opacity resulting from significant quantities of particulate (dust veils) may have resulted in 'volcanic winters', brief but significant episodes of surface temperature cooling, at a regional and perhaps a hemispheric scale; changes in stratospheric chemistry resulting from input into the atmosphere of gaseous acids are discussed. Possible impact mechanisms, both direct and indirect, of volcanic activity on vegetation are described, together with the possibility that major Holocene volcanic events may also be recorded in pollen data. Radiocarbon dated pollen levels obtained from published sites in two geographical areas, Northern Ireland and the eastern Alps, are used to outline this hypothesis. Separation between the long-term climate signal from short-term modifications induced by volcanic activity is also discussed.

RIASSUNTO - *Gli eventi vulcanici occorsi nell'Emisfero settentrionale durante l'Olocene possono ritrovare un riscontro nei dati pollinici?* - Il Quaternario, **6**(1), 1993, 119-138 - Si conosce che numerosi eventi vulcanici avrebbero avuto luogo nel tardo Olocene. Dati recenti suggeriscono una possibile connessione tra episodi di cambiamento climatico e gli effetti sul clima di polveri vulcaniche ed aerosol dispersi nell'atmosfera. Un aumento dell'opacità atmosferica conseguente ad elevate quantità di particolati e di gas acidi può dar luogo a 'inverni vulcanici', cioé brevi ma significativi episodi di abbassamento della temperatura sulla superificie terrestre, su scala regionale e forse emisferica; vengono considerati anche cambiamenti nella chimica della stratosfera derivanti dall'immissione di aerosol sulfurici. Questo articolo discute i possibili meccanismi d'impatto, sia diretti che indiretti, dell'attività vulcanica sulla vegetazione, unitamente alla eventualità che i più importanti episodi possano essere documentati nei dati pollinici olocenici. Livelli pollinici radiodatati ottenuti da località site in 2 distinte aree geografiche, l'Irlanda del nord e le Alpi Orientali, vengono impiegati per delineare quest'ipotesi. Viene discussa la separazione tra il segnale climatico a lungo termine e le modificazioni a breve termine nella vegetazione indotte dall'attività vulcanica.

Key words : Volcanic activity, palynology, climate change, principal components analysis, Northern Ireland, Eastern Alps, Holocene
Parole chiave: Attività vulcanica, palinologia, cambiamento climatico, analisi delle componenti principali, Irlanda del Nord, Alpi Orientali, Olocene

1. INTRODUCTION

Volcanism as a factor contributing to climate change during the Holocene has, during the last decade, become the focus of research in ancient history, archæology, geology and palæœcology. Research stems from a growing awareness of anthropogenic climate forcing (the so-called 'greenhouse effect') and the need to separate man-induced from natural forces operating on the climate system. In this perspective the historical, the archæological and the geological records can provide detailed long-term information on the different compartments of the biosphere and the geosphere and their response to different climatic impulses.

This paper discusses the possibility that the most important of the ~6000 volcanic events world-wide during the last 40 kyr (Bryson & Goodman,1980), and recorded in a number of palæoenvironmental indicators (bio- and geo-indicators), may also be recorded in pollen data. Discussion focuses on the major events which took place during the post-glacial Holocene in the Northern Hemisphere. The hypothesis is outlined using two palynological data sets, one from Northern Ireland and one from the Eastern Alps, each containing radiocarbon dated pollen levels only. Potential impact mechanisms of volcanic activity on vegetation are outlined, and put forward as a possible explanation for the short-term variations observed in the growth pattern of woody species recorded in dendrochronology, and the medium-term patterns observed in the pollen data.

2. MATERIALS

2.1 Bio- and geo-indicators of Holocene volcanism

Biological evidence from replicated tree-ring sequences developed in different parts of the world has already been correlated with glaciological and mineralogical data for at least 6 separate and large-scale Holocene episodes of volcanic activity (Hollstein, 1980; Baillie, 1991a; LaMarche & Hirschboek, 1984). Little attention has so far been paid to the older Holocene since no continuous dendrochronological curves are available which

Table 1 - Ice-layer and historical dates of volcanic events registered in Greenland ice cores and in other sources, together with the estimated quantity of global acid fall-out, expressed as 10^6 tons. The limit of the calibration curve for radiocarbon dates is shown.

Data per conteggio dei livelli di ghiaccio, dendrodata, e datazione storica di eventi vulcanici registrati nelle carote di ghiaccio della Groenlandia ed in altre fonti, e quantità globale di fall-out *acido espressa in 10^6 tonnellate emesso da ciascuna eruzione. Viene segnato il limite della curva di calibrazione delle radiodatazioni.*

ICE CORES Hammer *et al.*, 1981; 1987; Hammer, 1984					ERUPTION RECORD Rampino *et al.*, 1979				ERUPTION RECORD Simkin *et al.*, 1981				ERUPTION RECORD Stothers & Rampino, 1983				Hammer *et al.*, 1981
Greenland core name	Volcano	Location	AD/BC date	^{14}C date B.P.†	Volcano	Location	B.P. date	^{14}C date B.P.†	Volcano	Location	AD/BC date	^{14}C date B.P.†	Volcano	Location	AD/BC date	^{14}C date B.P.†	Global acid fallout x106 tons
AD																	
Crête	Unknown		1257/58	790													110
Crête	Hekla 1	Iceland	1104	920													45
Crête	Eldja	Iceland	934	1115													165
Crête	Unknown		622/23	1435									Unknown		626	1430	45
Dye 3 (1984 publication)	Yukon?	Alaska	540±10	1535					Rabaul?		540±100	1535					
					White River (eastern lobe)	Alaska	1250	1280			525±100	1545					
Dye 3 (1981 publication)	Yukon?	Alaska	516±4	1555													
					Ilopango (Tierra Blanca)	C. America	1690	1720			260±100	1720					
					Vesuvius	Italy	1871	1945									
					White River (northern lobe)	Alaska	1890	1975									
BC																	
									Etna	Italy	44	2050	Etna	Italy	44	2050	
Camp Century	Unknown		50±30	2055	Sunda	Indonesia	2000	2050									120
Camp Century	Unknown		210±30	2205													45
Camp Century	Unknown		260±30	2225													35
Camp Century	Hekla 3	Iceland	1120±50	2900													60
Camp Century	Santorini	Aegean Sea, Greece	1390±50	3055	Santorini	Aegean Sea, Greece	3450	3175	Santorini	Greece	1470±20	3200					125
					Vesuvius (Z1 layer)	Italy	3500	3320									
Dye 3	Santorini	Aegean Sea, Greece	1645±7	3325													
									Mt.St.Helens	USA	1900?	3560					
Camp Century	Hekla 4	Iceland	2690±80	4105													60
Camp Century	Unknown		3150±90	4535													160
Camp Century	Mt Mazama	Oregon, USA	4400±110	5575													200
					Akahoya	Japan	6900	6050									
Camp Century	Hekla 5/ Thjòrsa flow	Iceland	5470±130	6450													60
Camp Century	Unknown		6060±140	7040													75
Camp Century	Unknown		6230±140	7210													65
					Mt Mazama	Oregon, USA	7340	6360									
Camp Century	Unknown		7090±160	8070													50
Camp Century	Unknown		7240±160	8220													80
Camp Century	Unknown		7500±160	8480													35
Camp Century	Unknown		7640±170	8620													260
Camp Century	Unknown		7710±170	8690													45
Camp Century	Unknown		7810±170	8790													45
Camp Century	Unknown		7910±170	8890													60

† Corrected using the Pearson *et al.* (1986) calibration curve; see text for explanation.

Table 2 - Dendro-dates of major Holocene volcanic events recorded in the tree rings of Great Britain and Western America.

Dendro-date dei principali eventi vulcanici dell'Olocene identificati negli anelli di accrescimento di specie della Gran Bretagna e dell'America Occidentale.

Author-identified volcano	Baillie, 1988 Baillie, 1991a Dendro-date Year AD/BC	^{14}C date B.P.†	Author-identified volcano	LaMarche & Hirschboek, 1984 Dendro-date Year AD/BC	^{14}C date B.P.†
AD					
			-	1171	895
			-	1099	920
			-	1077	900
			-	1023	995
			-	1003	1045
			-	687	1280
			Rabaul?	628	1400
			White River	601	1490
-	536/540	1535			
			Ilopango	119	1880
BC					
	40/39	2040	Etna	42	2040
-	207*	2205	-	206 (see Baillie 1991a)	
-	1159	2955			
Santorini	1628/1627	3325	Santorini	1626	3320
			St. Helens	2035	3620
-	3195	4535			
-	4370	5560			

* also registered in Germany between 208-204 BC (Hollstein, 1980)
† Corrected using the Pearson *et al.* (1986) calibration curve; see text for explanation

span the period back to the end of the last Würmian glaciation, despite recent extensions in Central Europe (Becker *et al.*, 1991).

Pollen data have not so far been used to examine the potential large-scale impact of volcanic events on vegetation. Small-scale volcanic episodes are clearly recorded in pollen data obtained from sites situated near active volcanoes (Litchi-Federovich, 1970; Kawamuro and Torii, 1986; Igarashi 1987; Yonebashi 1987; Heusser *et al.,* 1988; Bakker & Salomons, 1989; Beaudoin & King, 1990; Heusser, 1990). Data indicates that (a) tephra levels can be identified in pollen cores; (b) pollen data reflects the negative impact of volcanic activity on vegetation; (c) post-impact re-forestation, in concomitance with slope stability and surface morphology (Chinen & Riviera, 1990), is rapid (Salomons, 1989) and may be complete within 125 yrs (Kuhry,1988) of total destruction of vegetation (Dale, 1989; Tsuyuzaki, 1989), a timespan sufficiently long to be within the 1st standard deviation of ^{14}C dating.

Table 1 gives the global emission of acid (H_2SO_4+HX) (expressed in 10^6 tons) for each of the known large-scale volcanic events recorded as acidity layers in Greenland ice cores (Hammer, 1977; Hammer *et al.*, 1980; Hammer, 1984; Hammer *et al.*, 1987); the eruption catalogue of Simkin *et al.* (1981); the historical and archæological records of vulcanism and atmospheric dust veils in the Mediterranean during the late BC/early AD period (Rampino *et al.*, 1979; Stothers & Rampino, 1983). Table 2 gives the dendrochronological data of 'narrow ring events' recorded during the development of the Northern Ireland chronology of bog oak (*Quercus petreæ* Liebl.) (Baillie & Munro, 1988; Baillie, 1991a) and 'frost rings' recorded by LaMarche & Hirschboek (1984) in the dendrochronological curve of bristlecone pine (*Pinus longæva* D.K. Bailey and *Pinus aristana* Engl.) for Western America (New Mexico, Colorado and California). Table 3 refers to some tephra/pumice levels recording volcanic events in soils and peat bogs in the Northern Hemisphere.

Volcanic eruptions listed in Table 1 are dated by ice-layer counting rather than in radiocarbon years: dates include an error margin; dendrochronological dating in Table 2 of volcanic events is absolute; an error margin is associated with the dating of historical documents; tephra/pumice levels in peat bogs given in Table 3 are dated by ^{14}C (expressed as corrected BC/AD or uncalibrated radiocarbon years) of under- or overlying organic material.

All dates [whether calibrated Before Present (BP), AD/BC, ^{14}C, ice-layer or historical] have been converted into 'uncalibrated radiocarbon years BP' using the ^{14}C calibration curve for Europe (Pearson *et al.,* 1986), in order to develop a common timescale. The calibration curve extends to ~6.2 ^{14}C kyr BP; dates beyond this limit have been corrected using an arbitrary correction factor of ±980 years, the calibration factor at 6.2 ^{14}C kyr BP. It is however known that during the late- and early post-glacial there have been modifications in world carbon sinks, ultimately affecting the atmospheric ^{13}C-^{14}C ratio, with not presently quantifiable effects on the correction of radiocarbon dates (Delmas *et al.,* 1980; Thompson & Schneider, 1981; Francey & Farquhar, 1982; Neftel *et al.,* 1982; Shackleton *et al.,* 1983; Siegenthaler & Wenk, 1984; Barnola *et al.,* 1987; Woodward, 1987; Boyle, 1988;

Table 3 - Dates of tephra levels from different areas of the Northern Hemisphere; indications of pollen analyses at single sites are also provided.

Date di livelli a tephra per diverse zone dell'Emisfero Settentrionale; viene fornita l'indicazione sull'esecuzione di analisi polliniche nelle singole località.

Tephra/pumice in soils and peat bog

Site	Location	Author-identified volcano	Location	AD/BC date †	B.P. date	Pollen anal.	Author/s
AD							
Hakkoda Mountains	Japan				~1000		(Torii *et al.*, 1987)
Hakkoda Mountains	Japan			950	1000	+	(Kawamuro & Torii, 1986)
NE Honshu Province	Japan			850	1100	+	(Yonebayashi, 1987)
Tomakomai	Japan				1100-1500	+	(Igarashi, 1987)
BC							
Otter Lake, Alberta	Canada	younger Bridge River	U. S.		~2000		(Westgate, 1977)
Central Alberta	Canada	Bridge River	U. S.	310	2260±180		(Zoltai & Johnson, 1985)
Central Alberta	Canada	Bridge River	U. S.	400	2350		(Mathewes & Westgate, 1980)
Central Alberta	Canada	Bridge River	U. S.	650	2600		(Westgate, 1977)
Rocky Mountains, Alberta	Canada	Bridge River	U. S.	810	2760±100		(Kubiw, 1987 in Zoltai, 1989)
Rocky Mountains, Alberta	Canada	Bridge River	U. S.	850	2800±120		(Kubiw, 1987 in Zoltai, 1989)
Central Alberta	Canada	Bridge River	U. S.	850	2800÷2890		(Zoltai, 1989)
Attu, Aleutian Islands	Alaska				~3200		(Heusser, 1990)
Tonquin Pass, B. C.	Canada	Mount St. Helens Y tephra	U. S.	1190	3140±70		(Luckman *et al.*, 1986)
Rocky Mountains, Alberta	Canada	Mount St. Helens Y tephra	U. S.	1350	3300±100		(Kubiw, 1987 in Zoltai, 1989)
Central Alberta	Canada	Mount St. Helens Y tephra	U. S.	1400	3350÷3860		(Zoltai, 1989)
Otter Lake, Alberta	Canada	Mount St. Helens Y tephra	U. S.	1600	3550±65		(Westgate, 1977)
Rocky Mountains, Alberta	Canada	Mount St. Helens Y tephra	U. S.	1720	3670±150		(Kubiw, 1987 in Zoltai, 1989)
Tonquin Pass, B. C.	Canada	Mount St. Helens Y tephra	U. S.	1730	3680±80		(Luckman *et al.*, 1986)
Hakkoda Mountains	Japan				~4000		(Torii *et al.*, 1987)
Rocky Mountain House, Alberta	Canada			2650	4600±110		(Kubiw, 1987 in Zoltai, 1989)
Rocky Mountain House, Alberta	Canada			2960	4910±200		(Kubiw, 1987 in Zoltai, 1989)
Attu, Aleutian Islands	Alaska				~5200		(Heusser, 1990)
Shiji pits, Shizuoka Prefecture	Japan			4090	6040		(Sakai & Kumada, 1985)
Rocky Mountains, Alberta	Canada	Mount Mazama	U. S.	4310	6260±120		(Kubiw, 1987 in Zoltai, 1989)
Rocky Mountains, Alberta	Canada	Mount Mazama	U. S.	4370	6320±290		(Kubiw, 1987 in Zoltai, 1989)
Tonquin Pass, B. C.	Canada	Mount Mazama	U. S.	4620	6570±70		(Luckman *et al.*, 1986)
Wilcox Park, Alberta	Canada	Mount Mazama	U. S.	4650	6600	+	(Beaudoin & King, 1990)
Rocky Mountain House, Alberta	Canada	Mount Mazama	U. S.	4650	6600		(Zoltai & Johnson, 1985)
Central Alberta	Canada	Mount Mazama	U. S.		5380÷6920		(Zoltai, 1989)
NW Whatcom County, Wash.	U. S.			4650	6600		(Goldin, 1986)
Rocky Mountains, Alberta	Canada			5130	7080±150		(Kubiw, 1987 in Zoltai, 1989)
Central Alberta	Canada			5530	7480±150	+	(Litchi-Federovich, 1970)
Central Alberta	Canada			6650	8600÷250		(Zoltai, 1989)
Tenerife	Canary Is.			7050	9000		(Tejedor-Salguero *et al.*, 1986)

† Corrected using the Pearson *et al.* (1986) calibration curve; see text for explanation.

Bard *et al.,* 1990; Prentice & Fung, 1990; Schlesinger, 1990; Adams *et al.,* 1990; Harden *et al.,* 1992).

The following abbreviations are used in the text and in the Tables: PCA-principal components analysis; PRIN-principal component; kyr - kiloyears (1 kyr = 1000 years); BP-before present.

2.2 The pollen data set

Two sample areas (Fig. 1), the eastern sector of the Alps and Northern Ireland, have been used to test the hypothesis that pollen-identified vegetation may register volcanic activity; site coordinates, together with the bibliographic reference of published diagrams, are given in Table 4. Details on the structure of the palynological sets (including ^{14}C dating) in each area may be found elsewhere (Evans 1992a; 1992b; 1992c).

Only radiocarbon dated (uncalibrated ^{14}C years BP) pollen levels from sites 2000 m above sea level in the eastern Alps and bog sites in Northern Ireland have been used (Table 5). Alpine treeline vegetation is sensitive to changes in climate: variations cause its downward or upward movement, sometimes accompanied by compositional changes (Tranquillini, 1979; Beug, 1982; Bortenschlager, 1982; Ellenberg, 1988). Bog vegetation is sensitive to changes in hydrological regimes associated with climate change.

3. METHODS AND RESULTS

Scores for each pollen-identified species in each set have been subjected to PCA; PCA has been widely used in palynology to highlight changes in climate-pollen signal; pollen stratigraphical data subjected to PCA give 'composite curves' (Birks, 1974; Birks & Berglund, 1979; Huntley & Birks, 1983; Birks & Gordon, 1985) which highlight gradients within the data, usually of the climate response type (see section 5.1 below).

Variance explained by the first component is low

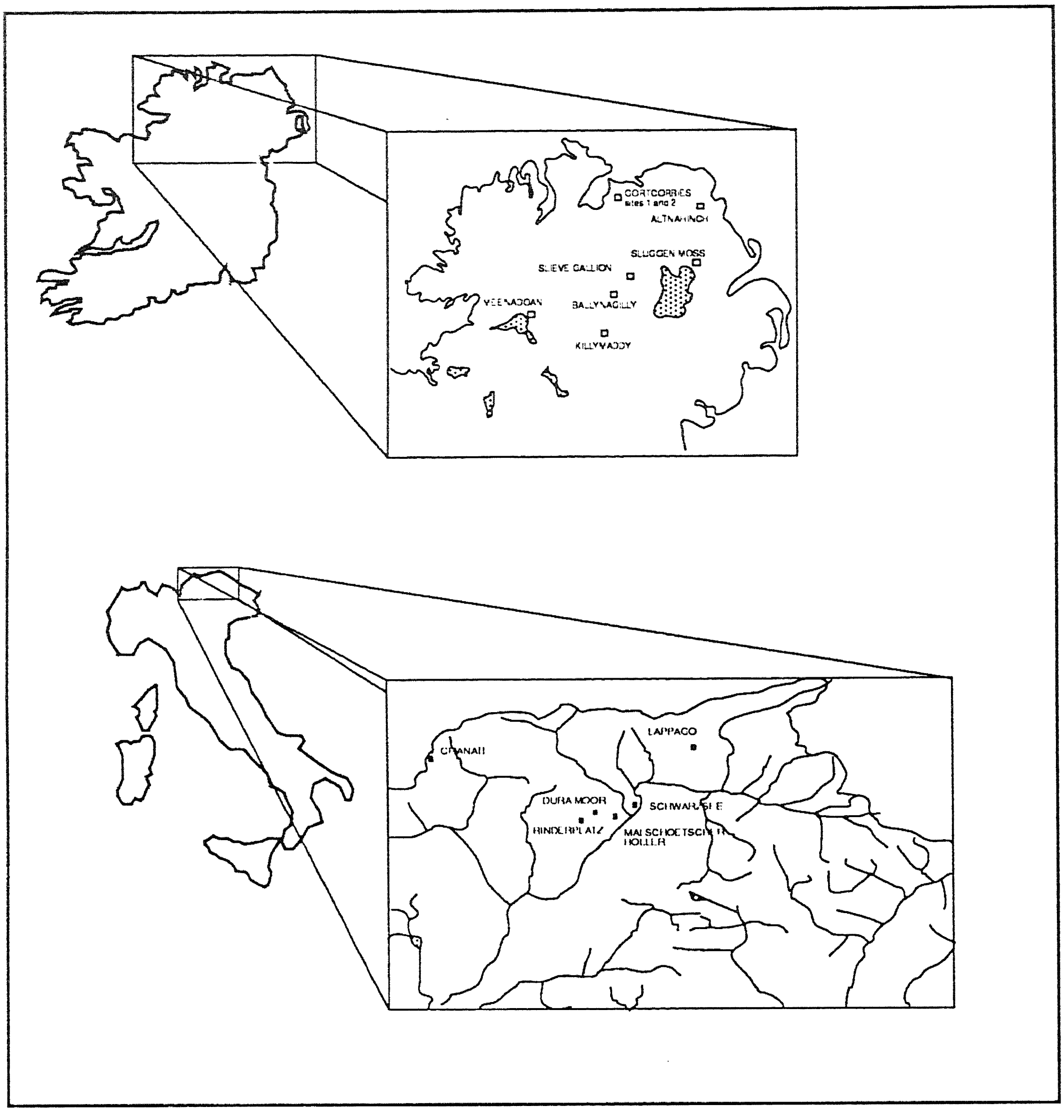

Fig. 1 - Sites in the Eastern Alpine and the Northern Ireland sets.
Località campionate ed Autori nell'Italia nord-orientale e nell'Irlanda del Nord.

Table 4 - Site coordinates and Authors.
Coordinate ed Autori delle località campionate

Set	site	coordinates		Author(s)
Eastern Alps	Lappago	46.55°N	11.48°E	Decarli & Rigotti (1982)
	Granati	46.54°N	11.06°E	Decarli & Rigotti (1983)
	Schwarzsee	46.42°N	11.34°E	Seiwald, (1980)
	Malschoetscher Holler	46.42°N	11.32°E	Seiwald, (1980)
	Dura Moor	46.41°N	11.32°E	Seiwald, (1980)
	Rinderplatz	46.43°N	11.33°E	Seiwald, (1980)
Northern Ireland	Killymaddy	54.40°N	7.02°W	Hirons & Edwards (1986)
	Gortcorbies	55.09°N	6.93°W	Hirons & Edwards (1986)
	Sluggan Moss	54.56°N	6.21°W	Goddard (1971); Smith & Goddard (1991)
	Altnahinch	55.16°N	6.12°W	Goddard (1971)
	Slieve Gallion	54.45°N	6.58°W	Pilcher (1973)
	Ballinagilly	54.58°N	7.00°W	Pilcher & Smith (1979)
	Meenadoan	54.52°N	7.45°W	Pilcher & Larmour (1982)

(26÷34%) (Table 3) because dynamic pollen data contain different types of information at any one point in time (climatic, pedological, ecological, biological and anthropic, when applicable).

Eigenvalues of the pollen-identified species in each set are given in Table 6.

The first principal component scores have been plotted along the timescale and against the quantity of

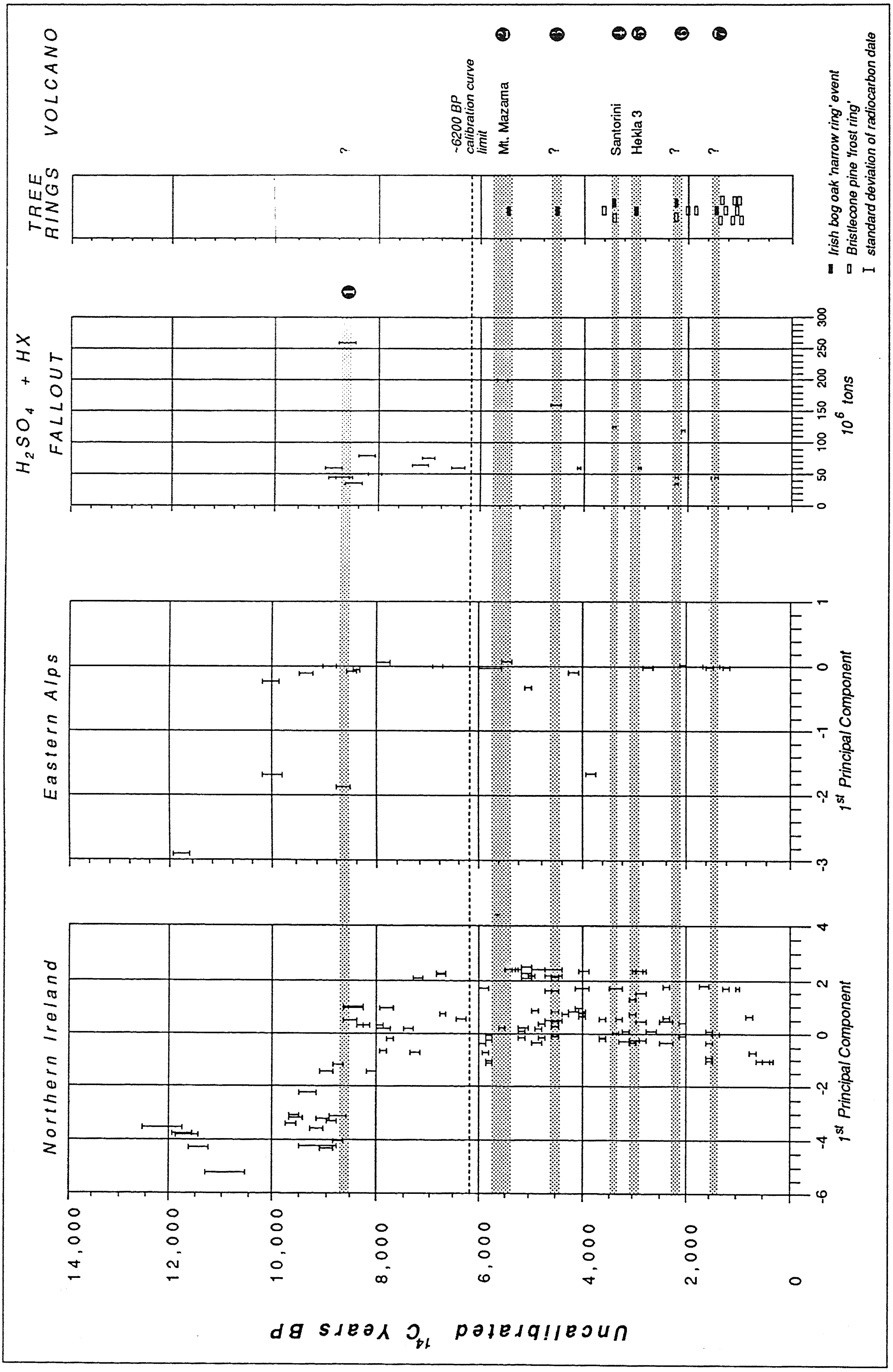
Uncalibrated ^{14}C Years BP
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Northern Ireland
1st Principal Component
-6
-4
-2
0
2
4
Eastern Alps
1st Principal Component
-3
-2
-1
0
1
H_2SO_4 + HX FALLOUT
10^6 tons
0
50
100
150
200
250
300
TREE RINGS
VOLCANO
~6200 BP calibration curve limit
Mt. Mazama
Santorini
Hekla 3
?
1
2
3
4
5
6
7
Irish bog oak 'narrow ring' event
Bristlecone pine 'frost ring'
standard deviation of radiocarbon date

Table 5 - Variance (%) explained by each principal component.

Varianza (%) spiegata da ciascuna componente principale.

Set	Observations	Principal Component	Proportion	% Cumulative
Northern Ireland	120	1	0.343	0.343
		2	0.190	0.533
		3	0.130	0.663
Eastern Alps	39	1	0.265	0.265
		2	0.170	0.435
		3	0.104	0.540

atmospheric H_2SO_4+HX resulting from each known volcanic event (Fig. 2) and the narrow/frost ring events recorded in tree rings.

Troughs with 1st component values below 0÷0.5 are present in both sets; these record modifications in the vegetation, discussed in sections 5 and 6 with reference to a range of events taking place at local, continental and hemispheric scales. Outlines of Holocene vegetation history in Europe (Huntley & Birks, 1983; Delcourt & Delcourt, 1987; Birks, 1990) and North America (Delcourt & Delcourt, 1987; Overpeck *et al.*, 1991; Prentice *et al.*, 1991) can be found elsewhere.

4. IMPACT MECHANISMS OF VOLCANIC EVENTS ON VEGETATION

Much of the discussion focuses on changes documented for recent volcanic events: it is assumed, following the principle of uniformitarianism (*sensu* Gould, 1965), that these are also valid for the Holocene. It should be noted that recent events are small compared to some of the eruptions recorded during the Holocene; although no proportional rule can be invoked, it is self-evident that the areal extent of impact increases with intensity.

Direct impact mechanisms on vegetation (blowdown, scorching, incineration, burial, tsunami, etc.) depend primarily on the type of volcanic and volcano-induced events, the type and the quantity of fall-out (ash, scoria, gases etc.); intensity is mitigated with reducing distance from the source (Watkins *et al.*, 1978).

Indirect, longer term and larger scale mechanisms include changes in stratospheric and soil chemistry, dust veils, shifts in temperature patterns, and acidic fall-out.

◄

Fig. 2 - Northern Ireland and Eastern Alpine pollen sets: plot of the 1st principal component score; global H_2SO_4 + HX emitted by single volcanic events; narrow/frost ring events. All data types have been plotted along an uncalibrated radiocabon timescale; the temporal limit of the calibration curve (Pearson *et al.*, 1986) is shown. Apparently synchronous pollen/volcano events are highlighted and numbered.

Irlanda del Nord ed Alpi Orientali: posizione dei valori della 1ª componente principale; emissione globale di H_2SO_4 + HX per ciascun evento vulcanico; eventi di anelli stretti/da gelo. Tutti i tipi di dato sono posizionati lungo l'asse temporale delle radiodatazioni non calibrate; il limite della curva di calibrazione adottata (Pearson et al., *1986) viene riportato. Eventi pollinici/vulcanici apparentemente sincroni vengono evidenziati e numerati.*

Table 6 - Eigenvectors of pollen-identified species for the first 3 principal components

Autovettori per ciascuna specie pollinica identificata e per le prime 3 componenti principali

SET	Northern Ireland			Eastern Alpine		
Pollen-identified Species	PRIN1	PRIN2	PRIN3	PRIN1	PRIN2	PRIN3
Abies				0.011	0.307	-0.369
Acer				0.049	0.240	0.213
Alnus	0.380	-0.358	0.010	0.238	0.197	-0.238
Alnus glutinosa				0.134	0.349	0.345
Alnus incana				0.132	0.317	0.326
Betula	-0.193	-0.111	0.710	-0.224	-0.037	0.251
Carpinus				0.277	-0.118	0.117
Castanea				0.102	0.262	0.285
Corylus	0.420	0.193	0.134	0.334	0.007	-0.003
Fagus				0.075	0.379	-0.137
Fraxinus	0.176	-0.437	0.159	0.259	-0.122	0.070
Juglans				0.161	-0.186	-0.079
Juniperus	-0.329	-0.031	0.210	-0.120	0.032	0.465
Larix				-0.007	0.117	0.077
NAP	-0.344	-0.212	-0.564			
Ostrya				0.070	0.013	0.120
Picea				0.034	0.380	-0.230
Pinus	0.083	0.524	-0.067	-0.333	-0.150	0.127
Pinus cembra				-0.147	0.095	-0.101
Quercetum mixtum				0.365	-0.126	-0.018
Quercus	0.447	-0.141	0.060	0.279	0.025	0.004
Salix	-0.269	0.331	0.272	0.081	-0.119	0.104
Tilia				0.290	-0.248	-0.004
Ulmus	0.320	0.422	-0.077	0.315	-0.150	0.136

These effects are further compounded by the number of eruptions associated with the event, which can be either single or multiple intermittent eruptions.

4.1 Local scale modifications

As outlined in section 2.1 and in Table 3, Holocene pollen data clearly indicates changes in composition of vegetation in areas close to volcanic sites; main impact mechanisms causing total destruction of plants at a small scale have been listed in section 4.

Partially destructive effects on arboreal vegetation have been registered after recent volcanic events, at varying distances from the eruptive source. Damage is primarily at leaf and tree crown level, leading to a reduction in leaf surface area and crown size respectively: persistence of tephra on foliage, especially polyennial needles of conifer species: chlorophyll content and leaf necrosis occurs (Bilderback & Carlson, 1987), together with reduced photosynthetic activity; foliar abscission; death of conifer needles following scorching due to hot air blowout (Winner & Casadevall, 1983); plant stress is registered by shoot elongation of surviving individuals (Zobel & Antos, 1988); ignition of vegetation with post-eruption fires caused by hot particulate fall-out. These effects are clearly reflected in the annual ring pattern of surviving woody individuals (Hinckley *et al.*, 1984; LaMarche & Hirschboek, 1984; Kaiser & Kaiser-Bernhard, 1987; Palmer *et al.*, 1988).

Negative effects are to be registered as a result of tephra and/or scoria deposition on soil surface (Hendrix & Smith, 1986; Antos & Zobel, 1986a) and plant burial (Zobel & Antos, 1992) which are accompanied by changes in soil chemistry (Higashi *et al.*, 1987).

4.2 Volcanoes, dust veils and climate

Volcanic particulate reaching the stratosphere form dust veils (Lamb, 1977; Stothers & Rampino, 1983; LaMarche & Hirschboek, 1984), which linger for a number of years (between 1-10 years depending on the intensity of the event) before disappearing. These result in a decrease in sunlight available for photosynthesis, and a consequential growth reduction of arboreal species for a number of years, as registered in Irish bog oak tree rings (Baillie & Munro, 1988). Fifth century AD chroniclers in Europe (Baillie, 1991a), the Middle East (Stothers, 1984) and China (Weisburd, 1985; Rampino *et al.*, 1988; Pang quoted in Baillie, 1991a) recorded the dimming of the sun and indicated this as the cause of successive crop failures. This phenomenon is now known to be the result of volcanic activity (Baillie, 1991a) and has been shown to be associated with complex climatological phenomena: lowered ground temperatures in conjunction with modern volcanic events (Kelly & Sear, 1984; Sear *et al.*, 1987); warming of the lower atmosphere due to increased energy absorption by $S0_2$ aerosols (Parker & Brownscombe, 1983; Rind *et al.*, 1992); tropospheric cooling both in the short and in the medium term (up to 50 years) (Hansen *et al.*, 1985) with interacting meso-troposphere dynamics (Rind *et al.*, 1992).

Instrumental meteorological series in the Tohoku district, Japan (Kondo, 1988) over the last 100 years have shown that average summer temperatures fell by 1-2°C one to two years after major world-wide volcanic events, and that periods of famine due to rice crop failures coincided with the eruptions.

4.3 Volcanism, stratospheric chemistry and UV radiation

The chemical impact of major volcanic explosions on stratospheric chemistry results from the large amounts of H_2S, SO_2, HCl and HF being projected into the stratosphere (Inn *et al.*, 1981; Mankin & Coffey, 1984). SO_2 is emitted in quantities calculated in units of millions of tons (Mt), while amounts of HCl and HF are comparatively small (Vogelmann *et al.*, 1992).

In the stratosphere H_2S and SO_2 (sulphur gases) bind with water to form H_2SO_4 (sulphuric acid); the amount of naturally present ambient water in the form of H_2O and CH_4 available for this conversion is $\sim 4 \cdot 10^{15}$ g (Rampino & Self, 1992). Large quantities of water are also emitted by the volcano during an eruption: it is estimated that the Toba eruption, dated to 73.5±3.5 kyr BP (Ninkovitch *et al.*, 1978), inputted $\sim 5.4 \cdot 10^{16}$ g of H_2O into the stratosphere (Rampino & Self, 1992) accompanied by ~2000 km^3 of bulk deposit, made up of acid pumice (Rampino *et al.*, 1979). Large quantities of volcanically erupted water are lost from the mesosphere as precipitation; remaining quantities together with ambient water are sufficient to covert all emitted sulphur gases into H_2SO_4; a conservative estimate for the Toba eruption indicates that ~10% of emitted H_2S and SO_2 will be converted into H_2SO_4 (Rampino & Self, 1992).

Sulphuric acid aerosol provides the surface for a number of chemical reactions which activate atmospheric chlorine into forms that catalyse ozone depletion (Prather *et al.*, 1984; Vogelmann *et al.*, 1992). Modern eruptions, minor if compared to the major Holocene events, are reported as causing depletion of 2-10% in affected atmospheric layers (12-24 km). Decreased levels of ozone cause an increase in the quantity of biologically effective ultraviolet radiation (UV-BE) reaching the earth's surface. UV radiation (Caldwell, 1978; Krupta & Kickert, 1989) is conventionally considered in 3 basic wavebands: UV-A, 315-400 nm; UV-B, 280-315 nm and UV-C, shorter than 280 nm; different types of plant damage are reported at each wavelength. Increases in UV-A cause a number of photochemical reactions which lead to growth repression; a slight increase in UV-B wavelength causes variations in DNA molecules (mutagenesis); UV-C is lethal to all forms of life after prolonged exposure. The extent of the damage depends on the phenological stage reached by a given species during the annual cycle.

It is however probable that the effects of increased UV-BE radiation would have been mitigated by the presence of volcanic dust veils in the atmosphere; dust veils may circumnavigate the globe a number of times before depositing to the ground (Lamb, 1969; 1977; Simkin *et al.*, 1981; Porter, 1986).

4.4 Acid precipitation and vegetation

All the aerosol and particulate inputted into the stratosphere are removed to the ground by precipitation (Sear *et al.*, 1987). The presence of large quantities of sulphuric acid in precipitations would have caused the acidification of rain water, in turn leading to plant damage analogous to that documented for acid rainfall both experimentally and near smelting plants (Hutchinson *et al.*, 1977; Rosenberg *et al.*, 1979): data indicates that (a) growth and death reduction of both herbaceous and woody species occurs (Bennett, 1975; Tingey & Reinert, 1975; Winner & Mooney, 1980a; Brennan *et al.*, 1981; Jensen, 1981; Karnosky & Steiner, 1981; Norby & Kozlowski, 1981a, 1981b; Whitmore & Freer-Smith, 1982; Freer-Smith, 1984; Saxe, 1988; van der Eerden, 1988; Schulze *et al.*, 1989; Geburek & Scholz, 1991; Olson *et al.*, 1992; van Hove *et al.*, 1992); visible foliar damage and foliar leaching (Linzon, 1966; Costonis, 1970; Caput *et al.*, 1978; Malhotra & Khan, 1978; Tsukahara *et al.*, 1985; Jung & Winter, 1992; Olson *et al.*, 1992); interference in photosynthesis and stomatal conductance (Lamoreaux & Chaney, 1978; Carlson, 1979; Winner & Mooney, 1980b; Kimmerer & Kozlowski, 1981; Hällgren & Gezelius, 1982; Jebsen & Roberts, 1986; Olson *et al.*, 1992); (b) heavy soil and soil-water contamination will also lead to reduced reproduction turn-over of grass, and to a lesser extent, of woody species since seedlings are affected (Berry, 1974; Roberts, 1976; Shanklin & Kozlowski, 1984; Riding & Boyer, 1986), which in turn reduces germination. Negative effects on overall tree performance may also be registered in annual increment rings of woody plants (Keller, 1980; Eagar & Adams, 1992; Olson *et al.*, 1992).

4.5 Post-impact succession mechanisms

Canopy disruption resulting from volcanic eruptions subject stressed individuals to increased competition and ultimately (and depending on the extent of disruption) to succession; forest gap formation (Remmert, 1991) may eventually also lead to forest succession (Ellenberg, 1988). The structure of the resulting vegetation will depend on the extent of damage, original forest structure and the ecosystem's response pattern to disturbance. Forest succession is documented in areas subjected to volcanic activity in recent times (Smale, 1984; Franklin *et al.*, 1985; Miles *et al.*, 1985; Nakamura, 1985; Antos & Zobel, 1986b; Adams *et al.*, 1987; Higashi, 1987; Mueller-Dombois, 1987; Tsuyuzaki, 1989).

Succession resulting from damage induced by volcanic activity near the sample site is also documented in the palynological literature (Dunwiddie, 1986; Igarashi, 1987; Yonebayashi, 1987; McGlone *et al.*, 1988; Bakker & Salomons, 1989; Rogers & McGlone, 1989; see also section 2.1).

5. CLIMATIC OVERPRINTING AND TEMPORAL PRECISION

In the present context two problem need to be discussed, of some bearing on the use of pollen as a bioindicator of Holocene volcanic activity, namely: (a) the climatic overprinting present in the pollen signal; (b) accurate dating of single events.

5.1 Climatic overprinting

Figure 3 illustrates a polynomial interpolation through the 1st principal component plotted along the uncalibrated ^{14}C timescale BP, for each of the two sample areas.

Similarity in the overall shape of the two curves is evident and appears to give weight to the assumption that pollen principal components primarily reflect vegetation response to changing climatic conditions in time. In the present context, bearing in mind that volcanic effects on vegetation may be absorbed within ~125 years of the event, the risk of climatic overprinting of vegetation response to volcanic activity is evident; the long-term climate signal reflected in pollen data may mask shorter term changes of non-climatic origin.

Two climatic episodes common to both sets appear to be identifiable: the late glacial Younger Dryas cold episode (①) and the mid-Holocene warming episode (②); one local climatic event may possibly be recorded in the Eastern Alpine set: the Piora oscillation (③); one local event may be recorded in the Northern Irish set, namely the 0.8-1 kyr BP warm period (④) (Lamb, 1969; 1977), although significant anthropic influences must also be taken into account.

5.2 Temporal precision

Partial solution to climatic overprinting is dating accuracy, although other analytical solutions can also be envisaged (absolute pollen counts, sample frequency, tephra identification, AMS ^{14}C dating etc.). Temporal precision by-passes the 'suck-in' effect (Baillie, 1991b), a term used to denote when two distinct events appear to be a single and synchronous event because of poor dating.

The numerical methodology adopted serves to highlight both the longer-term climatic signal, together with the shorter term changes deriving from non climatic event; the inherent weakness of ^{14}C dating is not solved.

6. DISCUSSION

Results are discussed with reference to climate (Fig. 3: ①↔⑦) and non-climate (Fig. 2: ❶↔❺) events.

6.1 The Bølling/Allerød-Younger Dryas transition

① – The trough in the Alpine set dates to the Bølling/Allerød-Younger Dryas interstadial. Improved climatic conditions during the Younger Dryas-Holocene transition are reflected in the pollen data of the Alpine set, with a return to forested conditions as climate improves.

The Younger Dryas interstadial is the last glacial cold period in the Northern Hemisphere characterized by expansion of glaciers in a period of glacial retreat. Oxygen-isotope profiles obtained from sediment cores containing planktonic and benthic foraminiferæ (for example Boyle & Keigwin, 1987; Jones & Keigwin, 1988; Overpeck *et al.*, 1989; Kudrass *et al.*, 1991) and coral studies (Fairbanks, 1989; Chappell & Polach, 1991) indicate a net reduction of meltwater discharge accompanied by a slight drop in sea levels. An AMS ^{14}C date for the Bølling of 12.5 kyr BP is available from a Swiss lake (Bard *et al.*, 1987); a *post-quem* date for the continental dating of the Younger Dryas of 12.97±0.18 kyr BP is available for southern Europe (Rossignol-Strick & Planchais, 1989), while in Sweden climate began to deteriorate ~11.8 kyr BP, and ~10.8 kyr arctic conditions prevailed with average summer temperatures of 10-13℃ (Lemdahl, 1991).

The Younger Dryas ends abruptly at 10.72±0.15 uncalibrated ^{14}C kyr BP (Dansgaard *et al.*, 1989) in

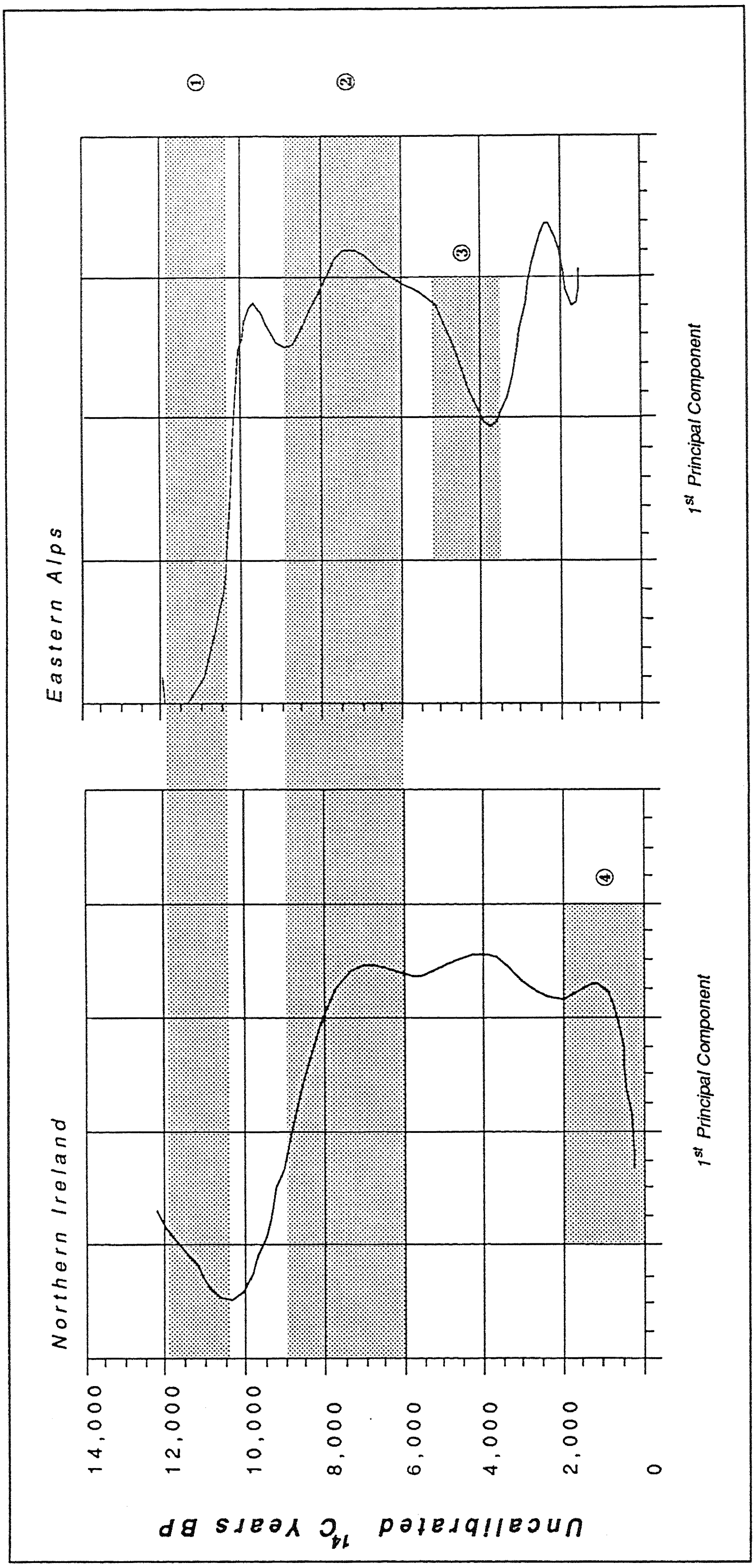

Fig. 3 - Northern Ireland and Eastern Alpine pollen sets: polynomial interpolation of the 1^{st} PC.
Irlanda del Nord ed Alpi Orientali: interpolazione polinomiale della 1^a componente principale.

Greenland; a dendro-date of 10,970 dendro-yr BP has been suggested (Becker *et al.*, 1991) for central Europe.

$\partial^{18}O$ and continental dust data from Greenland ice (Hammer *et al.*, 1980) and Swiss lake-sediment cores (Dansgaard *et al.*, 1989) register, within ~20 yr of ~10.75 kyr BP, a 7°C rise in temperature due to increased summer solar radiation at high altitudes. A similar pattern is recorded in pollen and oxygen isotope records in a Tyrrhenian (Mediterranean) (Rossignol-Strick & Planchais, 1989) sea core. Shifts in wood $\partial^{13}C$ levels from a Late Glacial/Holocene tree-ring sequence in Germany also point to a rapid climate change from dry cold conditions to warmer, more humid conditions following a 5°C rise in air temperature (Birks, 1990; Becker *et al.*, 1991).

Ocean pumps, and in particular the North Atlantic Deep Water (NADW) formation, have recently been identified as a priming mechanism of deglaciation (Broecker *et al.*, 1989; Street-Perrott & Perrott, 1990; Jones, 1991): reduced sea surface temperatures (SSTs), fluctuations in the production of NADW and the poleward transport stream of warm oceanic waters both in North Atlantic (Jansen & Veum, 1990; Veum *et al.*, 1992) and South Ocean (Charles & Fairbanks, 1992), changes in surface salinity (Duplessy *et al.*, 1992) are registered during the Younger Dryas in oceanic sea cores. It has been hypothesized that oscillations in NADW result from shifts in the oceanic input of thawing Laurentide ice sheet meltwater, diverted from the Mississippi River to the St. Lawrence river (Broecker *et al.*, 1985; 1989). Recent evidence does not give support to this hypothesis (Jansen & Veum, 1990; Lehman & Keigwin, 1992; Veum *et al.*, 1992), since it appears that despite glacial conditions on continents and a drop in SSTs, deep ocean ventilation continues, even if reduced.

The first standard deviation of ^{14}C dates for the 2 Alpine scores indicates a date within the range of the Younger Dryas-Holocene transition. Vegetation shows a dominance of *Pinus cembra* and *Pinus* sp, and an almost synchronous shift to milder conditions with more mesic conifers (Evans, in prep.). The Northern Ireland set lacks ^{14}C dated pollen levels for this period documenting ice-sheet expansion southwards during the ~12÷10.5 kyr BP period, later retreating northward (Synge, 1970) with the Younger Dryas-Holocene transition. The *Salix-Juniperus* dominated shrub vegetation present at this time is generally restricted to lowland sites (Evans, 1992b).

It is interesting to note that there is a delay in vegetation development between the two sets after this event, with the Northern Ireland set reflecting a slower patten of vegetational formation; this may in part be due to the insular nature of Ireland, with colonization resulting primarily from species migrating from Britain. It is also possible that this may also be indirectly reflecting the spatial and temporal pattern of the retreating North Atlantic ice front (Bard *et al.*, 1987); AMS ^{14}C dated oxygen-isotope evidence off Portugal and Ireland indicates that there is a temporal lag in the moment when totally ice-free conditions prevailed in these two areas (~2000 km apart), at the former ~12.5 kyr BP, at the latter 11.5 kyr BP. During the Younger Dryas sea ice advanced >5 km yr $^{-1}$, with a simultaneous advance of land ice. It is plausible to assume that a return to normal conditions at higher latitudes is achieved more slowly than at lower latitudes (Lehman *et al.*, 1991; Veum *et al.*, 1992).

6.2 The mid-Holocene warming episode (9,000÷ 6,000 years BP)

② – The mid-Holocene warming episode is a period lasting ~3 kyr characterized by higher planetary obliquity and eccentricity than at present, producing >7% increase for July and an equal decrease for January in incoming solar radiation (figures for 9 kyr BP) (Kutzbach, 1981; Kutzbach & Guetter, 1986; Kutzbach & Gallimore, 1988; Mitchell, 1990).

Ice sheet retreat is complete in continental Europe by 9 kyr BP; global temperatures are ~2-4°C warmer than at present due increased insolation (COHMAP, 1988): North American pollen records indicate a 2-fold increase in total pollen influx ~10 kyr BP, coinciding with maximum insolation (Ritchie *et al.*, 1983; Prentice *et al.*, 1991); other indicators highlight shifts in vegetational distribution (COHMAP, 1988), lake levels (Kutzbach & Street-Perrott, 1985), oxygen isotope records from ice cores (Koerner, 1989) and precipitation patterns (Kutzbach, 1981).

The climatic effects of this episode produced increased precipitation, as reflected in high lake levels in the tropics and subtropics, while in Europe at 6 kyr BP, July temperatures reconstructed using pollen data were ~2°C higher in Northern and Atlantic Europe, and between 0-2°C in the Alpine area (Huntley & Prentice, 1988). It is probable that the Alpine set may be reflecting even higher values, given the height above sea level of the sites.

6.3 The 8,750 BP volcanic event

➊ – Negative component scores are recorded in both sets during the 8th millennium. A total of seven separate volcanic events are recorded in this period: one of these is the single most important volcanic event registered throughout the Holocene. Pollen-identified vegetation values drop significantly in Northern Ireland, raw NAP scores by ~30%, with the exception of *Corylus*, which rises.

A similar trend has been observed in synchronous radiocarbon dated levels in the South Pennine moorlands of Central England (Tallis & Switzur, 1990); in this area blanket bog formation is almost totally interrupted throughout the 8th millenium. At ~8-7.8 kyr radiocarbon

BP, NAP values rise and *Corylus* values drop, blanket bog formation re-begins. Large quantities of carbonized plant parts are recorded; it has been hypothesized that this testifies to the controlled burning by Mesolithic 'broad-blade' culture hunting bands of upland forest vegetation to favour formation of pasture for wild herbivores (Tallis & Switzur, 1990). An alternative explanation can be offered in the light of these volcanic events: the drop of NAP values (and perhaps the lack of peat formation) may be explained by the drop in overall plant numbers as a result of the death of herbaceous plants. Excessively acid rain may in fact have lead to the partial combustion of organic material, similar (despite lower concentrations) to that observed with the use of sulphuric acid as a herbicide in early 20th century agriculture; alternatively ignition of vegetation may have been caused by hot fall-out, although given the distance involved, this should be excluded. In either case this would also lead to an over-representation of extra-local and regional arboreal vegetation.

The hypothesis indicating man as the causal factor of change may also be valid for Northern Ireland: the earliest traces of man date to the ~9 kyr BP. However 'landnam-type' clearance only begins ~4750 BP with the Neolithic; prior to this, evidence indicates only localized and minor clearance.

The Alpine set indicates a similar pattern, with a significant rise of *Pinus* and *Pinus cembra* values, and a drop in *Larix* values. Mesolithic hunter-gatherer bands belonging to the Sauvetterian cultural complex were present in the Alps at ~10 kyr BP and several open air sites have been found between 1800-2300 m a.s.l. (Broglio, 1984). However artefactual and faunal evidence indicate hunting and gathering activities and not clearance.

In general no climatic explanation has been proposed for this specific event; the pattern is suggestive of a small-scale shift in vegetation, perhaps related to the major volcanic event ~8750 yr BP. Global atmospheric gaseous fall-out is estimated at ~$260 \cdot 10^6$ m^{-3}; to this should be added the ~$300 \cdot 10^6$ m^{-3} of acid fall-out contributed by the other 8 kyr BP volcanic eruptions. Model simulations of climatic change (COHMAP, 1988) for the 9-6 kyr BP indicate stronger than present westerly and north-westerly surface winds during January, and parallel to the jet stream. This may have favoured the atmospheric dispersion of volcanic ash and gaseous fall-out into Europe emitted by an Icelandic volcano; tephra originating from an unidentified volcano has been found in soil samples from Tenerife, Canary Islands (Tejedor-Salguero *et al.*, 1986).

6.4 The Mount Mazama eruption

❷ – This event is registered clearly only in the Northern Ireland set with pollen-identified vegetation indicating a return to climatically cooler conditions. No data are available for the Alpine set.

The eruption had first been identified as one taking place in Iceland, and there has previously been some confusion as to the dating (see Table 1); it is now generally accepted (Baillie, pers. comm.) that this is the Mount Mazama eruption; radiocarbon-dated tephra levels in peat bogs have been identified in central Canada (see Table 4).

Global atmospheric fall-out from the Mt. Mazama explosion is estimated at ~$200 \cdot 10^6$ tons and resulted in the formation of a severe narrow-ring event (frost-ring?) in the Irish oak tree-ring chronology (Baillie, 1991a). Independent and absolutely dated biological evidence is therefore available for the negative impact on tree-growth of acid fall-out.

6.5 The unknown/Santorini/Hekla 3/unknown volcanic episodes

❸❹❺❻ – A number of negative PC scores in the Northern Ireland set fall within the range of each of these volcanic events, which are recorded as 'narrow/frost ring' events in tree ring sequences; gaps are evident in the Eastern Alpine sequence.

6.6 The Piora climatic oscillation

③ – This climatic event is registered only in the Alpine set, with cooler wetter conditions documented by a lowering of the treeline and the development of an open vegetation of contorted *Pinus cembra*. Dating would seem to coincide with the Piora oscillation (Beug, 1984) of ~5.3-4 kyr BP (Bortenschlager, 1982; Tallis & Switzur, 1990); however the presence of only 1 radiocarbon date limits the validity of a possibly climatic explanation of the episode. The Northern Ireland set is probably not affected given that mountains reach max 1200 m a.s.l. and climate is generally milder, due to exposition to more Atlantic conditions.

6.7 The 536-540 AD volcanic event

❼ – This event is registered only in the Northern Ireland set. *Corylus* and NAP values drop by ~15%, and stabilize immediately after the event.

Documentary and archæological evidence point to a range of negative effects world-wide (Baillie, 1991a). Tree-ring evidence, with the formation of a narrow-ring is available from Northern Ireland, Germany and the US, and document the direct effects of the event on tree growth.

Alpine radiocarbon dates cover this event, but do not register any change. Contemporary historical records in Italy document sudden negative climatic change, followed by crop-failure, famine and outbreaks of plague (Baillie, 1991a). The apparent inconsistency may perhaps be explained by the error margin associated with radiocarbon dating compared to absolute dendro-dating (Baillie, 1991b).

7. CONCLUSIONS

Evidence from different compartments of the bio- and geosphere indicates that modern volcanic events activate complex interactions and feedback processes which may be reflected in vegetation, both as a result of direct impact, or resulting from a number of indirect mechanisms, foremost climate. Overall volcanoes tend to have an negative impact on vegetation, and a return to 'normal' conditions depends on the intensity of change.

A number of different bio- and geo-indicators agree in indicating synchronous and sometimes intense volcanic activity in different moments of the Holocene. These are accompanied by short-term perturbations in the system; given the dating accuracy associated with these indicators, the timespan associated with these perturbations is measurable in terms of years.

Pollen is commonly used as an indicator of past climatic conditions, given that pollen-identified vegetation reflects shifts in climate patterns lasting a few centuries or millenia. Because of dating inaccuracy associated with the ^{14}C dating technique (on average ± 120 years) palynological data has not been used to register large scale but short-lived events such as those resulting from volcanic eruptions.

The methodology adopted highlights two long-term and almost synchronous trends of climatic change (the Younger Dryas and the mid-Holocene warming) in pollen-identified vegetation in two areas of the Northern Hemisphere (Northern Ireland and the Eastern Alps) characterized by different edapho-climatic characteristics; other more local phenomena as also recorded.

The data also seems to reflect at least three episodes of short-term change which apparently coincide with the major volcanic eruptions taking place in the Northern Hemisphere during the Holocene.

A number of volcanic events are not recorded in the sets: acidity levels in ice cores indicate that the unrecorded eruptions projected smaller amounts of acid fallout into the atmosphere; pollen identified vegetation may not be able to record smaller scale events at large distances from the source. However an increase in the overall number of sites in different geographical locations could well lead to a better understanding of the geographical extent of volcanic-induced change on vegetation.

It is not yet clear whether pollen is reflecting response to 'volcanic winters', brief but significant climatic impulses with sharp drops in temperature and shifts in precipitation patterns, or whether volcanic events induce phytosociological change as a result of direct impact on vegetation; evidence for direct damage to arboreal vegetation can in the long term lead to shifts in dominance patterns. It is however less clear what happens at greater distances from the volcano, although indirect evidence points to a range of mechanisms not favorable to vegetation.

This separation between 'climatically-induced' and 'vegetationally-induced' change is further compounded by the climatic overprinting of long-term climate change inherent in pollen data; further research is required in order to develop methodologies better able to separate climatic overprinting from temporally brief but climatically significant events.

Bio- and geo-indicators provide temporally precise indications that a number of volcanic events did take place during the Holocene; they do not however provide medium-term indications as to the effects on the biosphere of volcanic activity. Pollen data at a continental scale may be integrated with these to provide a picture of the medium-term effects of major volcanic eruptions in a way similar to that currently adopted for evaluation of Holocene climatic change.

The discussion and the examples given are intended as preliminary evidence that major volcanic events may have had a significant effect on continental, and perhaps hemispheric, vegetation. If this should be proven correct, major volcanic events should be taken into consideration as one of the factors contributing to short- and medium-term climate change in the Holocene, measurable in years up and up to a century.

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