
Chapter 1 Introduction to the Quaternary

S. Campbell and J.E. Gordon

Introduction

This chapter is a general account of the Quaternary. Together with the conclusions presented at the end of each site account, it is intended for the less specialist reader.

The Quaternary is the most recent major subdivision of the geological record, spanning the late Cenozoic. Traditionally, it is divided into two intervals of epoch status — the Pleistocene and Holocene. The Holocene occupies only the last 10 000 years of geological time and is the warm interval or interglacial in which we now live. Consequently, it is often regarded as part of the Pleistocene rather than a separate epoch. In a strict geological sense, the base of the Pleistocene (and also, by default, that of the Quaternary) is defined in Italy at the type locality of Vrica, where it is dated to about 1.64 Ma (million years) (Aguirre and Pasini, 1985). However, it is now known from many parts of the world that glacial advances occurred well before the start of the Pleistocene *sensu stricto*, and recent evidence from ocean-floor sediments shows a major climatic deterioration in the northern hemisphere at around 2.4 Ma (Shackleton *et al.*, 1984; Ruddiman and Raymo, 1988). Indeed, it is now well established that the current warm period, the Holocene, is simply the latest interglacial in a long series of profound climatic fluctuations which has characterized the last 2.4 Ma.

The term Quaternary is used here in a somewhat loose sense, following its traditional usage for the last part of Cenozoic time. Where greater precision is required, the terms Pleistocene and Holocene are used.

The character of the Quaternary

The Quaternary is often assumed to be synonymous with the 'Ice Age', an association which can be traced back to Forbes (1846) who equated Pleistocene with the 'Glacial Epoch'. In reality, however, there have been many ice ages (glacials) separated by warmer episodes (interglacials), when the Earth's climate was similar to that of today, if not warmer. Indeed, the deep-sea sedimentary record shows that up to 50 'warm' and 'cold' climatic oscillations have occurred within the last 2.4 Ma (Ruddiman and Raymo, 1988; Ruddiman *et al.*, 1989) (Figure 1.1). Equally, the glacial and interglacial periods cannot be characterized simply as 'cold' or 'warm', respectively; the ice ages were not unbroken in their fridity since the exceptionally cold phases (stadials) were punctuated by warmer periods (interstadials), in some cases lasting for several thousand years (Gordon and Sutherland, 1993). The fundamental characteristic of the Quaternary is therefore one of change through time and space in geomorphological processes, floras, faunas and environmental conditions, all modulated by the changing climate. The record of such changes is preserved in a variety of forms of interest to the Quaternary scientist, including landforms, sediment sequences and organic remains.

Climate change in the Quaternary

The abrupt onset of the late Cenozoic ice ages is, as yet, unexplained. However, the succession of ice ages (glacials) and interglacials has occurred at known frequencies (Campbell and Bowen, 1989), and changes in insolation (the receipt of solar radiation at the Earth's surface and throughout its atmosphere) associated with orbital rhythms are now established as the principal external driving forces of the Earth's climatic system.

Terrestrial evidence for long-term climate change is incomplete and fragmentary. This is because the continental environment is largely one of net erosion; evidence for earlier events has been, and is being, continually destroyed. In contrast, long, more or less continuous sequences of sediments have built up on the deep ocean floors. Studies of cores from these presumed uninterrupted sedimentary sequences have provided a finely detailed stratigraphic and climatic framework unrivalled in its completeness (Shackleton and Opdyke, 1973; Shackleton *et al.*, 1990). Cycles of changing ice volumes, and hence climatic variability as shown by the deep-sea record, can be matched with the pattern of the Earth's

orbital rhythms — namely its cycles of eccentricity (with a periodicity of c. 100 ka (thousand years)), tilt (41 ka) and precession (23 ka and 19 ka) (Hays *et al.*, 1976; Imbrie and Imbrie, 1979; Imbrie *et al.*, 1984; Berger, 1988).

Although orbital changes have played a crucial role in triggering the succession of Quaternary ice ages (and interglacials), it is still not clear how climate change actually occurs and how the relatively small variations in radiation occasioned by the orbital changes are amplified by the Earth's climate system. However, it is likely that the orbital fluctuations trigger a complex set of interactions and feedbacks involving the atmosphere, oceans, biosphere, cryosphere (the realm of snow and ice) and global tectonics (which in part determine the configuration of the world's oceans and landmasses). Although no convincing unifying theory has yet been put forward, several potential key links have been identified. It appears that the role of atmospheric carbon dioxide is fundamentally important. It has been shown that changes in the atmospheric content of the gas follow orbital periodicities (e.g. Barnola *et al.*, 1987), but precede changes in ice volume (Shackleton *et al.*, 1983; Shackleton and Pisias, 1985). Although the interchange of carbon dioxide between the oceans and atmosphere may amplify orbital effects (cf. Saltzman and Maasch, 1990), modelling experiments have shown that reductions in atmospheric carbon dioxide alone are insufficient to produce the magnitude of global cooling necessary for ice-sheet growth (Broccoli and Manabe, 1987; Broecker and Denton, 1989).

The changing configuration of the Earth's landmasses and oceans has also been seen as a key factor; for example, uplift in the American southwest and in the Tibetan Plateau may have affected the pattern of atmospheric circulation in the northern hemisphere, causing waves in the upper atmosphere, bringing colder air to lower middle latitudes and producing the cooling necessary for the onset of Quaternary glaciation (Ruddiman and Raymo, 1988; Ruddiman and Kutzbach, 1990). Likewise, variations in the configuration of land and sea and in oceanic salinity have produced major changes in global oceanic circulation and thus in climate (Broecker and Denton, 1989, 1990). The oceans, in particular, may play a crucial role, and much interest has focused on the pattern of circulation in the North Atlantic which appears to undergo sudden changes between glacial and interglacial modes (Broecker and Denton, 1990), although the 'switching' mechanism is uncertain. Other factors which do not involve a clear linear relationship with climate change have also been identified in the growth and decay of ice sheets. Perhaps the most notable is the inherent instability of marine-based ice sheets (e.g. Hughes, 1987; van der Veen, 1987; Jones and Keigwin, 1988) and, in particular, the effects of topography on ice-sheet growth (e.g. Payne and Sugden, 1990) and decay (e.g. Eyles and McCabe, 1989). It is thus clear that climate change is not simply a direct linear result of astronomical 'forcing'.

The deep-sea record

One of the most significant developments in Quaternary science during the last 40 years or so, has been the recovery of sediment cores from the floors of the world's oceans and the resolution of the climatic and other environmental records which they contain (Bowen, 1978; Imbrie and Imbrie, 1979). Since these incomparably detailed sedimentary sequences are recognized in oceans throughout the world, they provide a stratigraphic/climatic framework of global significance and applicability.

Ocean sediments have provided three major lines of evidence for climate change in the Quaternary. First, oxygen isotope analysis of the carbonate in the shells of marine microfossils (e.g. foraminifera) preserved in the sediments provides a measure of isotopic variability in the $^{18}\text{O}/^{16}\text{O}$ ratio through time in the global ocean (Emiliani, 1955, 1957; Shackleton, 1969; Shackleton and Opdyke, 1973). During cold episodes, water molecules of the light isotope (^{16}O) are evaporated from the sea more readily and 'stored' as ice, leaving the remaining sea water relatively enriched with the heavier isotope (^{18}O). The changing pattern of isotope composition in the ocean thus provides a signal of ice-sheet growth and decay, and a record of such changes has been reconstructed through time (Figure 01.1): this also forms the basis for oxygen isotope stratigraphy (see below). Although this signal provides an indication of changing ice volumes, it must be stressed that this is not a direct measure of global climate or vegetational development (Bridgland, 1994).

Second, variations in past sea surface temperatures (SST) may be determined from assemblages of marine microfossils and biomarkers (molecular stratigraphy), and trace element ratios from calcareous microfossils found in the sea-bed sediments (Brassell *et al.*, 1986; De Dekker and Forester, 1988). Third, variations in the percentages of calcium carbonate (often higher during warm episodes), and the occurrence of ice-rafted or wind-blown detritus (higher during

cold periods) can also provide measures of climatic variability (Ruddiman *et al.*, 1986).

The isotopic and dust records in the polar ice sheets have also provided detailed proxy climate records, extending back some 250 ka (e.g. Johnsen *et al.*, 1972; Jouzel *et al.*, 1987; Oeschger and Langway, 1989; Jouzel *et al.*, 1993). In particular, new cores from the Greenland ice sheet have revealed exceptional, high-resolution records of climatic fluctuations during the Devensian (Johnsen *et al.*, 1992; Dansgaard *et al.*, 1993; Taylor *et al.*, 1993). These fluctuations are notable for their frequency and rapidity; for example 24 interstadial phases interrupted the last glacial cycle, and abrupt rises in temperatures of 5–8°C occurred within a few decades. At the end of the last glaciation, a warming of 7°C occurred within a period of 20–25 years (Dansgaard *et al.*, 1989). Comparison of recent ocean-core data with the Greenland ice-core records indicates a good correlation between the different sets of information and demonstrates a close coupling between the atmosphere, oceans and ice sheets in the North Atlantic region (Bond *et al.*, 1993; Bond and Lotti, 1995). The results from this work have given new impetus to the search for links between the offshore marine records, the Greenland ice-core records and the responses of terrestrial systems and biota to the inferred fluctuations in the climate (e.g. Lowe *et al.*, 1994; Lowe *et al.*, 1995; McCabe, 1996; Whittington *et al.*, 1996). Many of these recent advances and their significance are described in more detail in the papers presented by Gordon (1997).

Subdividing the Quaternary

The oxygen isotope chemistry of the deep-sea sediment pile now provides the main basis for subdividing the Quaternary, with a number of successive oxygen isotope stages recognized globally (Figure 1.1). These stages, running counter to normal geological practice, are numbered backwards in time and down through the geological column. Warm periods with correspondingly low volumes of ice are given odd numbers; the present interglacial, the Holocene, is numbered as Stage 1. Times of high ice volume (glacials) are given even numbers, the last main cold phase in Britain, the Late Devensian, being numbered as Stage 2. Stages are also divided into sub-stages, for example, Stage 5 into sub-stages 5a–5e, often reflecting stadial or interstadial events.

The position in the deep-sea sediment cores of a major reversal in the Earth's magnetic field, the Matuyama–Brunhes Reversal at 780 ka, provides a yardstick with which to calibrate the oxygen isotope record. The boundaries of the different isotope stages have also been adjusted and refined with respect to known orbital patterns (Imbrie *et al.*, 1984; Martinson *et al.*, 1987; Shackleton *et al.*, 1990).

The history of the ice ages

The earliest evidence for significant climatic deterioration in late Cenozoic times comes from planktonic fossils found in North Atlantic ocean sediments. A cycle of northern hemisphere glaciation may have been initiated about 3.1 Ma with the closure of the Straits of Panama and the creation of the Isthmus of Panama by crustal upheaval (Keller and Barron, 1982). This ended the latitudinal movement of surface waters between the Atlantic and Pacific oceans, and replaced it with a meridional flow in the North Atlantic. In this way, warmer waters were able to reach higher latitudes, thus creating the potential for increased precipitation and ice-sheet growth on adjacent continents. As sea temperatures fell, polar ice sheets grew and launched ice floes into the surrounding seas (Ruddiman and Wright, 1987; Ruddiman and Raymo, 1988). Shortly afterwards, glaciers developed in Iceland (Einarsson and Albertson, 1988), although it was not until about 2.4 Ma that large ice sheets spread to middle latitudes (Shackleton *et al.*, 1984). These ice sheets, between about 2.4 and 0.9 Ma, seem to have fluctuated in harmony with the 41-ka cycle of obliquity (variations in the tilt of the Earth's axis). Subsequently, northern hemisphere glaciation intensified and ice sheets grew to maximum volumes about twice their previous size, and fluctuated with a 100-ka rhythm, namely that of orbital eccentricity. After about 0.45 Ma, the 100-ka rhythm became dominant, although other fluctuations in ice volume were superimposed on the long-term pattern. These smaller-scale fluctuations occurred at frequencies of 41 and 23 ka, corresponding to the cycles of orbital precession (Campbell and Bowen, 1989).

Why there should be a shift in ice-age rhythms at about 0.9 Ma is unknown, although some have attributed this to continued uplift of the Tibetan Plateau which would have caused reorganization in global atmospheric circulation (Ruddiman and Raymo, 1988; Ruddiman *et al.*, 1989). However, the change may be related to variations in the

behaviour of the ice sheets themselves. It is known that after this time, marine-based ice sheets developed on continental shelf areas such as Hudson's Bay and the Baltic and Irish seas. They grew rapidly and reached considerable thicknesses, prompted perhaps by cooler air brought to lower middle latitudes as a result of topographic uplift elsewhere in the world. Equally, their collapse and disappearance were also probably dramatically swift.

In Britain, the area covered by ice varied considerably during different glaciations. During the last (Late Devensian) glaciation, ice extended as far south as the north Midlands, impinging on the north coast of East Anglia and covering most of South Wales. During earlier glaciations ice sheets were more extensive, but probably never reached farther south in south-central and south-east England than the present Thames Valley (Bridgland, 1994). In the South-West, there is a longstanding debate over whether pre-Devensian ice masses reached the northern shores of Devon and Cornwall and even the Isles of Scilly (Chapters 6, 7 and 8). The sedimentary record of the Quaternary in Britain is far from complete; the most comprehensive record comes from East Anglia and the Midlands where a series of glacials and interglacials has been recognized. The correlation of Quaternary deposits across Britain has long been based on a series of reference localities and stratotypes (e.g. Mitchell *et al.*, 1973b), but the problem remains, however, to relate the fragmentary terrestrial record to the oxygen isotope timescale, particularly before the last interglacial (Ipswichian Stage) (Gordon and Sutherland, 1993). Nevertheless, in recent years progress has been made in relating the British terrestrial evidence to the comprehensive deep-sea record, particularly in Wales (Bowen and Sykes, 1988; Campbell and Bowen, 1989; Bowen, 1991), the Midlands and the Thames Valley (Bridgland, 1994) and East Anglia (Bowen *et al.*, 1989). Significant advances in this respect have also come from South-West England, the subject of this volume.

British Quaternary environments

The major shifts of climate which characterize the Quaternary were accompanied by equally profound changes in environmental conditions which left a strong imprint on the landforms, fossils and sediments of Britain. During the cold or glacial stages, substantial areas were subjected to the effects of glacial erosion and deposition and a wide range of landforms and deposits was produced. The erosional and depositional legacy of the Pleistocene glaciers has been documented in many publications; for Wales and Scotland the evidence has been reviewed comprehensively in recent Geological Conservation Review volumes (Campbell and Bowen, 1989; Gordon and Sutherland, 1993, respectively). One of the main controversies in the Quaternary history of South-West England has been the extent to which the Pleistocene ice sheets affected the region, and this aspect is explored fully in subsequent chapters.

As ice sheets melted, vast quantities of meltwater were liberated, giving rise to characteristic suites of landforms and deposits. Even in South-West England, an area relatively untouched by the ice sheets, a variety of controversial landforms may bear witness to meltwater erosion at glacial margins (Chapters 7 and 10).

Repeated climate change also subjected the flora and fauna of Britain to stress: fundamental changes in the distribution of plants and animals took place. Beyond the margins of the ice sheets and during the cold climatic phases of the Quaternary, periglacial conditions prevailed. Such environments were characterized by frost-assisted processes and by a range of frost- and ground ice-generated landforms and deposits. Mass wasting (downslope movement of soil on both large and small scales) and increased wind action were prevalent, also producing a range of characteristic features. In the fossil record, the flora and fauna of these cold periods is, not surprisingly, restricted in diversity and dominated by cold-tolerant species; large areas were dominated by tundra vegetation. Although periglacial processes are still active today in some of Britain's uplands, their Pleistocene legacy is nowhere better recorded than in South-West England, where many of the most spectacular landforms and most intricate sequences of deposits were formed (Chapters 4, 6, 7, 8 and 9).

Conversely, the warmer or interglacial periods of the Quaternary are characterized by the absence of glacial, periglacial and glaciofluvial features, and there were times when chemical weathering, soil formation and the accumulation of organic sediments took place. Variations in the quantity and type of pollen grains preserved in organic deposits, such as peats and lake muds, have been used to define systems of pollen zones or pollen biozones. These zones are characterized by particular vegetational assemblages which can be used to chart sequences of vegetational, climatic and environmental change. Traditionally, these have been used as the principal basis for distinguishing between various

interglacial phases in the land-based Quaternary record and for the definition of chronostratigraphic stages (West, 1963, 1968; Mitchell *et al.*, 1973b). Unfortunately, although several distinctive interglacial episodes in the British Pleistocene can be distinguished, very little evolution of the flora actually occurred, thus hindering biostratigraphic correlation. However, interglacials can be differentiated broadly on the basis of pollen assemblage zone biostratigraphy, with individual parts of interglacial cycles (substages) being recognized; for example, pre-temperate, early temperate, late temperate and post-temperate sub-stages (Turner and West, 1968). The pollen-based 'climatostratigraphic' model which has formed the basis of most British Pleistocene studies, is now evidently too simple to represent the full complexity of the climatic record as revealed by the deep-sea sequences (Bridgland, 1994). Also, many former plant communities lack direct modern counterparts, and the geological dictum that 'the present is the key to the past' is not always applicable. Interglacial environments in the British Isles were generally characterized by a climax vegetation of mixed deciduous oak forest. The last time Britain experienced conditions similar to today was about 125 ka, when the interglacial (part of the Ipswichian Stage) lasted about 10 ka.

Unlike the flora, some elements of the Quaternary fauna have evolved. Therefore, certain glacial and interglacial periods can be characterized broadly by distinctive fossil assemblages, particularly those of large mammals. During the last interglacial, for example, creatures such as the hippopotamus, lion and elephant were indigenous to Britain. Likewise, fossils of both terrestrial and marine molluscs and Coleoptera (beetles) can be sensitive indicators of changing climatic conditions by analogy with their present-day environmental tolerances and geographical ranges.

The succession of glacials and interglacials and the growth and decay of ice sheets have been accompanied by equally profound changes in the coastal zone. World sea level has varied in time with the amount of water locked up in the ice sheets, and during glacial stages, world or eustatic sea levels have been lowered. The converse is true during warmer interglacial phases. The level of the land has also varied, sinking under the weight of advancing ice sheets and rising up or rebounding when they melted (isostasy). This complex interplay of changing land and sea levels has left a widespread legacy in Britain, manifested by the many beaches, shore platforms and marine sediments which now lie above the present sea level. This is particularly true in South-West England where prominent shore platforms and raised beach deposits have provided the focus for much research and interest in the Quaternary history of the region (Chapters 6, 7 and 8; (Figure 1.2)). Equally, a range of submerged shoreline features, drowned forests and valleys provide important evidence for sea levels which were relatively lower in the past. The complex story of changing land and sea levels is superbly illustrated by the sediments and fossils of the Somerset lowlands, a key area for sea-level studies in Britain (Chapter 9).

Significant changes in the courses of rivers and their channel patterns have also occurred in the Quaternary. These are related to changes in discharge, sediment supply and sea level. Some rivers have reworked and built up large quantities of glacially derived sediments along their floodplains. Subsequent down-cutting has sometimes resulted in 'staircases' of terraces both in rock and superficial materials. In some valleys, terraces have been traced for considerable distances and been assigned specific names and ages with respect to their contained fossils and stratigraphic position; in many cases they can be ascribed with some certainty to particular interglacial or glacial phases or, more recently, to the oxygen isotope timescale (Bridgland, 1994). Although terrace stratigraphy has not featured prominently in research on the Quaternary history of South-West England, evidence of this nature abounds: the Axe Valley terraces are significant as the most prolific source of Palaeolithic hand-axes in the South-West, and reveal a unique record of Quaternary events (Chapter 9), while the terraces of the Bath Avon furnish some of the most detailed Quaternary sedimentary evidence found in the Bristol and Bath areas (Chapter 10). Spectacular abandoned channels, such as the Valley of Rocks in north Devon, may have been formed by the combined effects of river capture and coastal retreat, reflecting major landscape changes during the Quaternary; alternatively, glacial meltwater may have played a role in their formation (Chapter 7).

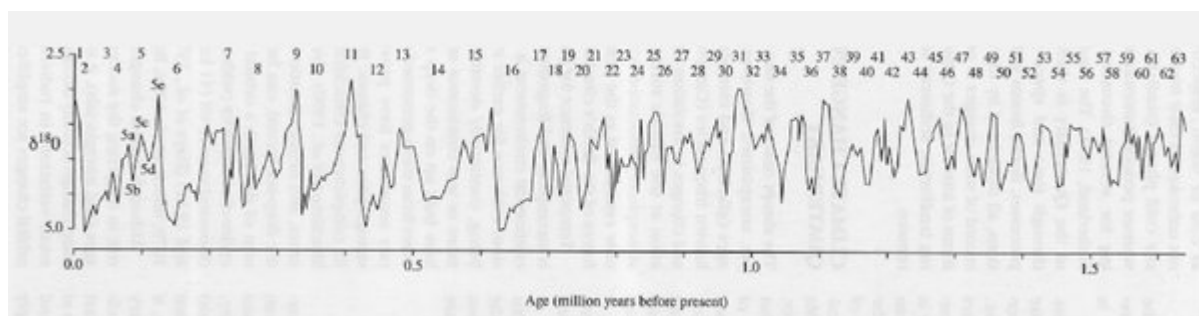
The challenge for Quaternary science

Quaternary science has made a fundamental contribution to understanding landscape evolution and past environmental change. This understanding has much broader relevance in areas such as climate dynamics, sea-level changes, the history of flora and fauna and engineering site investigations. Interest in the Quaternary has therefore burgeoned in recent years, and many texts explain the fundamentals of the science and environmental changes in Britain (e.g. West,

1977a; Bowen, 1978; Lowe and Walker, 1984; Bradley, 1985; Dawson, 1992; Jones and Keen, 1993). Change through time is a fundamental aspect of Quaternary studies. Often, successive climatic and environmental changes are recorded by a variety of indicators in layers or sequences of sediments. For example, raised beach sediments may be overlain by periglacial slope deposits and in turn by glacial sediments such as till, thus recording changes from times of relative high sea level and temperate conditions through a periglacial regime to fully glacial conditions. Quaternary environmental changes and processes have not been uniform in their operation throughout Britain. This, coupled with a phenomenal complexity of geological composition and structure, has given rise to a remarkable regional diversity of landforms and Quaternary deposits (Gordon and Sutherland, 1993). The challenge for the Quaternary scientist is to establish the precise nature of the deposits and the sequence of inferred environmental and climatic events at a given locality, and then to classify the results and correlate the site evidence with other sequences and areas (Bowen, 1978). In doing so, the history of geomorphological events and processes can be pieced together, changes in the development of the flora and fauna charted and new insights gained into the processes which drive climate and other environmental changes.

A crucial challenge at present is to relate the fragmentary land-based evidence to the deep-sea oxygen isotope record (Shackleton and Opdyke, 1973; Sibrava *et al.*, 1986). The latter provides the standard stratigraphic scale with which sequences are now routinely correlated (e.g. Bowen *et al.*, 1989; Campbell and Bowen, 1989; Ehlers *et al.*, 1991; Gordon and Sutherland, 1993; Bridgland, 1994). A variety of improved dating techniques, both numerical and relative, extending back beyond the range of the radiocarbon method (e.g. amino-acid, U-series and ^{36}Cl methods), is assisting greatly in this respect (Kukla, 1977; Bowen, 1978; Bowen *et al.*, in prep.). Because of the complexity of the evidence and the range of techniques now available, Quaternary science is based increasingly on a multidisciplinary approach. Although the heart of the subject still relies heavily on geological, stratigraphical methods, the combined efforts of geologists, geographers, geomorphologists, botanists, zoologists and archaeologists are necessary to achieve the maximum resolution of the available evidence.

References



(Figure 1.1) The oxygen isotope record, as represented in a borehole (Site 607) in the Mid-Atlantic at latitude c. 41°N. Numbered stages are shown at the top; even-numbered ones are relatively cold (more ice) and odd-numbered ones relatively warm (less ice). Note that the amplitude and wavelength of the curve increases at c. 0.7 million years ago (the $\delta^{18}\text{O}$ scale is a ratio obtained by comparing the proportion of ^{18}O to ^{16}O in samples to that in a mean sea-water standard). (From Bridgland, 1994, compiled from data published by Ruddiman *et al.*, 1989).



(Figure 1.2) Portland Bill, Dorset, was chosen as a GCR site for its complex sequence of terrestrial and marine sediments. The site is exceptional in demonstrating raised beach deposits which can be assigned to two separate interglacials. These have been correlated with Stage 7 (c. 200 ka BP) and Stage 5e (c. 125 ka BP) of the deep-sea oxygen isotope record. The photograph shows the Stage 7 raised beach deposits, overlain by loam and head, on the west side of Portland Bill. (Photo: D.H. Keen.)