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The historical record in the Scaglia limestone at Gubbio: magnetic reversals and the Cretaceous-Tertiary mass extinction

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ABSTRACT

The Scaglia limestone in the Umbria-Marche Apennines, well-exposed in the Gubbio area, offered an unusual opportunity to stratigraphers. It is a deep-water limestone carrying an unparalleled historical record of the Late Cretaceous and Palaeogene, undisturbed by erosional gaps. The Scaglia is a pelagic sediment largely composed of calcareous plankton (calcareous nannofossils and planktonic foraminifera), the best available tool for dating and long-distance correlation. In the 1970s it was recognized that these pelagic limestones carry a record of the reversals of the magnetic field. Abundant planktonic foraminifera made it possible to date the reversals from 80 to 50 Ma, and subsequent studies of related pelagic limestones allowed the micropalaeontological calibration of more than 100 Myr of geomagnetic polarity stratigraphy, from *ca* 137 to *ca* 23 Ma. Some parts of the section also contain datable volcanic ash layers, allowing numerical age calibration of the reversal and micropalaeontological time scales. The reversal sequence determined from the Italian pelagic limestones was used to date the marine magnetic anomaly sequence, thus putting ages on the reconstructed maps of continental positions since the breakup of Pangaea. The Gubbio Scaglia also contains an apparently continuous record across the Cretaceous–Tertiary boundary, which was thought in the 1970s to be marked everywhere in the world by a hiatus. A geochemical study of the Gubbio Cretaceous–Tertiary boundary accidentally uncovered an unexpectedly large concentration of iridium in the boundary clay, providing the first evidence for a large comet or asteroid impact at the time of the Cretaceous–Tertiary mass extinction. The sudden foraminiferal extinction in the essentially complete Gubbio Scaglia showed that the Cretaceous–Tertiary extinction was a catastrophic event. After publication of the Gubbio Cretaceous–Tertiary iridium anomaly in 1980, a decade followed in which more and more evidence for a catastrophic impact challenged the traditional uniformitarian viewpoint of geologists. In 1991, the impact site was discovered at Chicxulub, in the Yucatán Peninsula of Mexico. The Gubbio area has thus emerged as a classical geological locality. It has been critical in the development of geomagnetic reversal stratigraphy, a third system for dating Earth history, complementing biostratigraphy and radiometric age dating. Gubbio was also central to the recognition that occasional catastrophic events like great impacts require a rejection of strict uniformitarianism.

Keywords Age calibration, Apennines, Cretaceous–Tertiary impact, geomagnetic reversals, Gubbio, Italy, mass extinction, micropalaeontology, palaeomagnetism, pelagic limestone, solution cleavage, stratigraphy.

INTRODUCTION

This review is based on an oral contribution to a symposium entitled 'Major Discoveries in Sedimentary Geology in the Mediterranean Realm, from a Historical Perspective to New Developments', that was held at the 32nd International Geological Congress, at Florence, in August 2004. The location was appropriate. Stratigraphy began in the 17th Century with Nicolaus Steno in Tuscany, and the Mediterranean has continued to be of central importance to stratigraphy, with a disproportionate number of global stratotype sections and points located in Italy (Cita, 2008).

The Apennine Mountains, running the length of the Italian Peninsula, have been an unusually rich source of geological discoveries that have revealed a great deal about Earth history. Of particular importance are the Umbria-Marche Apennines in the eastern half of the Peninsula between the latitude of Florence and that of Rome (Alvarez, 2009). This range has extensive exposures of pelagic carbonate rocks. Pelagic limestones and marls provide a particularly valuable record of Earth history because of their deposition at intermediate oceanic depth; they accumulate below the wave and current disturbances of shallow water, resulting in slow but continuous deposition so that there are few if any hiatuses in the record. On the other hand, these rocks are deposited above the calcite compensation depth and thus are rich in calcareous plankton, including foraminifera, providing a basis for refined biostratigraphic age control.

The pelagic rocks of the Umbria-Marche Apennines cover an interval from early in the Jurassic to early in the Miocene. A substantial portion of that record is provided by a single 400 m thick formation of pink to red pelagic limestone with a component of marls and with chert bands or nodules in two intervals. This formation is known as the Scaglia rossa and represents the Turonian to Early Eocene. 'Rossa' refers to the red colour and 'Scaglia' to the scaly, conchoidal fracture of this compact, well-lithified limestone. Bonarelli (1891) first noted the metre-thick interval of anoxic black shale between the white limestone of the Cenomanian Scaglia bianca and the Turonian base of the pink Scaglia rossa (Bernoulli & Jenkyns, 2008; Emeis & Weissert, 2008). This interval is now called the Bonarelli level and is well-exposed in the Bottaccione Gorge, adjacent to the little mediaeval city of Gubbio (Fig. 1).

BIOSTRATIGRAPHY

Before the advent of micropalaeontology, it was difficult to determine the ages of the pelagic limestones of the Umbria-Marche Apennines. For example, Bonarelli (1901), although correctly dating the Jurassic limestones in which ammonites are abundant, considered the Upper Eocene–Oligocene Scaglia cinerea to be Late Cretaceous in age and placed the Lower Miocene Bisciaro in the Danian (Alvarez, 2009).

These age assignments began to be corrected when Renz (1936, 1951) recognized the stratigraphic value of the particularly complete and well-exposed section of the Scaglia rossa in the Bottaccione Gorge and pioneered the study of planktonic foraminifera in thin section as a dating tool for these hard limestones. Luterbacher & Premoli Silva (1962) carried out a more detailed foraminiferal study of the Scaglia at Gubbio and then studied the interval across the Cretaceous–Tertiary (K-T) boundary in the Scaglia rossa throughout the Umbria-Marche Apennines (Luterbacher & Premoli Silva, 1964).

Calcareous nannoplankton was also found to be useful for biostratigraphy in the Umbria-Marche pelagic carbonates and numerous studies of nannoplankton and/or foraminifera have refined progressively the biozonation to which other kinds of stratigraphic investigation can be tied (Premoli Silva *et al.*, 1977, 1988b; Wonders, 1979, 1980; Monechi & Thierstein, 1985; Cresta *et al.*, 1989; Coccioni *et al.*, 1992; Cecca *et al.*, 1994; Premoli Silva & Sliter, 1995; Galeotti *et al.*, 2000).

TECTONIC PALAEOMAGNETISM

In the early 1970s, the author and palaeomagnetist William Lowrie became interested in the Scaglia rossa of the Umbra-Marche Apennines because it seemed to offer the potential for a study of tectonic palaeomagnetism (Alvarez & Lowrie, 1974). This limestone is very weak magnetically but new digital spinner magnetometers that had just become available made it possible to measure its magnetization.

In the early 1970s, the plate tectonic revolution was in full flower, as palaeomagnetism made it possible to track the history of motion of continents. The basic technique was to determine paths of apparent polar wander and then adjust past continental positions so as to remove the apparent polar wander. That kind of continent-scale work was well-developed by 1974 and,

Fig. 1. The Bottaccione Gorge in the mountains behind Gubbio, looking towards the north-east. The large mountainside in the rear is made of Upper Cretaceous and Palaeocene Scaglia rossa, dipping moderately away from the viewer. The horizontal structure is a Mediaeval aqueduct that supplied Gubbio with water.

trying to go beyond it, interest focused on the more complicated, small-scale tectonics of the Mediterranean. Palaeomagnetists had already shown that Corsica and Sardinia had rotated away from an original position south of France to their present position (Nairn & Westphal, 1968; De Jong *et al.*, 1969; Zijderveld *et al.*, 1970) and an obvious question was whether Italy had also rotated.

Various rotation scenarios had been proposed, and the aim of the Alvarez–Lowrie project (1974) was to use the magnetic declinations in the Scaglia rossa to show what rotation had actually taken place. Good magnetic data were obtained but, unfortunately, the pelagic limestones of the Umbria-Marche Apennines, including the Scaglia rossa, have so many bedding planes with clay partings that there is a possibility of rotational interbed slip, in addition to thrust decoupling from the basement, and these problems prevented definitive statements about rotations of the Italian crust.

However, latitudinal motions of the Italian crust could be determined from the palaeomagnetic inclinations and this work was done mainly by Dutch colleagues (Klootwijk & van den Berg, 1975; van den Berg, 1976). In addition, from this study, something could be learned about the deformation of the sedimentary cover of which the Scaglia was a part, and it was demonstrated that the fold-and-thrust belt of the Umbria-Marche Apennines has been bent into its present curving, oroclinal pattern (Channell *et al.*, 1978). Nevertheless, it was clear that the utility of the Scaglia rossa for research into tectonic palaeomagnetism was limited.

MAGNETIC POLARITY STRATIGRAPHY

Fortunately, there was something even better in the palaeomagnetic record of the Scaglia and that was magnetic polarity stratigraphy. In a classic case of scientific serendipity, Lowrie and Alvarez stumbled onto the polarity record of the Scaglia, while focusing upon tectonic palaeomagnetism.

Gubbio and the outcrops of Scaglia rossa in the Bottaccione Gorge soon emerged as the focal point for work on magnetic polarity stratigraphy. These micropalaeontologically datable deep-water limestones were deposited over a long interval of time, during which the magnetic field of the Earth reversed many times and the magnetic reversals are recorded clearly in the Scaglia. Lowrie and Alvarez found this polarity record at just about the time that it was independently discovered by Alfred G. Fischer, Giovanni Napoleone, Isabella Premoli Silva, Michael Arthur and William Roggenthen, who were specifically looking for the polarity sequence. The two teams joined forces and together determined the reversal pattern in the Scaglia rossa at Gubbio for the Late Cretaceous and the Palaeocene.

The interval studied is 270 m thick and sample spacing ranged from 10 cm to a metre. In studies of tectonic palaeomagnetism, it was traditional to drill a number of 'sites', each with half a dozen or a dozen cores, in order to get good statistics. For accurate magnetic stratigraphy, it was critical to recognize and correct for any section that was missing or repeated by faults. Therefore, it was necessary to develop extremely careful field techniques and a system was adopted where all samples were referred to a detailed section measured down to the centimetre.

The reversal record from the Bottaccione Gorge turned out to be a useful component of the plate tectonic revolution. That revolution was triggered in part by the discovery of the magnetic stripes on the ocean floor, giving a record of polarity reversals during sea floor spreading. Studies of the Scaglia showed that its reversal history matches the polarity record based on marine magnetic anomalies from the Pacific Ocean, the Indian Ocean and the Atlantic. It thus became clear that two high-resolution magnetic tape recorders are operating in the Earth, one in the ocean crust and the other in pelagic limestones. The oceanic recorder is running as much as 6000 times faster than the limestone recorder but the same characteristic fingerprint pattern of long and short normal and reversed polarity zones has been captured by both recorders – in several hundred kilometres of ocean crust and in 150 m of pelagic limestones (Fig. 2) (Lowrie & Alvarez, 1977a,b).

At the time, there was no good way to date the sea floor magnetic anomalies directly but planktonic foraminifera in the Scaglia allowed Premoli Silva (1977) to determine the ages of the reversals in the Scaglia and, for the first time, there was a good age calibration of the sea floor spreading record of the Late Cretaceous and Early Palaeogene from the ocean basins (Larson, 1977). The equivalent calcareous oozes are abundant beneath the sea floor and the Deep-Sea Drilling Project cored many ooze sequences but, for a long time, drilling disturbance made their magnetism unusable. As a result, the Cretaceous and Palaeogene reversal record was determined first in the Apennines.

In 1976, the first synthesis of palaeomagnetic results from the Scaglia was presented at a Perugia meeting (Fig. 3) (Pialli, 1976) and published in the *Geological Society of America Bulletin* as a set of five papers (Alvarez *et al.*, 1977; Arthur & Fischer, 1977; Lowrie & Alvarez, 1977a; Premoli Silva, 1977; Roggenthen & Napoleone, 1977).

The work on reversal stratigraphy continued, involving quite a number of geologists, palaeontologists and palaeomagnetists, extending to other Apennine pelagic units and other sections in the Apennines (Premoli Silva *et al.*, 1974, 1988b; Lowrie *et al.*, 1982; Napoleone *et al.*, 1983; Lowrie & Alvarez, 1984; Napoleone, 1988; Channell *et al.*, 1995). By the time the useful sections had all been studied, various researchers had age-calibrated a substantial part of the reversal history known from the ocean floor. In the Cretaceous, the Late Valanginian–Barremian geomagnetic record was dated from the Maiolica Limestone, the Aptian and Albian from the Fucoid Marls, the Cenomanian from the Scaglia bianca and the

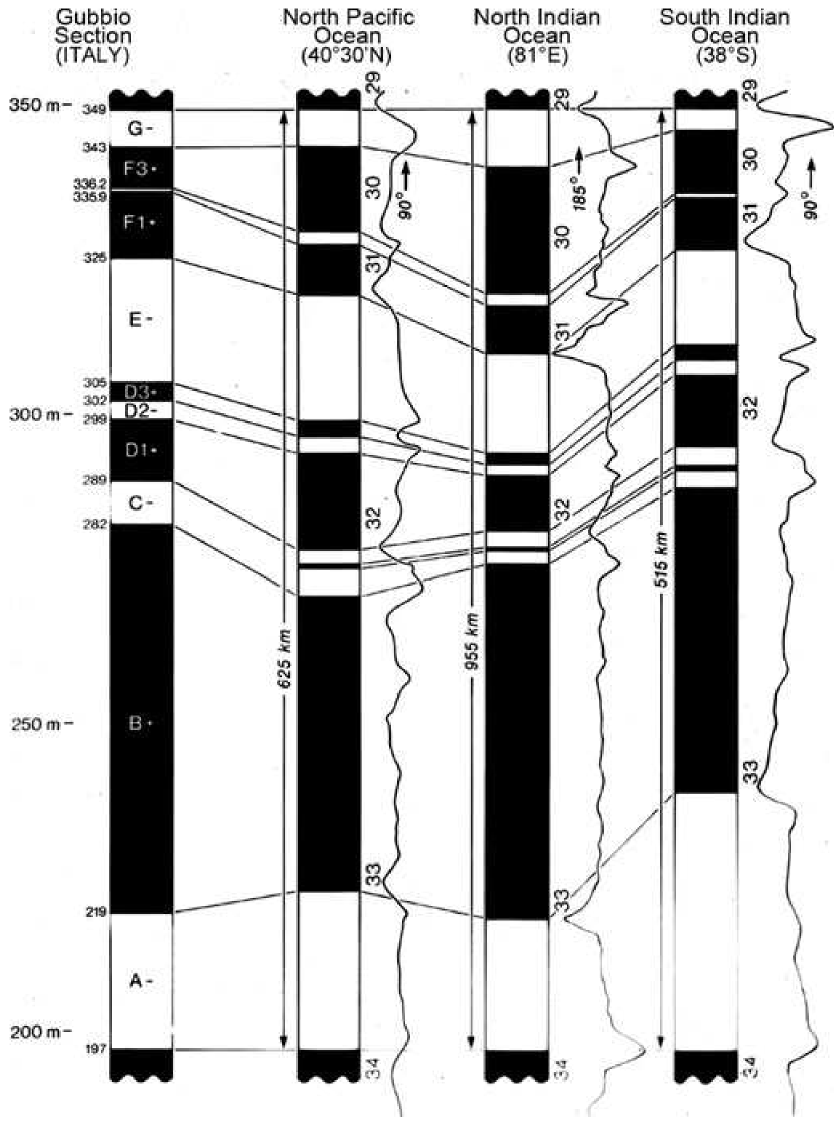

Fig. 2. Comparison between the Upper Cretaceous polarity record (Campanian and Maastrichtian, with the top of the Cretaceous at 347·6 m) from 150 m of pelagic limestone at Gubbio, and the polarity record from several hundred kilometres of sea floor in three different oceans (Lowrie & Alvarez, 1977a). The one thin normal interval missing in zone C at Gubbio was missed between samples in this initial paper; it was found to be present in a more detailed follow-up study (Lowrie & Alvarez, 1977b).

other five Late Cretaceous stages from the Scaglia rossa. In the Tertiary, the Palaeocene and Early Eocene reversals were also dated from the Scaglia rossa, most of the Middle Eocene from the Scaglia variegata and the rest of the Eocene and the Oligocene up to the base of the Miocene from the Scaglia cinerea (Fig. 4). So Gubbio and nearby sections were the critical centres for the development of magnetic reversal stratigraphy, a third method of correlating and dating rocks that is independent of, and supplementary to, biostratigraphy and radiometric age dating.

RADIOMETRIC AGE CALIBRATION OF THE TIME SCALE

The pelagic carbonates of the Umbria-Marche Apennines came to play an additional role in the development of the modern geological time scale when it was recognized that the pelagic units above the Scaglia rossa include a number of thin, distal, volcanic air-fall ash layers. These layers in the Scaglia variegata (Middle–Upper Eocene), Scaglia cinerea (Oligocene–Lower Miocene), and Bisciaro and Schlier (Miocene), contain well-preserved crystals, including feldspar and biotite, that can be dated using a variety of radioisotopic methods, especially $^{40}Ar/^{39}Ar$. Because the eruption and deposition ages of these crystals are the same, their occurrence in a pelagic carbonate sequence well-tied to the geological time scale using planktonic foraminifera, calcareous nannofossils and geomagnetic reversals has made it possible to attach reliable numerical ages to this part of the Palaeogene and Neogene time scale.

Montanari *et al.* (1985) presented the first dates, using the K/Ar and Rb/Sr methods. In the 1980s,

Fig. 3. At the Bottaccione Gorge during the 1976 meeting on palaeomagnetic stratigraphy of pelagic carbonate sediments. Front, from left to right: Roger Larson, Alfred G. Fischer, Walter Alvarez, William Roggenthen, Giampaolo Pialli. Rear, left to right: Roberto Colacicchi, Giovanni Napoleone, William Lowrie. The Cretaceous–Tertiary boundary is the colour change behind Lowrie's head.

this work concentrated on dating the Late Eocene and Oligocene (Montanari *et al.*, 1988; Premoli Silva *et al.*, 1988a) and was critical in the selection of Massignano, in the Umbria-Marche pelagic carbonates near Ancona, as the Global Boundary Stratotype Section and Point (GSSP) for the Eocene–Oligocene boundary (Premoli Silva & Jenkins, 1993).

In the 1990s, radioisotopic dating of air-fall ash layers in the Umbria-Marche carbonates was extended to the Miocene (Montanari *et al.*, 1991, 1997) and led to the establishment of the Serravallian–Tortonian Boundary GSSP at Monte dei Corvi, also near Ancona (Hilgen *et al.*, 2005). The levels of volcanic ash in the Umbria-Marche pelagic carbonates and their ages are summarized by Montanari & Koeberl (2000). Recently, it has been possible to extend radiometric dating of ash layers in the Scaglia down to the Campanian (Bernoulli *et al.*, 2004).

OTHER DISCOVERIES

As the work continued, other discoveries emerged from the Apennine Scaglia. For example, at Furlo, the Bonarelli level – the anoxic marker bed at the Cenomanian–Turonian boundary – is repeated twice through slumping (Fig. 5). It was possible to work out a detailed history of those obvious slumps as well as a set of slumps that are invisible in outcrops but could be identified because their palaeomagnetic declinations have been rotated during movement of the slump (Alvarez & Lowrie, 1984; Alvarez *et al.*, 1985).

In another example, it was found that in many places in the Apennines near Gubbio the bedding in the Scaglia is intersected by close-spaced cleavage surfaces. Surfaces like these had traditionally been called 'fracture cleavage' and they were thought to represent a few

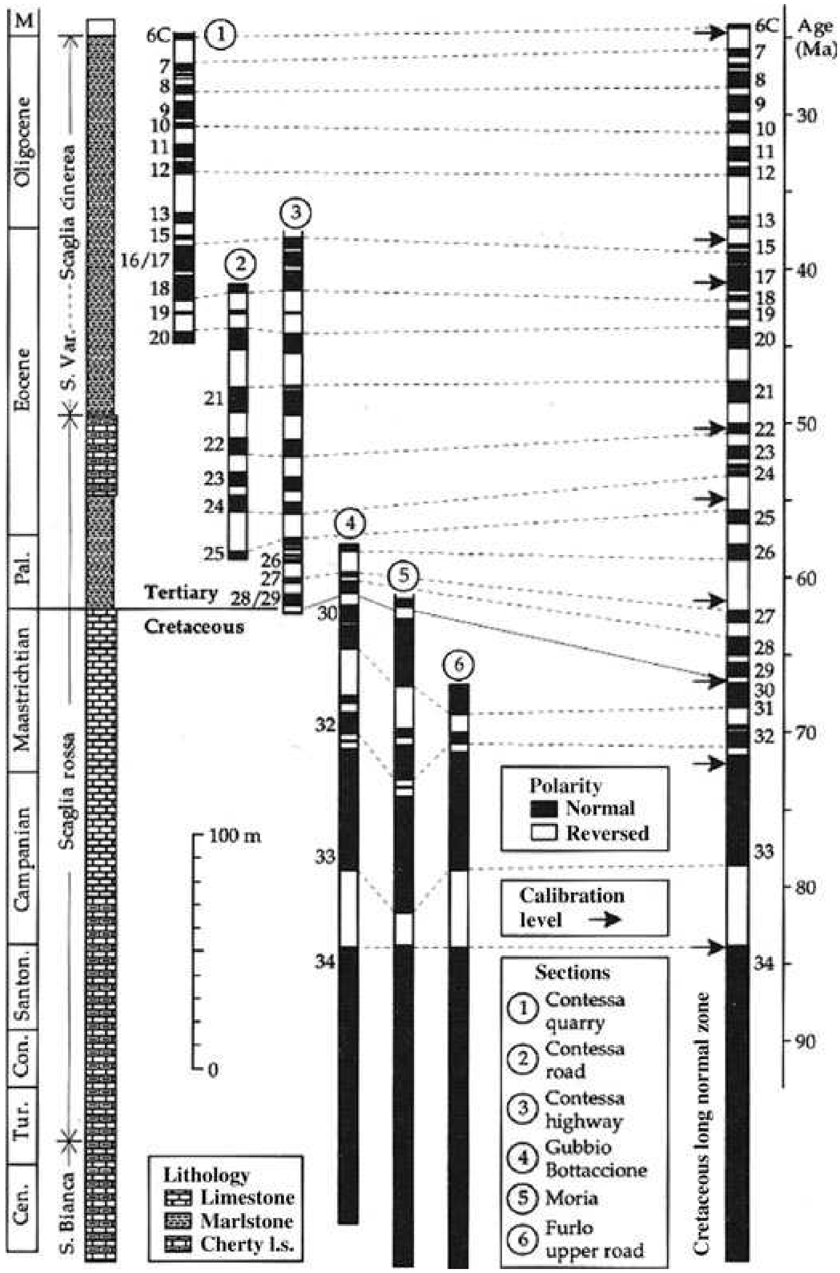

Fig. 4. 100 million years of geomagnetic polarity history measured in the pelagic carbonate rocks of the Umbria-Marche Apennines (Lowrie & Alvarez, 1981).

percent extension; but studies of the Scaglia rossa demonstrated that they are actually produced by pressure solution during compression, like stylolites. The telescoped overlap of chert beds in Scaglia limestone outcrops that contain closely spaced cleavage surfaces showed that there has been tens of percent shortening because of dissolution of the limestone (Alvarez *et al.*, 1976, 1978). Instead of a minor extensional fracture cleavage, this structure is a compressional solution cleavage representing major shortening (Fig. 6).

THE IMPACT AT THE CRETACEOUS–TERTIARY BOUNDARY

A major by-product discovery came from a careful study of the 1 cm layer of clay that Luterbacher & Premoli Silva (1962) had discovered at the K-T boundary in the Bottaccione Gorge at Gubbio. A full treatment of this whole episode is available in Alvarez (1997). Under the microscope, the large planktonic foraminifera of the end Cretaceous are replaced by the extremely small ones of the base Tertiary (Luterbacher & Premoli Silva, 1964). It

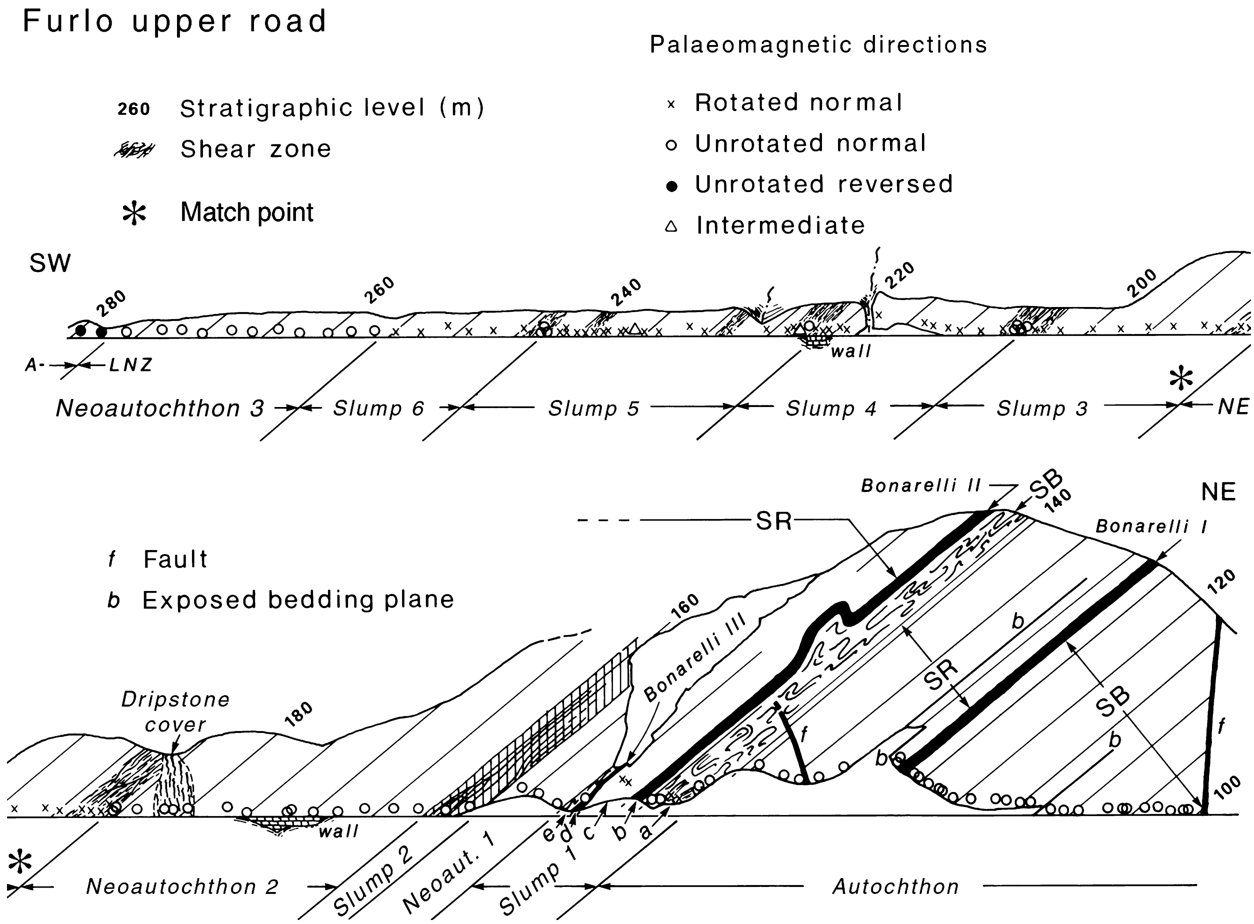

Fig. 5. Exposures of the Scaglia bianca and Scaglia rossa along the upper road at Furlo, in the Marche Apennines north-east of Gubbio. The strongly deformed slump that repeats the anoxic Bonarelli bed close to the Cenomanian–Turonian boundary is clearly visible in outcrop. The more obscure slumps numbered '3' to '6' were found because their palaeomagnetic declinations were rotated during slump movement; once they were located in this way, they were seen to be bounded by subtle sheared intervals in the limestone. From Alvarez & Lowrie (1984).

looked like a sudden, even catastrophic, mass extinction in which almost all of the planktonic foraminifera had disappeared during a very brief time when only a thin bed of clay had been deposited. This theory was in conflict with the uniformitarian tradition that then dominated geological thinking.

Trying to understand whether this clay had been deposited suddenly or slowly, a research group at Berkeley (Luis W. Alvarez, Walter Alvarez, Frank Asaro and Helen Michel) made measurements of the element iridium, to see how much extraterrestrial dust had fallen during the deposition of the clay. Iridium is rare in asteroids, comets and the Earth as a whole but, because most of the iridium in the Earth is in the core, alloyed with iron, crustal rocks and deep-sea sediments have vanishingly small amounts of iridium. It was originally expected that most iridium in the Scaglia rossa would have resulted from the slow, steady infall of cosmic dust, originally derived from comets and asteroids. If that were the case, it should be possible to determine just how sudden the extinction had been by finding out how long it had taken to deposit the centimetre of clay. If that clay layer represented the normal 5% or 10% clay in the Scaglia, but the limestone deposition had stopped for an interval of time, there would be a substantial level of iridium because of the cosmic dust that had fallen in that interval. On the other hand, if the extinction had been essentially instantaneous, with the clay dumped in all at once, there would be virtually no iridium in the clay.

Surprisingly, there was a dramatic iridium peak in the K-T boundary clay (Fig. 7), with far more iridium than could be explained by either of the two scenarios (Alvarez *et al.*, 1979). After a year of attempts to understand it, in 1980 the Berkeley group proposed that the iridium came from a

Fig. 6. William Lowrie pointing to insoluble chert nodules (darkest colour) that were driven over each other during solutional shortening of Scaglia rossa limestone beds (dipping steeply to the left). Dissolution of the limestone along many parallel surfaces produced the solution cleavage (dipping moderately to the right).

large comet or asteroid, whose impact on Earth caused the giant K-T mass extinction (Alvarez *et al.*, 1980). Other researchers confirmed the iridium anomaly as a worldwide feature and began to find other evidence for a K-T impact. Jan Smit discovered spherules representing droplets of impact melt that had been outside the atmosphere of the Earth (Smit & Klaver, 1981; Montanari *et al.*, 1983) and Bruce Bohor found K-T quartz grains with the deformation produced by shock during impact (Bohor *et al.*, 1984).

This hypothesis, that a major geological event had an extraterrestrial cause, required a change in some of the ways in which geologists think. Although lunar and planetary geologists had long been interested in impacts and impactors, terrestrial geologists now began to look upward at the sky and started paying attention to comets and asteroids which, on rare occasions, will produce big impacts on Earth. This planet is so active geologically that few impact craters are preserved here, but craters are abundant on all other rocky planets and satellites. Yet Lyell (1830–1833) had forbidden geologists to think about catastrophes and, through the 1980s, there was intense debate between uniformitarians and neo-catastrophists.

For 11 years, beginning in 1980, there was a frustrating search for the large crater required by the impact theory for the K-T extinction. Finally, the crater was identified, buried beneath the surface of the Yucatán Peninsula of Mexico and centred on the village of Puerto Chicxulub (Hildebrand *et al.*, 1991). This development is not reviewed here because, although triggered by the work at Gubbio, it took place elsewhere. A full account is given in Alvarez (1997).

Three years after the recognition of the Chicxulub Crater, a truly catastrophic geological event was actually observed and strict uniformitarianism

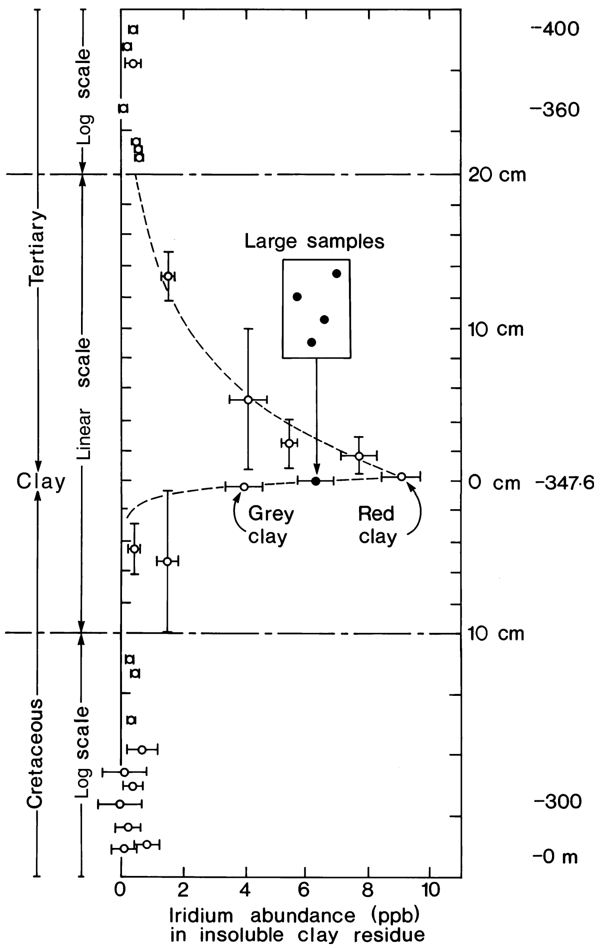

Fig. 7. The first plot of the Cretaceous-Tertiary boundary iridium anomaly from the Bottaccione Gorge at Gubbio and nearby sections, which was slightly modified for publication by Alvarez *et al.* (1980).

finally was laid to rest. An old, dead comet, whose dried-out surface coating of stony material prevented the degassing necessary to produce a tail, came too close to Jupiter and was torn apart by tidal forces. The fresh surfaces gave off new gases, the fragments lit up in the sunlight and they were seen by Eugene and Carolyn Shoemaker and David Levy. In July 1994, one fragment of Comet Shoemaker-Levy-9, after another ploughed into Jupiter, producing a series of impact fireballs of giant dimensions (Shoemaker, 1995). Geologists could no longer doubt the reality of catastrophic impact events.

The K-T impact, first recognized at Gubbio, was a truly catastrophic event in Earth history, whose history is written in detail in the rock record. It correlates with, and probably caused, the great mass extinction 65 Ma. After a century and a half, the uncompromising uniformitarian gradualism of Lyell was dead.

CONCLUSION

In summary, Gubbio, with its wonderful outcrops of pelagic carbonates, was the place where magnetic reversal stratigraphy came of age. This development added a third major method of determining the ages of sedimentary rocks, supplementing biostratigraphy and radiometric dating. In fact, the Scaglia outcrops at Gubbio are made of microfossils and nannofossils, their component of magnetic minerals records geomagnetic polarity, and they contain levels of distal volcanic ejecta that can be dated radiometrically, thus offering the remarkable possibility of tying together all three major geological dating methods in a single sedimentary unit. Gubbio was also the place where the impact–extinction link first was forged and where strict uniformitarianism was finally defeated. The Apennine pelagic carbonates have turned out to be exceptional recorders of many other aspects of Earth history as well, including several kinds of isotopic and trace-element stratigraphy, cyclostratigraphy, the Eocene–Oligocene impact events, and the biostratigraphy of foraminifera, calcareous nannoplankton, ammonites and inoceramids. It seems a remarkable scientific harvest to have come from one little mediaeval city and the surrounding mountains.

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