Diagenetic processes and remagnetization in Permo-Triassic reb beds

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INTRODUCTION

Palaeomagnetic methods of analysis have largely been concentrated on distinguishing between the relatively hard and soft components which make up the natural remanent magnetization (NRM) of sedimentary rocks. This has been because of the widespread belief that, in general, the hard components are primary in origin while the soft components are secondary, having been acquired a long time after deposition. Also it is generally assumed that the primary components originate from depositional processes rather than diagenetic (post-depositional) alteration. Magnetic components acquired by in situ alteration are usually attributed to chemical remanent magnetization (CRM) with no more specific reference to the processes of magnetization. Furthermore the general practice has been to assume that the magnetic components with higher blocking temperatures or coercivities faithfully record the ambient geomagnetic field at or near the time of deposition despite any direct geological evidence of the age of the components. This simplistic view of palaeomagnetism arises from the Neel equation which relates relaxation time to coercive force, particle volume and temperature for an assembly of non-interacting single-domain grains:

$$\tau^{-1} = C \exp(-v\, J_s\, H_c / 2kT)$$

Where C is the characteristic frequency of thermal fluctuation, v is the particle volume, J_S spontaneous magnetization, H_c the microscopic coercive force, k Boltzmann's constant and T is absolute temperature. This equation holds good given the constraints indicated. However it is obvious that in nature many problems will arise. In sedimentary rocks these include changes in particle volume and composition and the precipitation of completely new magnetic minerals. Most of the problems arise directly as a result of diagenetic processes; they can be grouped into three classes:

1. Post-depositional chemical alteration of magnetic grains (phase transition).
2. Changes in the particle volume (grain growth).
3. Neoformation of magnetic minerals (authigenesis).

Using data from continental red beds examples of these processes will be used to demonstrate how they can produce secondary magnetizations. The role of the Neel equation in remagnetization of red beds in deeply buried sedimentary basins will also be described.

LOWER PERMIAN OF THE SOUTHERN NORTH SEA; BURIAL REMAGNETIZATION

The Lower Permian of the southern North Sea is an excellent example of an ancient desert basin (Glennie, 1985). It has been buried to depths in excess of 3000m and is one of the UK's principal gas reservoirs. Gas and hydrocarbon exploration in the area has provided much borehole data from which burial and thermal histories can be constructed (methods described by Waples 1980, and Guidish et al. 1985). Fig. 1 shows a burial history diagram for a southern North Sea well from which palaeomagnetic samples have been studied. The diagram shows that the Lower Permian (Leman Sand Formation) reached its maximum depth of burial in late Cretaceous times (65 Ma) and was then uplifted (inverted) during the lower Tertiary. With some basic assumptions of the regional geothermal gradient (say 32° C/km) it is a simple matter to transpose the burial history diagram into a horizon-temperature plot (Fig. 2). This diagram is significant because it shows, even at a conservative estimate, that the Leman Sand Formation must have been buried to a temperature of over 100° C for a minimum of 150 Ma. These data provide the basis to test whether or not the Leman Sand Formation has been remagnetized in accordance with the Neel equation. Mineralogically the material is suitable for such a test since the magnetic phases consist of an assemblage of fine grained pigmentary haematite with no other known phases.

Pullaiah et al. (1975) calculated blocking temperature curves for haematite based on the Neel equation. These are shown in Fig. 3. In particular they show the relationship between relaxation time and blocking temperature as measured in the laboratory during thermal demagnetization. For any given curve grains in the area to the right would behave superparamagnetically and become unblocked whilst those to the left of the curve would remain blocked. The areas A and B on Fig. 3 depict differences

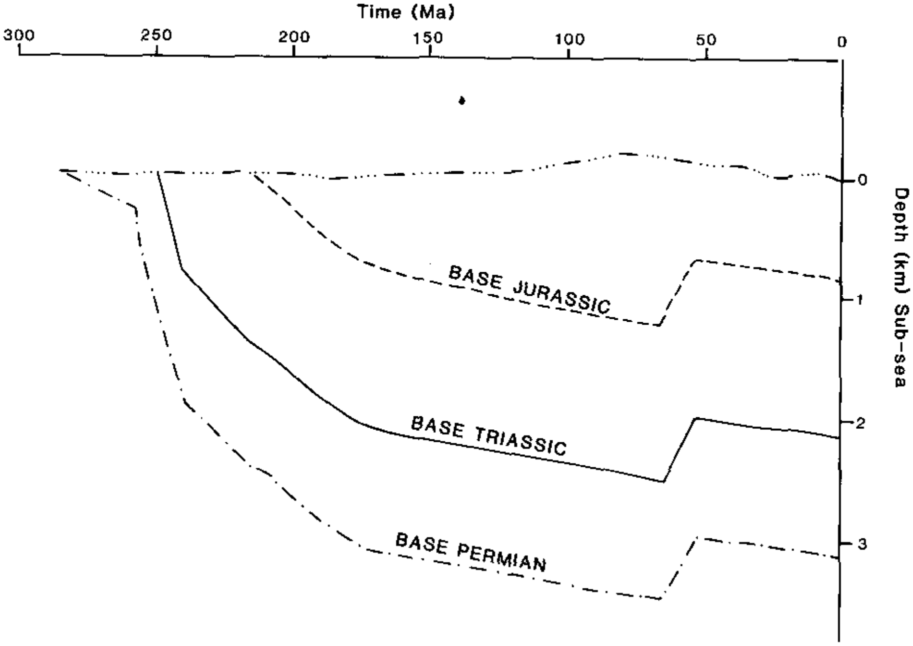

Fig. 1. Burial history diagram for the southern North Sea. It should be noted that the amount of inversion varies from place to place.

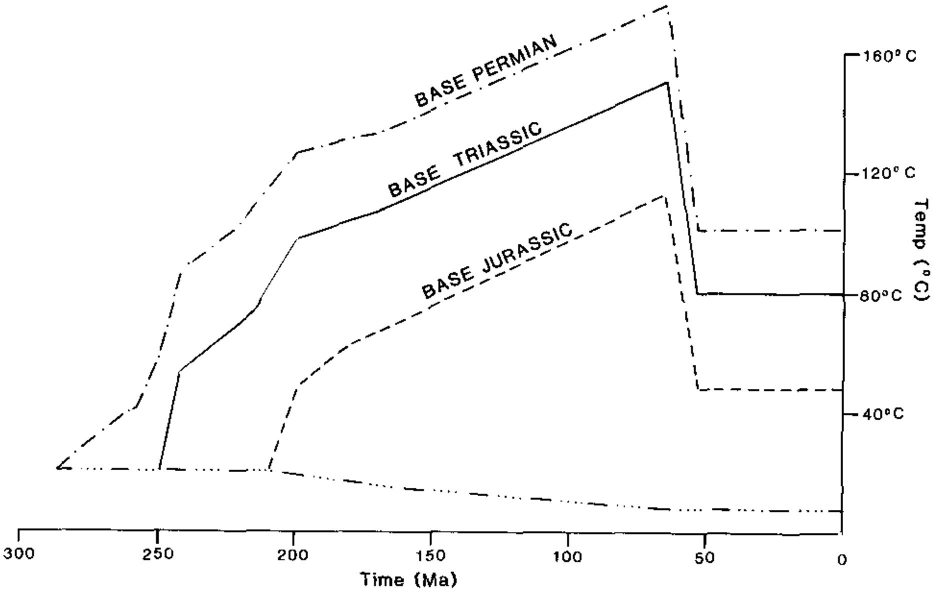

Fig. 2. Horizon-temperature plot for the burial curve in Fig. 1. Note the time-temperature parameters for the Leman Sand Formation.

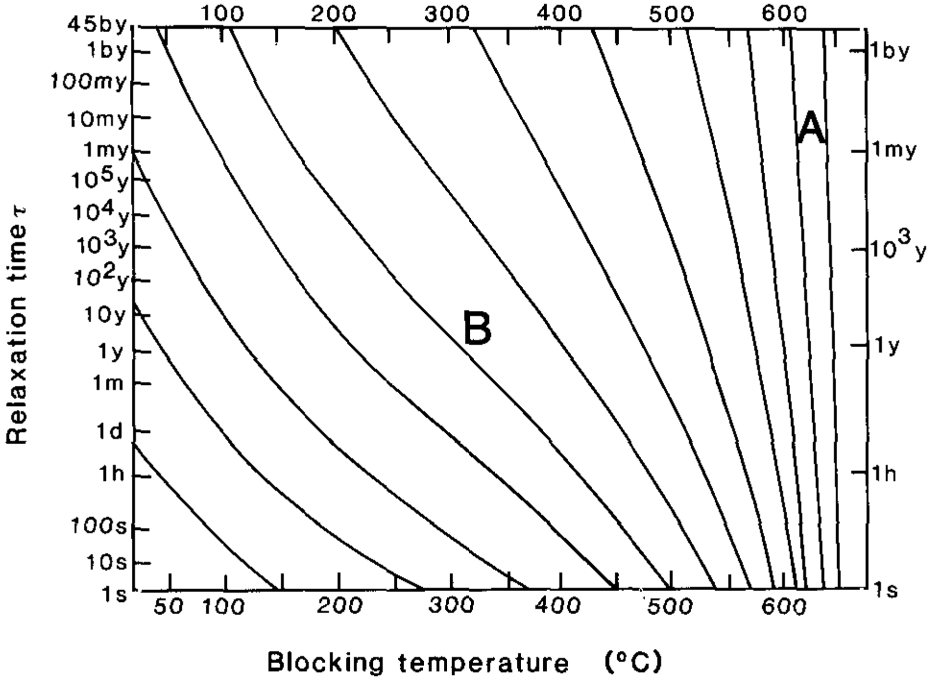

Fig. 3. Curves showing the relationship between blocking temperature and relaxation time for haematite (after Pullaiah et al. (1975).

in blocking temperature spectra; A is thermally distributed with a steady NRM decay curve whereas B is thermally discrete and would show a flat decay curve with a sharp shoulder at the unblocking temperature. For a Formation such as the Leman Sand the burial history suggests that a temperature of 550-600° C would be required to remove secondary magnetizations associated with burial.

Palaeomagnetic results from borehole cores of the Leman Sand Formation are consistent with the above predictions and furthermore suggest that the haematite in these rocks behaves as an assemblage of non-interacting single domain particles. Fig. 4 shows the results of thermal demagnetization of two specimens. In both cases the normalized intensity decay shows a progressive linear decrease to a blocking temperature at 600° C. The NRM directions in each case are characterized by steep positive inclinations near to the local geomagnetic inclination value (69°). Although declination is arbitrary in these unoriented borehole specimens it is reasonable to assume that the two directions represented are close to the geomagnetic direction for the area. They provide firm evidence of remagnetization due to increase in temperature and burial. The negative directions which form end-point in each thermal demagnetization are not sta-

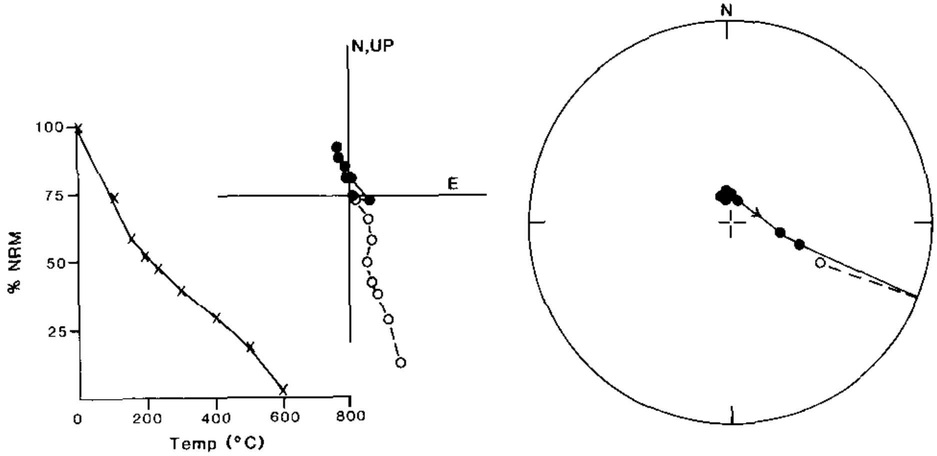

Fig. 4. The results of partial thermal demagnetization of a specimen from the Leman Sand Formation. Right: stereographic projection, Left: normalized intensity decay curve and Center: orthogonal plot.

tistically well-defined and could represent original Permian components or possibly reversed Tertiary directions.

The significant thing about remagnetization associated with burial is that it may be very difficult to identify in ancient rock sequences, particularly those which have been structurally inverted. Turner (1979) identified a distinctive type of magnetization (Type C) in ancient continental red beds characterized by closely grouped directions near to the present Earth field. It is quite possible that such sequences represent structurally inverted basins which were remagnetized during deeper burial earlier in their geological history.

TRIASSIC RED BEDS FROM THE UK: REMAGNETIZATION ASSOCIATED WITH AUTHIGENESIS OF IRON-TITANIUM OXIDES

The Triassic of the UK comprises a sequence of mixed fluvial and aeoliam sediments with marginal marine clastics, and mudstones with evaporites in the upper part (see Warrington et al 1980). The diagenesis has been the subject of a number of detailed studies (e.g. Burley 1984 and Fine 1987). In this section the relationships between diagenesis and magnetization will be described. Important processes include phase transition and the precipitation of authigenic iron oxides. Iron oxide diagenesis can be demonstrated to be closely linked to conventional diagenetic processes, particularly the alteration of iron silicates and the dissolution of iron bearing carbonates.

In the St. Bees Sandstones, a lower Triassic sequence exposed on the Cumbrian coast of England (Turner and Ixer 1977; Turner 1981) the initial measurements of NRM indicate the presence of normal and reversely magnetized zones. During detailed thermal demagnetization of individual specimens it becomes apparent that superimposed normal and reversed components are present. Fig. 5 shows a stereographic projection of site mean directions after blanket thermal cleaning at 300° C. It should be noted that the normal directions are on average steeper than the reversed ones and nearer the present axial dipole for the area. Many sandstones

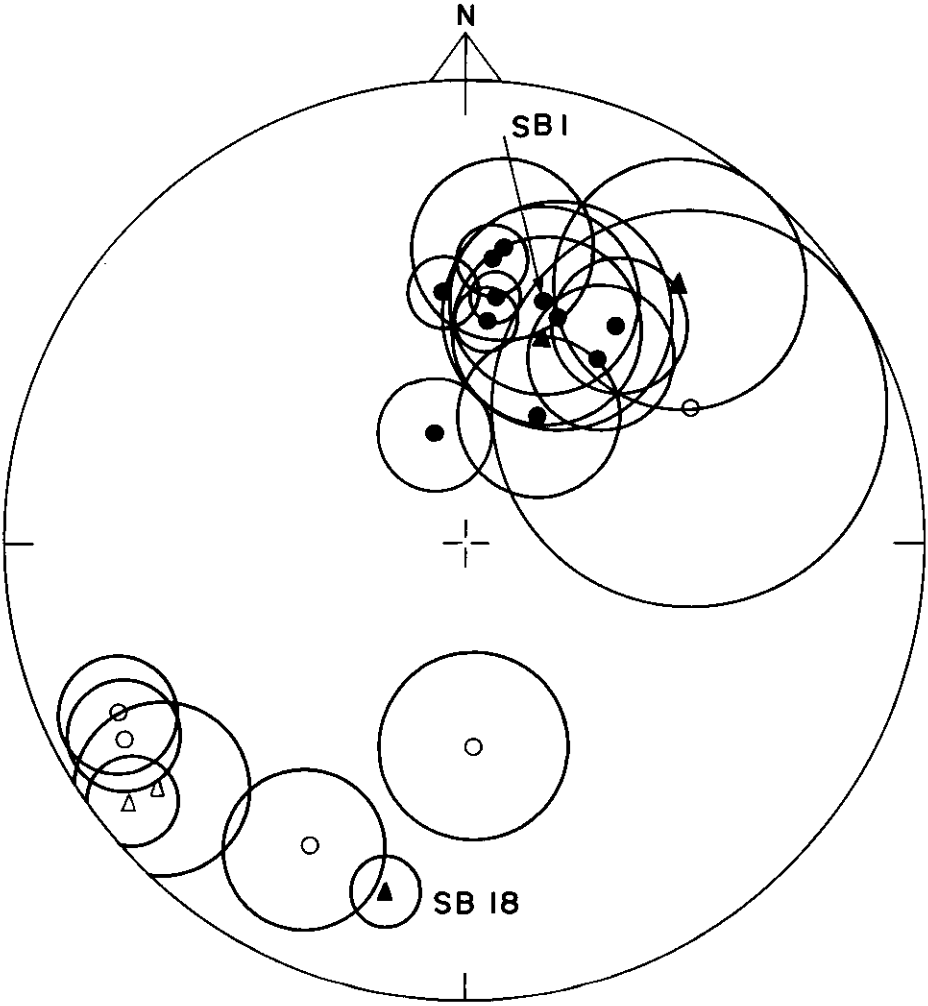

Fig. 5. Stereographic projection of site mean directions from the St. Bees Sandstone (Triassic) of Northern England.

with abundant red pigmentary haematite carry secondary components of magnetization which are near to the present Earth field direction and characterized by a marked linear decay in normalized NRM intensity (Fig. 6). Such components are believed to represent the thermal influence associated with burial as described above for the Lowe Permian of the southern North Sea.

Other material in the St. Bees Sandstone shows superimposed components of magnetization which are associated with phase transition and the authigenesis of iron-titanium oxides. The mineralogy of some of these phases has been described by Ixer et al (1979). Fig. 7 shows the results of thermal and chemical demagnetization of a sandstone which contains no pigmentary haematite, only coarse opaque material is present. Both the chemical and thermal demagnetization results show the progressive removal of a normal component of magnetization to reveal a higher blocking temperature reversed direction. The implications of the chemical demagnetizaton are that the lower blocking temperature phase (carrying the normal component) is more soluble in HCl than the higher blocking temperature phase which carries the reversed component. Mineralogical studies of this sandstone show that it contains haematite grains with abundant syntaxial authigenic overgrowths. These are most clearly seen in SEM photomicrograps which reveal perfectly euhedral crystals of authigenic haematite growing into pore spaces (Fig. 8 A). Reflected light photomicrographs clearly indicate the extent of these newly precipitated phases (Fig. 8 B, C) and X-ray scanning images show that they are generally titaniferous (Fig. 8 D). Electron probe microanalysis confirms up to 6 wt. % TiO_2.

Palaeomagnetic components isolated from the thermal demagnetization data reveal that the magnetization of this sandstone comprises both normal and reversed directions. The best estimate of these components based on the technique of least squares fit to data points is: normal component Dec=70°, Inc=+33°; reversed component Dec=190°, Inc=–44°. It can be seen from this that the two components lie within an arc being directly antiparallel and it is quite likely that they could represent normal and reversed Triassic magnetizations. The implications for magnetostratigraphic studies in continental red beds are clear. Discrete zones of reverse and normally magnetized rock could reflect variations in the relative amounts of authigenic iron oxides rather than changes in the geomagnetic field direction at the time of deposition. It should also be noted that diagenetic zonation of this would be expected to be parallel to bedding because of the depositional control of detrital oxides acting as nuclei to the authigenic phases. Without detailed studies of diagenesis, apparent polarity reversals such as that described by Herrero-Bervera and Helsley (1983) cannot be regarded as unequivocal evidence of geomagnetic changes at or near the time of deposition in red beds.

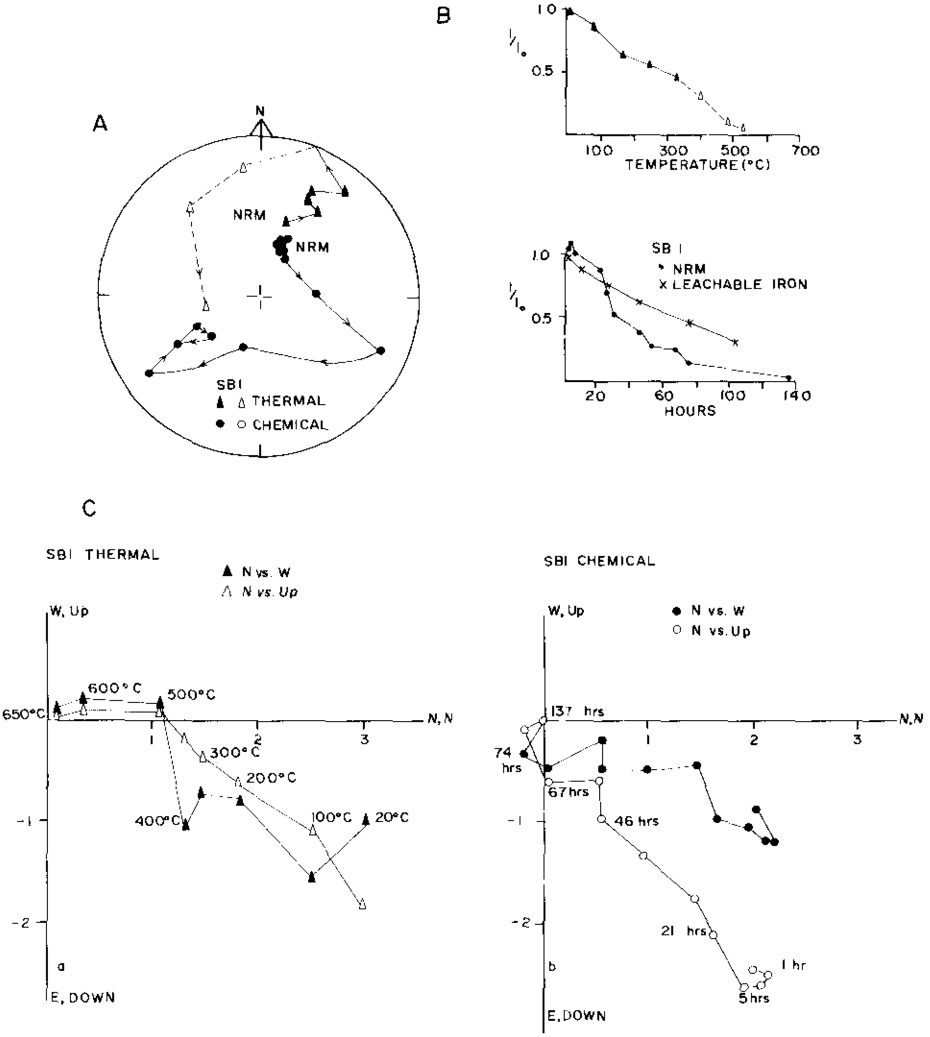

Fig. 6. The results of partial thermal and chemical demagnetization of a St. Bees Sanstone specimen which has abundant authigenic pigmentary haematite. A shows a stereographic projection, B normalized intensity decay curves and C orthogonal plots.

It is significant that the Triassic red beds studied here reveal differences in the mineralogy of detrital and authigenic oxide minerals. In general the authigenic phases have lower blocking temperatures due partly to their grain size distribution and partly to their composition. In particular, titanium bearing haematites have lower Curie temperatures than pure haematite. This means that partial thermal demagnetization my be

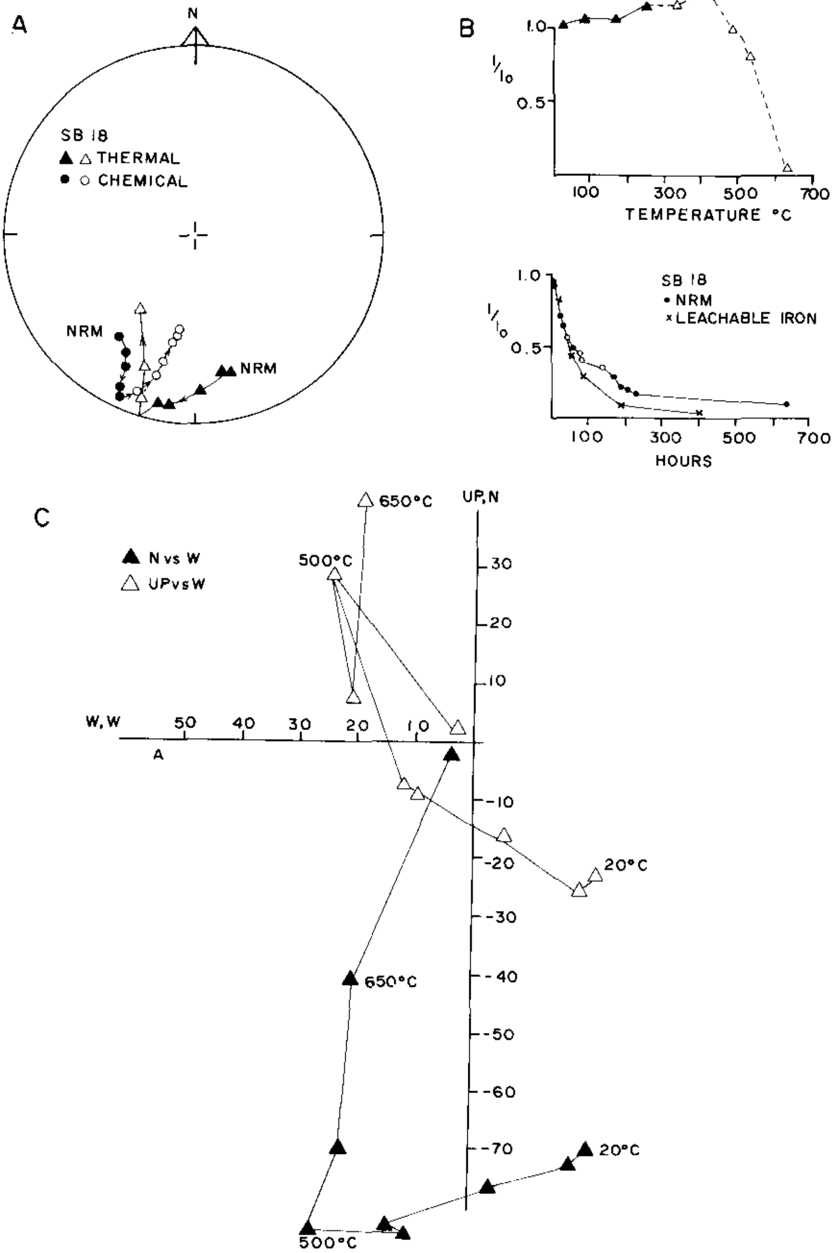

Fig. 7. The results of partial thermal and chemical demagnetization of a St. Bees Sandstone Specimen which has abundant detrital haematite with syntaxial overgrowths. A shows a stereographic projection, B normalized intensity decay curves and C shows an orthogonal plot.

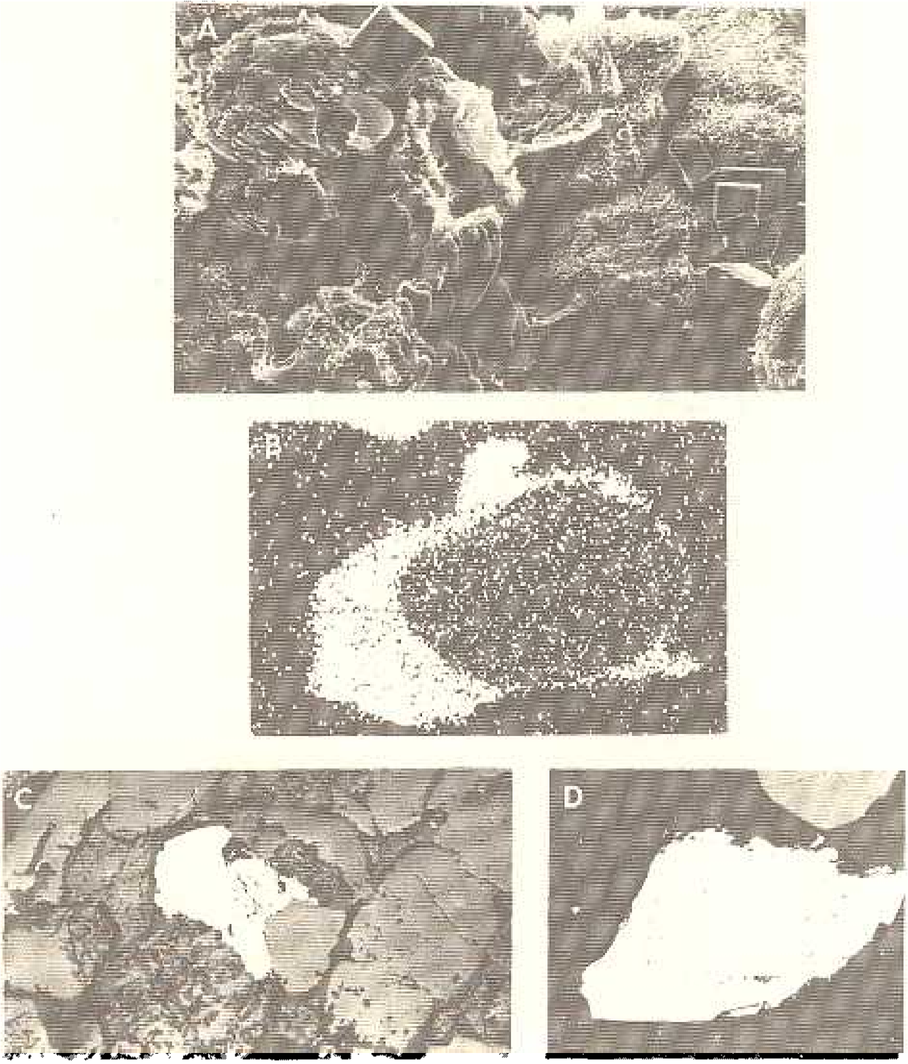

Fig. 8. Petrographical features of the St. Bees Sandstone. A. SEM photomicrograph showing discrete crystals of anatase and disc-like crystals of haematite growing on a detrital grain B. X-ray scanning image (Ti Kα) of a detrital haematite with a syntaxial overgrowth of titaniferous haematite. C. Reflected light photomicrograph of detrital haematite with very large area of pore-filling authigenic haematite. D. Detail of detrital haematite with single syntaxial authigenic overgrowth. *All* the detrital host grains are *80-100* μ m in size.

effective in removing diagenetic components of magnetization relative to the higher blocking temperature primary or characteristic remanence.

THE PERMO-TRIASSIC OF THE IBERIAN CORDILLERA: REMAGNETIZATION ASSOCIATED WITH SECONDARY POROSITY GENERATION AND UPLIFT

The stratigraphy and sedimentology of the Permo-Triassic continental sequences of the Iberian Cordillera have been described by Virgili et al. (1983), Sopeña et al. (1983) and Ramos et al. (1986). Previous palaeomagnetic results (Van der Voo, 1967 and 1969) detailed the rotation of Iberia relative to the stable European plate. A detailed palaeomagnetic study has been made of four stratigraphical units including the Autunian, Saxonian, Buntsandstein and Muschelkalk.

Autunian (Lower Permian) sediments are mainly non-red alluvial fan, lacustrine and volcaniclastic facies which show exclusively reversed charateristic magnetizations similar to those described by Van der Voo (1969). The overlying Saxonian (Upper Permian) and Buntsandstein (Upper Permian-Lower Triassic) are red in colour and show much more complex magnetizations. The Buntsandstein in particular shows close relationships between structurally controlled diagenesis and remagnetization.

Fig. 9 shows a stereographic projection of the initial mean NRM directions of all the measured samples. Note how the Buntsandstein directions group near to the local geomagnetic direction. When individual specimens are subjected to partial thermal demagnetization the near- present Earth field direction is extremely stable. This is illustrated in Fig. 10 which shows no evidence of any original characteristic magnetization. In some cases (Fig. 11) there is evidence of a relict Triassic magnetization especially where there are abundant detrital grains.

The remagnetization of the Buntsandstein was probably a complex process. Petrographical studies (Fig. 12) show a variety of iron oxide textural phases. Magnetite appears to be completely absent and detrital haematites are rare, often showing much alteration and comprising titanium oxide intergrowths. One of the commonest textural phases of haematite is microcrystalline pore-filling and pore-lining material which has formed as a result of the dissolution of ironbearing carbonate cement. Carbonate dissolution of this type is known to be associated with secondary porosity generation (Schmidt and McDonald, 1979). Sometimes the post-secondary porosity iron oxides are coarser grained and can be seen clearly postdating syntaxial overgrowths of quartz (Fig. 12 E, F).

It is not a straightforward matter to absolutely date the secondary porosity generation in the Buntsandstein using the remanence directions (cf. Elmore et al. 1985). The authigenic haematite may have formed recently, perhaps in association with the present ground water zone. Alternatively the haematite may have formed at deeper burial depths and remained in the superparamagnetic state until the remanence was blocked-in, possibly as a result of structural uplift in recent times. It is interesting to note that

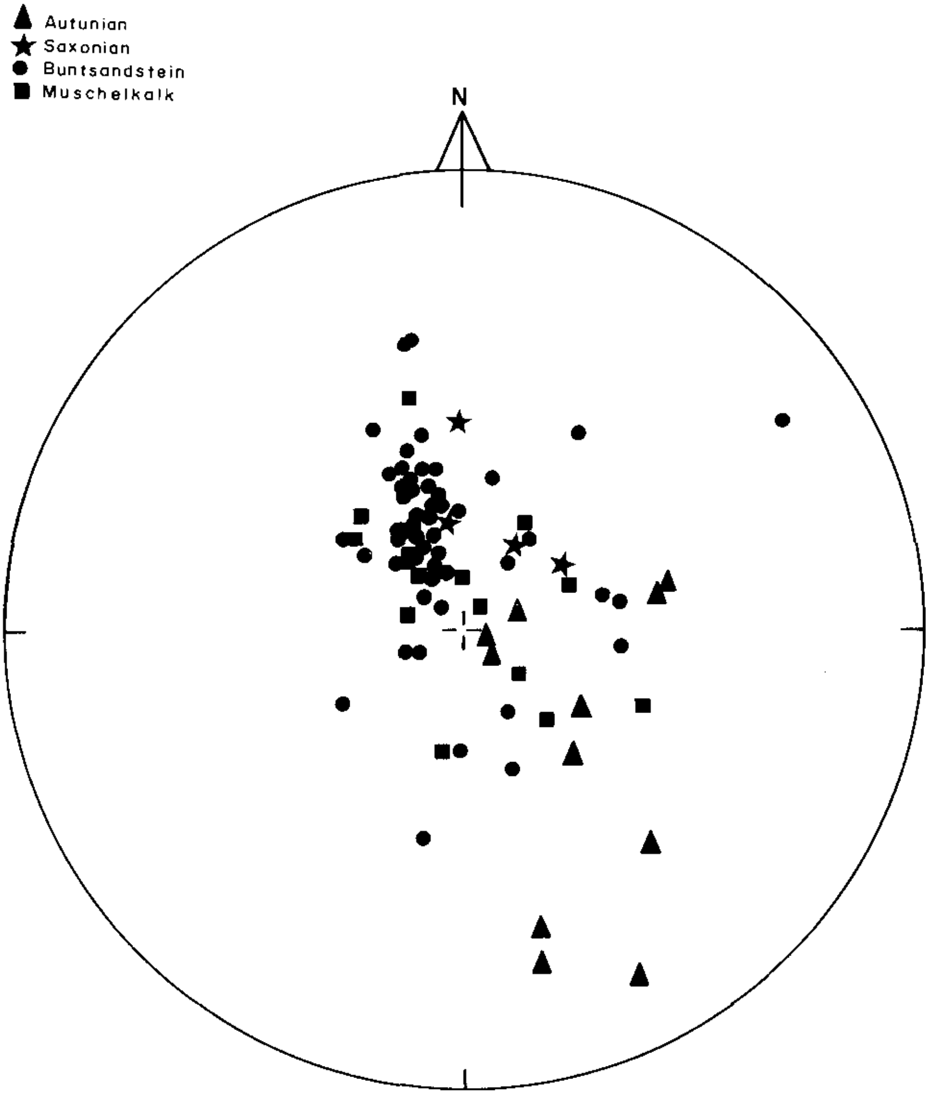

Fig. 9. Stereographic projection of initial site mean directions of Permo-Triassic sediments from the northern Iberian ranges.

earlier work of Van der Voo (1969) places some constraints on the remanence acquisition; characteristic magnetizations (where preserved) must have been acquired prior to the rotation of Iberia whereas the secondary magnetization clearly took place after rotation.

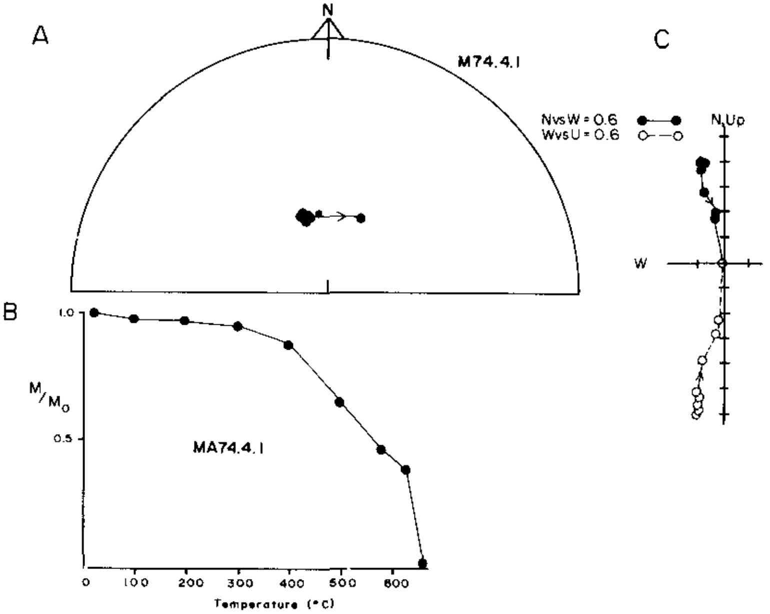

Fig. 10. The results of partial thermal demagnetization of a Spanish Buntsandstein specimen which is completely remagnetized. A shows a stereographic projection, B a normalized intensity decay curve an C an orthogonal plot.

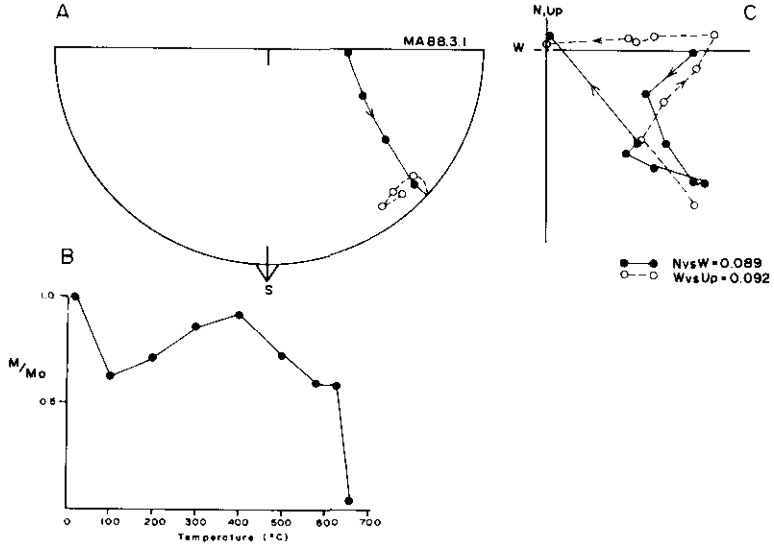

Fig. 11. The results of partial thermal demagnetization of a Spanish Buntsandstein specimen which is partly remagnetized and shows evidence of an original reversed Triassic magnetization. A shows a stereographic projection, B a normalized intensity decay curve and C an orthogonal plot.

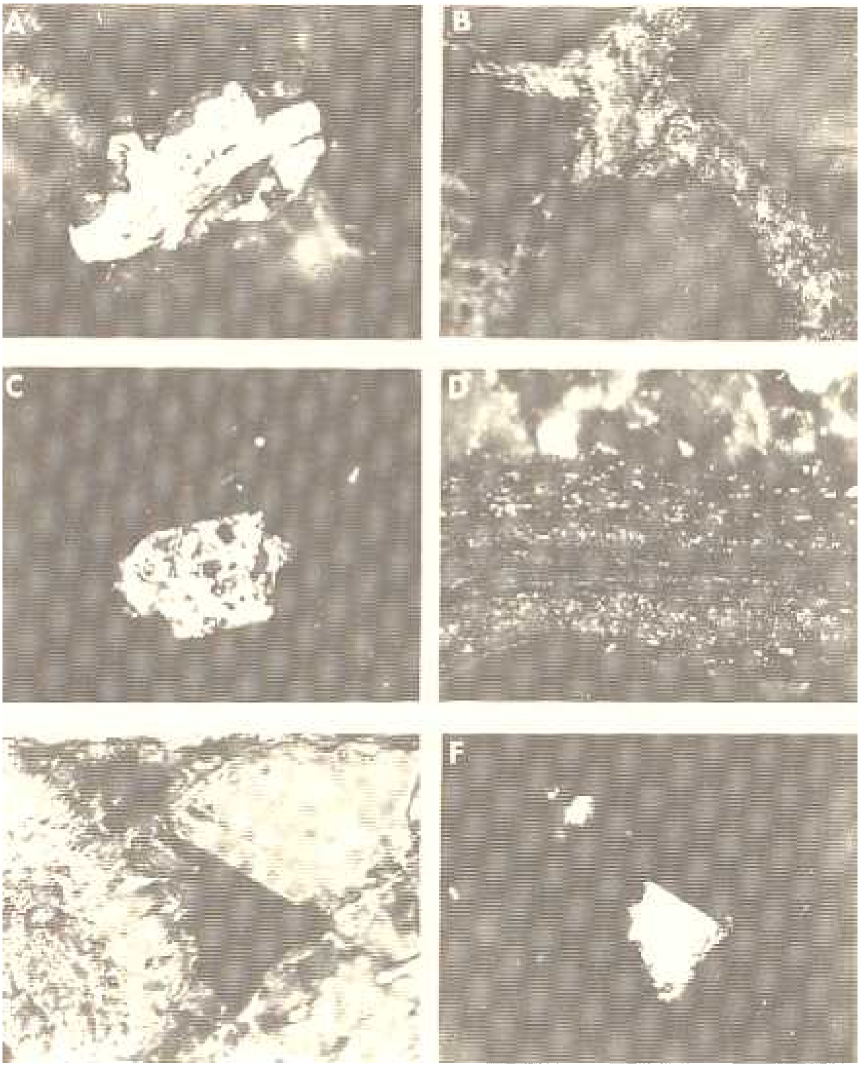

Fig. 12. Photomicrographs of detrital and authigenic iron oxides in the Buntsandstein of the northern Iberian ranges. A. Composite grain of haematite and titanium oxide with a strongly embayed appearance, reflected light, oil. B. Porefilling microcrystalline haematite and clay minerals, reflected light, oil. C. Detrital haematite with pitted appearance and authigenic projections on left and right side, reflected light, oil. D. Biotite partly replaced by haematite crystals parallel to cleavage planes, reflected light, oil. E,F Pore-filling authigenic haematite postdating syntaxial quartz overgrowsths (E thin section in ppl, F reflected light, oil). All photomicrographs are approximately 150 μ m in width.

CONCLUSIONS

The described examples show some of the ways in which diagenetic processes can generate secondary magnetizations in continental red bed sequences. Similar processes are important in all sediments, but particularly those which are subjected to deep burial and which retain sufficient porosity to facilitate diagenetic processes. The best potential materials for palaeomagnetic study are those in which diagnesis was rapidly completed and subjected to only shallow burial.

In practical terms diagenitically-induced magnetizations can be preferentially removed by partial thermal demagnetization because of inherent differences in the grain size and composition of authigenic minerals. However, it is quite conceivable that many sediments have been completely remagnetized and as such are very difficult to detect in nature. This is especially so where superimposed magnetizations show apparent polarity stratigraphy which is bedding parallel.

Palaeomagnetic studies should always be accompanied by relevant rock magnetic and mineralogical studies in attempts to ascertain the age of the remanence. Geological criteria such as structural and burial history may provide crucial clues to remanence acquisition. The established field tests of remanence age (fold and conglomerate tests) should also be applied wherever possible, although in themselves they do not prove that magnetization and depositional age were closely coincident.

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