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CHEMICAL REMANENT MAGNETIZATION (CRM)

Chemical remanent magnetization (CRM) refers to remanent magnetism imparted isothermally to magnetic particles produced by chemical processes below their Curie temperature in an ambient magnetic field. In rocks, CRM is usually a secondary remanence superimposed on a preexisting remanence, such as thermal remanent magnetization (TRM) in igneous rocks or depositional/post depositional remanent magnetization (DRM/PDRM) in sediments. It is generally a nuisance remanence that has to be removed to get at the primary remanence, which hopefully was recorded at the time of initial rock formation. Occasionally, CRM is the remaining characteristic remanence, the primary remanence having been obliterated, and it can be useful for paleomagnetism provided that the time of CRM production is known, or that the chemical processes have not changed the primary remanence direction, as is the case for some submarine basalts. In nature CRM is usually acquired in the presence of the Earth's magnetic field, but it can also be produced in the laboratory and in zero external field, where CRM alignment might be achieved by the sample's own internal magnetic field.

In terrestrial rocks the most common magnetic minerals are the iron-titanium (Fe-Ti) oxides of the ternary system $FeO-TiO_2-Fe_2O_3$ (Fig. 1), primarily the cubic titanomagnetite series along the line joining magnetite (Fe_3O_4) and ulvöspinel (Fe_2TiO_4) and the rhombohedral titanohematite series with compositions between hematite (αFe_2O_3) and ilmenite ($FeTiO_3$) (see *Magnetic Properties of Minerals*). Although other magnetic species, such as certain iron sulfides, sometimes contribute to the paleomagnetic signal, our examples of CRM in rocks will be confined to the Fe-Ti oxides. However, the physical and chemical mechanisms responsible for CRM production, and which determine its magnitude and stability, are general and apply equally to other magnetic minerals.

The earliest CRM experiments were done over a century ago in association with electrolytic deposition of iron and other magnetic metals. Beetz (1860) produced CRM in electrolytically deposited iron supporting Weber's hypothesis that some atoms possess intrinsic magnetic moments. Similar experiments producing CRM by electrolytic deposition of iron and nickel in the presence of external fields were also reported by Maurain (1901, 1902). Koenigsberger (1938, part 1, p. 122) envisioned a *crystallization remanence* "impressed by the Earth's field at temperatures between about 100°C and 500°C during the time of lattice changes in magnetite which result very probably from unmixing of Fe_2O_3," and he advanced this as a possible mechanism for the strong, coherent remanence of some sediments (Koenigsberger, 1938, part 2, p. 319). With the growth of research in paleomagnetism after World War II it became apparent to many rock magnetists in Europe, North America, and Japan that the remanence of many sediments, especially red beds, was at least partially controlled by magnetic minerals chemically precipitated subsequent to deposition (e.g., Blackett, 1956).

CRM research has been relatively neglected in comparison with that of other naturally occurring remanences, such as TRM, viscous RM (VRM), and DRM/PDRM, because it is often difficult to distinguish CRM from these remanences, because of overlapping stabilities and intensities and because of difficulties in designing well controlled laboratory experiments.

Grain Growth CRM

In this section we discuss grain growth CRM, because, conceptually, it is the simplest form of CRM, and because the evolution of its intensity and stability can be understood as a particular example of a more general treatment of remanent magnetism. In addition, grain growth CRM has been used to explain the often stable remanence of many chemically altered sedimentary and igneous rocks.

Néel (1949, 1955) developed a theory for the remanence of noninteracting single domain (SD) particles. The theory has been highly successful in explaining many features of TRM, particularly its relatively high intensity and stability as compared with IRM (isothermal remanent magnetization) produced in comparable fields at room temperature. (See *Thermoremanence* and *Viscous Remanent Magnetization (VRM) and Viscous Remagnetization.*) Following Néel's treatment, the remanence, M_R, of a magnetized body will decay in zero field, seeking the new state of thermal equilibrium (zero remanence), at a rate determined by the relaxation time, τ, such that
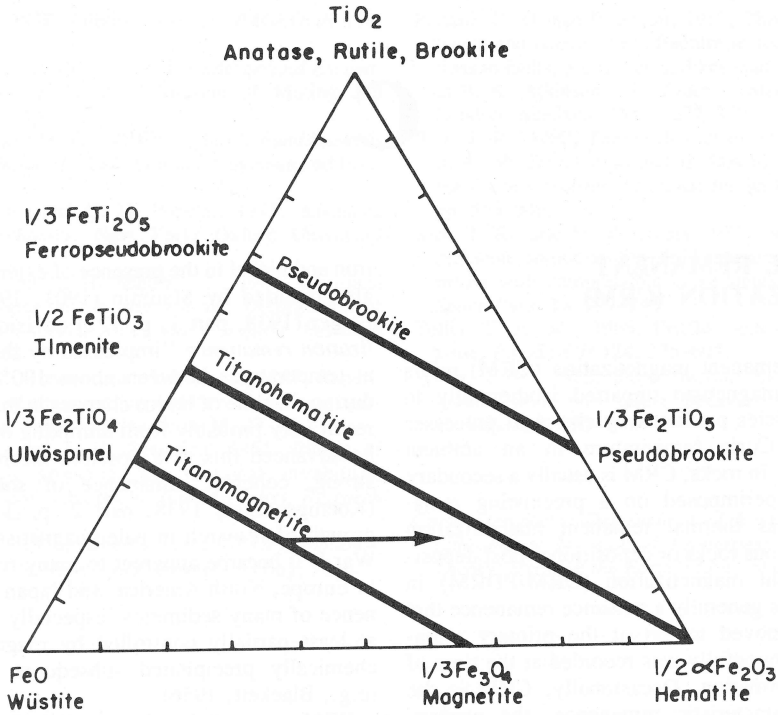
FIGURE 1. Compositional diagram for the ternary system $FeO-TiO_2-Fe_2O_3$, normalized with respect to cations, such that horizontal lines have constant Fe:Ti ratios, indicating pure oxidation/reduction reactions. The three principal Fe-Ti oxide solid solution series are shown by heavy lines. All members of the pseudobrookite series are paramagnetic at room temperature.

$$M_R = M_0 \exp [-t/\tau] \qquad (1)$$

where M_0 represents the initial remanence, and t is the time. Néel derived an expression for τ, which for mathematical simplicity considers an assemblage of identical noninteracting spherical SD particles with uniaxial anisotropy and aligned easy axes of magnetization. Then in zero external magnetic field

$$\tau = C^{-1} \exp [Kv/kT] \qquad (2)$$

where K = the uniaxial anisotropy energy coefficient; v = the particle volume; k = Boltzmann's constant; T = the absolute temperature (°K). C is the frequency factor whose value is on the order of 10^9 sec^{-1}. Although C depends on the temperature and temperature-dependent material properties, it is usually considered constant in comparison with the exponential factor. In contrast, τ, which is a measure of the remanence stability, varies orders of magnitude as a result of modest changes of the argument (Kv/kT). Thus, the Néel theory provides an explanation for the observed blocking/unblocking process and the additivity of partial TRMs (PTRMs) of noninteracting SD particles.

CRM production is an isothermal process, where

τ increases exponentially with volume for homogeneously magnetized grains. The precipitating ferro/ferrimagnetic particles grow from atomic/molecular paramagnetic nuclei to larger superparamagnetic (SPM) grains having spontaneous magnetization but no remanence, $\tau \ll \tau_L$, where τ_L is a characteristic laboratory time usually on the order of minutes. As the volume increases, the blocking volume, v_B, may be exceeded, $\tau \gg \tau_L$, the magnetic moments are stabilized, and the magnetization is said to be blocked. This is exactly analogous to TRM, where v is constant and τ increases as the temperature decreases. ($T_B \equiv$ blocking temperature; $T_C \equiv$ Curie point or temperature). Above the blocking temperature ($T_B < T < T_C$), $\tau \ll \tau_L$, thermal equilibrium is quickly established, and the ferri/ferromagnetic grains are in the SPM state with no remanence. For $T < T_B$, $\tau \gg \tau_L$, and the remanence is blocked. Thus, as the temperature decreases from above T_C the particle assemblage progresses from paramagnetic to SPM to the stably magnetized state.

As long as the magnetic ensemble consists of homogeneously magnetized SD grains, τ will increase exponentially with particle volume (recall that Eq. 2 for τ was specifically derived for noninteracting SD particles). For multidomain (MD)
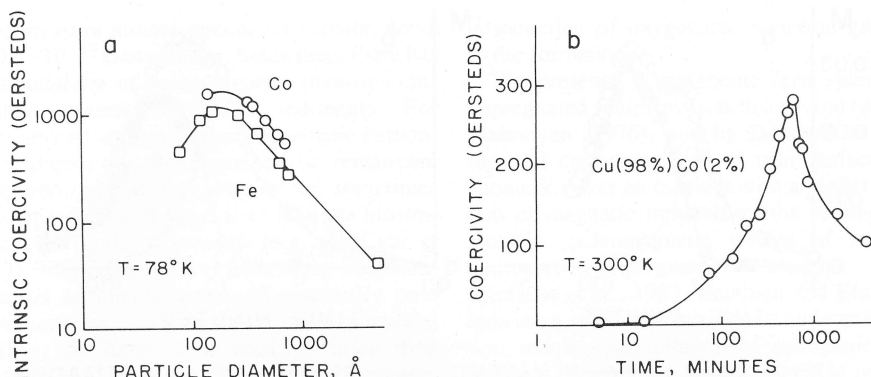
FIGURE 2. (*a*) Intrinsic coercive force of iron and cobalt as a function of particle sizes at liquid nitrogen temperature (from Meiklejohn, 1953). (*b*) Change in coercive force of the alloy Cu (98%) Co (2%) as a function of annealing time (particle size) at 700°C, measured at 300°K. (From Becker, 1957)

particles τ will decrease with increasing volume, principally because it becomes progressively easier to alter the remanence by domain wall movements in contrast to rotating the magnetic moments of SD particles. (For further discussion consult *Rock Magnetism* and *Thermoremanence*.) These conceptual considerations of the particle size dependence of the remanence stability (relaxation time) were demonstrated experimentally by coercivity measurements of dispersed fine particles of magnetic metals (Fe, Ni, Co), as the grain sizes were increased by progressive heat treatments (e.g., Meiklejohn, 1953; Becker, 1957). Zero initial coercivity in the SPM region is followed by increasing coercivity with particle sizes, presumably in the SD size range,

which then decreases for larger presumably MD particles (Fig. 2). Similar results have also been obtained for magnetite particles.

Haigh (1958) was first to apply Néel's theory and the grain size dependence of the coercivity to rock magnetism, to explain the CRM properties observed during laboratory reduction of hematite to magnetite, where the CRM resided in growing particles of magnetite. Kobayashi (1959) also examined CRM in magnetite obtained from hematite reduction and showed that CRM stability with respect to both alternating fields and thermal demagnetization was much greater than for IRM and very similar to the stability of TRM (Fig. 3). Kobayashi (1961) produced CRM in cobalt grains precipitated from
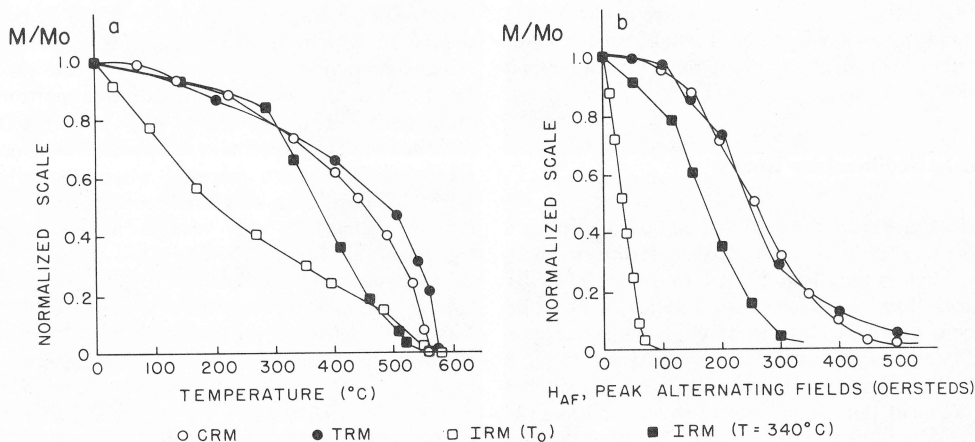

FIGURE 3. (*a*) Thermal, (*b*) alternating fields demagnetization of remanence in magnetite. All remanence measurements were made at room temperature. CRM was produced at 340°C with external field of 3 Oe (*a*), 10 Oe (*b*); total TRM was produced with 3 Oe (*a*), 0.5 Oe (*b*); IRM (T_0) at room temperature was produced with 200 Oe (*a*), 30 Oe (*b*); IRM(T) was produced at 340°C with fields of 20 Oe (a), 10 Oe (*b*). CRM (T = 340°C) and IRM (T = 340°C) were cooled to T_0 in zero field prior to demagnetization. (From Kobayashi, 1959)
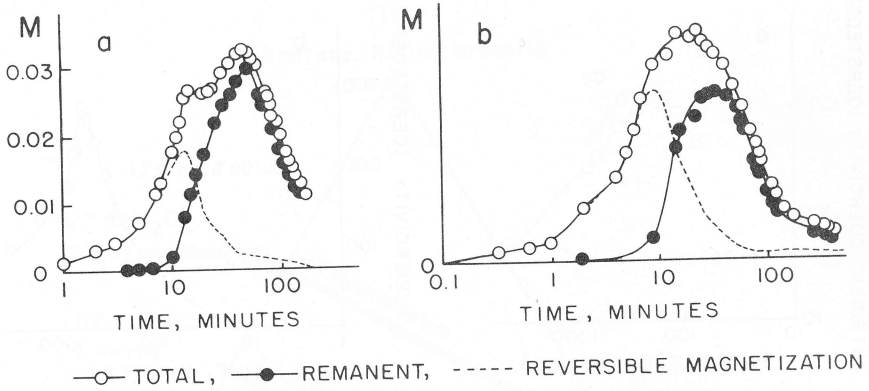
FIGURE 4. Total, remanent, and reversible magnetization of Cu-Co alloy as a function of annealing time (particle size) at 750°C, (measured at 750°C). Experiments were done in external fields of (a) 1 Oe and (b) 20 Oe. The reversible magnetization is the difference between the total magnetization (in presence of an applied field) and the remanence. (From Kobayashi, 1961)

Cu-Co alloy and showed that the specific CRM intensity had a similar bell-shaped grain size dependence as the coercivity, increasing from zero for SPM particles, attaining a maximum value and then decreasing for inhomogeneously magnetized MD particles (Fig. 4).

Evidence has been accumulating during the last few years that nearly pure SD magnetite produced by magnetotactic bacteria may be a significant source of magnetic particles for some marine and lacustrine sediments. The bacterial magnetite is thought to attain its stable SD configuration by biologically mediated grain growth in the bacteria.

Although grain growth is conceptually the simplest form of CRM, it can be used to explain many examples in paleomagnetism, in which the NRM is predominantly a secondary remanence in chemically altered rock, and where new particles of a chemically nucleated magnetic phase have grown beyond the SPM size range.

CRM In Sedimentary Rocks

Oxidized Red Sediments. Red beds comprise a broad category of loosely defined sediments with colors that range from brown to purple, usually resulting from secondary fine particles of hematite or ferric oxyhydroxide. Red sediments have been used extensively for paleomagnetism since the late 1940s, because (1) they are extensively distributed geographically and with respect to geologic time; (2) their bedding orientation can often be inferred from field observations, and (3) their remanence is often stable and sufficiently intense for paleomagnetic measurements, even prior to the development of the super sensitive cryogenic magnetometer. As we noted earlier, already in the 1950s it was deduced that low temperature oxidation was responsible for

removing the original magnetite and the precipitation of fine hematite particles, which give rise to the color and CRM of red beds (Blackett, 1956). Larson and Walker (1975) conducted a detailed study of CRM development during early stages of red bed formation in late Cenozoic sediments; they showed that in their samples CRM resided in several authigenic phases including hematite and goethite. Moreover, the CRM, which obscured the original depositional remanence, had formed over a protracted period spanning more than a single polarity interval, as indicated by the different polarities of the different authigenic phases. Complex patterns of remanent magnetization, associated with several generations of CRM, including multiple polarities within single specimens, have been observed in Paleozoic and Mesozoic red beds. The degree to which the secondary CRM affects the remanence depends on the stability of the precipitated iron oxides and on the relative proportions of authigenic CRM carriers to the primary DRM recorded in detrital particles of specularite hematite. Examples have been reported where the primary DRM in specularite hematite remained the characteristic remanence with respect to CRM (e.g., Collinson, 1974). In some cases distinct CRM components can be isolated by thermal demagnetization, selective leaching in acid (e.g., Collinson, 1967) and selective removal of altered phases of sediment by selective destructive demagnetization, SDD (Larson, 1981).

Nonred Sediments. The discussion in the following paragraphs deals with CRM in a subset of nonred carbonate sediments, whose remanence is usually much weaker than that of red beds. The low intensity remanence of these sediments was one of the main reasons that they were often bypassed for paleomagnetic studies until the introduction in the early 1970s of cryogenic magnetometers with the

ability to measure minute remanence signals, down to the 10^{-9}–10^{-10} Gauss range. Since then, there has been a flourishing of paleomagnetic investigations of weakly magnetized nonred sediments. For example, several studies of early Paleozoic carbonates have shown that the characteristic remanence was acquired in the late Paleozoic, sometimes hundreds of millions of years later than the biostratigraphic ages of the formations (e.g., McCabe et al., 1983). Magnetic extracts from these diagenetically altered sediments contained essentially pure magnetite particles, whose botryoidal and spheroidal forms (Fig. 5) have been used to infer their secondary origin, and they are thought to be responsible for the secondary characteristic remanence of these formations. In the absence of evidence of significant heating of these sediments, their remanence has been interpreted as being predominantly a low temperature CRM in secondary magnetite, which might have been produced by "diagenetic alteration of preexisting iron sulfides (e.g., framboidal pyrites)" (McCabe et al., 1983). For the analogous Miocene dolomites and limestones of the Monterey Formation, Hornafius (1984) concluded that the secondary remanence, presumably a low temperature CRM, resides in diagenetic magnetite produced by the partial oxidation of pyrite upon the introduction of oxygenated meteoric groundwaters to the formation.

The presence of magnetite (and siderite) in oil-impregnated sediments was discovered by Bagin and Malumyan (1976), and by Donovan et al. (1979) reported correspondence of near surface magnetic anomalies over an oil field with a higher concentration of magnetic minerals in the sediments. More recently, paleomagnetic studies of remagnetized hydrocarbon-impregnated Paleozoic sediments (McCabe et al., 1987; Benthien and Elmore, 1987) indicate a relationship between hydrocarbon migration and the precipitation of authigenic magnetite particles, wherein the secondary CRM resides. This scenario is supported by extracted magnetite spherules up to several tens of microns in diameter (Fig. 5) and the presence of other authigenic textures in the sediments. All these studies suggest a net reduction of ferric ions in oxides, hydroxides, and silicates, caused by the biodegradation (oxidation) of the hydrocarbons with a net production of more reduced phases such as magnetite (Fe_3O_4), siderite ($FeCO_3$), and wustite (FeO). Of these, only magnetite is ferrimagnetic, and therefore it is responsible for the measured secondary CRM and also for being preferentially extracted during magnetic separations.
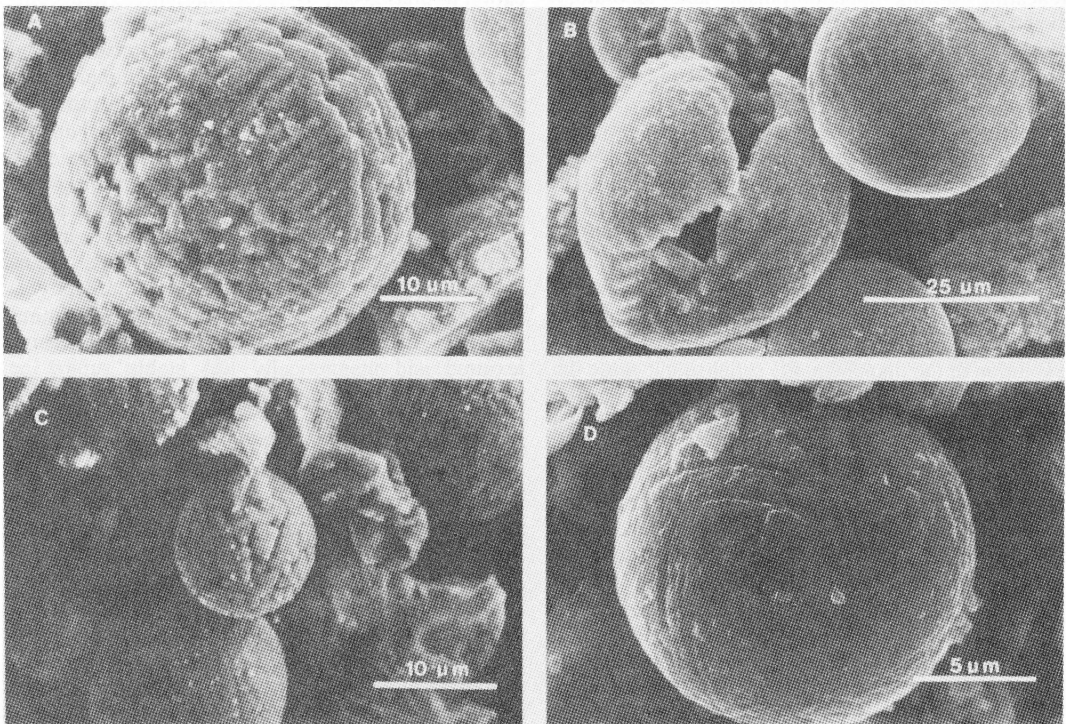

FIGURE 5. Scanning electron micrographs of magnetite crystal aggregates isolated from Thornton Quarry bitumen (A and B), Bonneterre Dolomite (C), and Cynthia Quarry bitumen (D). Many of the spheroidal aggregates have hollow cores. (From McCabe et al., 1987).

Comparisons of the paleomagnetic directions of some of these Paleozoic sediments with available apparent polar wandering paths, suggest that the CRM may have been imparted on the order of 10^8 years after deposition. In contrast, paleomagnetic and rock magnetic studies of Recent hemipelagic sediments, accumulating in suboxic environments (Karlin et al., 1987) indicate the authigenic production of magnetite downcore, as the sediment becomes progressively more reducing, accompanying the oxidative decomposition of organic matter. The time resolution of paleomagnetic results could be significantly reduced in sediments where CRM occurs in authigenic magnetic minerals, formed below the initial fixing depths of the remanence.

CRM in Igneous Rocks

General Considerations. CRM in igneous rocks often results from grain growth of magnetic particles or the transformation of one magnetic phase to another at lower temperatures than the final blocking temperatures of the new magnetic species. Merrill (1975) presented an excellent review of "magnetic effects associated with chemical changes in igneous rocks" in a paper by that title. Grain growth CRM in igneous rocks is often complicated by probable effects associated with temperature changes, such as reheating during metamorphism and laboratory experiments or the slow cooling of an intrusive unit resulting in the exolution of a new magnetic phase.

The direction and intensity of the secondary CRM depends among other factors on the resultant magnetic field and the dominant magnetic interactions at the site of the newly forming magnetic phase. The external magnetic field exerts an important influence; however, if the new phase is created in the presence of an existing magnetic substance with higher blocking temperatures, the CRM will also depend on the magnetic interactions between the various magnetic species. Intimate contact between two magnetic phases such as might occur during exolution of the titanohematite series might cause the CRM to be controlled by local fields produced by the higher blocking temperature phase through magnetostatic or exchange interactions (see *Rock Magnetism*). Occasionally, such interactions might produce CRM of opposite polarity to that of the existing magnetic phase (negative magnetic interactions), and in rare cases a self-reversal may ensue (Néel, 1955) (see *Magnetic Self-Reversal*).

· It is usually difficult to distinguish CRM in igneous rocks from TRM and VRM, because of overlapping stabilities, and also because of possible associations between CRM, partial TRM (PTRM) and high temperature VRM. Consider, for example, grain growth CRM produced at an elevated temperature $T_1 > T_0$, where T_0 denotes room temperature. The CRM carriers have blocking temperatures $T_B > T_1$.

The chemically precipitated particles with $T_B < T_1$ contribute no remanence at T_1. However, on cooling from T_1 to T_0 a PTRM will be blocked in the particles with $T_1 > T_B > T_0$, in addition to the growth of spontaneous magnetization of most magnetic particles. Moreover, ubiquitous time effects might result in significant VRM being superimposed on the CRM. Such commonplace complexities make it difficult to uniquely isolate CRM from other remanences in rocks. Hence, it is probable that CRM occurrences in the paleomagnetic record are considerably more numerous than is usually recognized.

CRM Origin of Marine Magnetic Anomalies. Submarine basalts are an example of igneous rocks that undergo chemical change whereby the initial magnetic phase (titanomagnetite, $x\mathrm{Fe_2TiO_4}$ $(1-x)\mathrm{Fe_3O_4}$) is transformed by topotactic low temperature oxidation at the sea floor to cation deficient titanomaghemites. This reaction is described in Fig. 1 by the arrow to the right, emanating from near the middle of the titanomagnetite series. Horizontal lines in Fig. 1 denote pure oxidation-reduction processes at constant Fe/Ti ratios. Freshly extruded submarine basalts at spreading centers comprise stoichiometric titanomagnetite with $x \cong 0.6 \pm 0.1$, that is, about 60% molar ulvöspinel, with Curie points between 100°–150°C. Oxidation is thought to proceed by a net cation migration out of the crystal lattice, to accommodate the decrease in ferrous to ferric ratio, with possible changes of the Fe/Ti proportions. The resulting cation deficient phase has higher Curie points, up to nearly 500°C, lower saturation magnetization, and diminished lattice size. These time-dependent chemical modifications of the magnetic properties are responsible for the rapid diminution of the observed marine magnetic anomaly amplitudes away from spreading centers. Therefore marine magnetic anomalies over the world's oceans can be considered to be preserved predominantly as CRM in oxidized Fe-Ti oxides. However, the natural remanent magnetization (NRM) of some coarse textured and magnetically less stable submarine basalts is occasionally dominated by VRM, which can frequently be removed by low to moderate alternating field demagnetization.

The consistency of various marine magnetic anomaly time scales and their agreement with polarity time scales from continental lavas and marine sediments, as well as agreement with many oriented dredged and drilled submarine basalts indicate that the CRM is usually of the same polarity as the primary TRM recorded upon extrusion. This result is also supported by several laboratory CRM experiments, which investigated the low temperature oxidation of titanomagnetites (e.g., Marshall and Cox, 1971; Johnson and Merrill, 1974; Özdemir and Dunlop, 1985).

The preservation of marine magnetic anomalies despite ubiquitous low temperature oxidation of submarine basalts suggests that CRM production is not primarily influenced by the external magnetic field, whose effect during protracted oxidation would be expected to shift anomaly boundaries to older ages—greater distances from respective spreading centers. This might lead to systematically older Brunhes/Matuyama boundary ages and a general tendency of obscuring short polarity events or subchrons in marine magnetic anomaly profiles. However, (1) there is a remarkable correspondence between geomagnetic polarity time scales from marine magnetic anomalies, independent sedimentary sections, and subaerial volcanic sequences, and (2) there is no evidence for a systematically older Brunhes/Matuyama boundary age in marine magnetic anomaly records. Consequently, CRM modification of anomaly boundaries by submarine basalt oxidation may not be a significant effect in areas of coherent, "high quality" anomalies.

Alternatively, prevailing positive superexchange interactions during submarine basalt oxidation might successfully explain the above observations. The low temperature oxidation leads to cation depletion and lattice shrinkage, but the titanomaghemites retain the cubic crystal structure of the original titanomagnetite minerals. The superexchange interactions will vary with changes in cation distribution and lattice dimensions, as indicated by the reduced saturation magnetization and higher Curie points. However, it is possible that the orientations of the sublattice magnetic moments of the titanomagnetite minerals remain intact during low temperature oxidation. Therefore the ensuing CRM will retain or inherit the original TRM direction, depending on one's point of view. Hence, positive superexchange interactions between the original stoichiometric titanomagnetite phase and the oxidized titanomaghemites might be an important mechanism for preserving the marine magnetic anomaly patterns, even though the remanence, to a large degree, is CRM.

CRM Control of Paleointensity Determinations. At present, only TRM can be used to determine the absolute paleointensity of the Earth's magnetic field. (See *Paleomagnetic Field: Intensity.*) All the paleointensity methods require that the NRM be essentially a pure TRM, and they all call for laboratory heating of the specimens to produce a new TRM in the known laboratory field. Chemical and mineralogical alterations of the specimens during the laboratory heatings often preclude reliable paleointensity determinations. Therefore, the different paleointensity procedures apply various tests of the magnetization before and after heating to assess the extent of chemical changes on the remanence and paleointensity experiments. Several paleointensity methods require one heating of the specimens to above their highest Curie temperatures to produce a total laboratory TRM. This procedure tends to maximize chemical alterations, because the reaction rates increase at higher temperatures.

In contrast, the Thelliers' double heating method (Thellier and Thellier, 1959) was developed to remedy this problem, by increasing the temperature gradually in steps from room temperature. At each temperature (T_M) two heatings are conducted to determine the thermally demagnetized PNRM and the other for the acquired PTRM between T_M and room temperature. The Thellier procedure depends on the following observed properties of remanence, which have been explained theoretically by the Néel theory for noninteracting SD particles: first, PNRMs and PTRMs produced in different temperature intervals are independent and additive; second, the PNRM and PTRM blocked in any temperature interval are linearly proportional to the external fields in which they were blocked; that is, PNRM (T_0, T_M) = $A_M h$ and PTRM (T_0, T_M) = $A_M h_L$, where A_M is constant for a particular temperature interval (T_0, T_M). h_L is the known laboratory field and h is the unknown paleointensity, which is assumed constant during the original TRM production for rapidly cooled extrusives and archeomagnetic artifacts. Therefore, in the absence of chemical changes on heating, and the satisfaction of the above assumptions the ratio PNRM (T_0, T_M)/PTRM (T_0, T_M) = h/h_L should be the same for each temperature interval; hence, at each temperature step an independent paleointensity value is calculated. Thus, a primary advantage of the Thellier technique is the consistency checks provided by the independent paleointensity estimates at the different temperatures. The results can be shown on a PNRM versus PTRM diagram, with data corresponding to the different temperature steps (Fig. 6). Ideal behavior in the Thellier sense implies linear data with slope equal to h/h_L (line A, Fig. 6). Chemical modifications, which are common at relatively higher temperatures, can often be detected as deviations from the ideal straight line, and often a paleointensity can still be determined by using the linear lower temperature points (e.g., Fig. 6, curve B, $T_1 - T_3$). Another feature of the Thelliers' procedure is that PTRM checks can be conducted. A PTRM check is a repeat PTRM at a lower temperature $T_P \leq T_M$, which provides information about changes in the PTRM capacity due to chemical alterations and CRM production in grains with $T_B \leq T_P$. Therefore, the Thellier method is usually considered to be more reliable than other paleointensity procedures.

High temperature CRM during the Thelliers' paleointensity procedure is one of the more common causes for unsuccessful or abbreviated paleointensity experiments. In these cases a CRM is produced at an elevated temperature $T_M > T_0$ in new magnetic particles with blocking temperatures $T_B > T_M$. In general, the CRM produced at T_M may not be
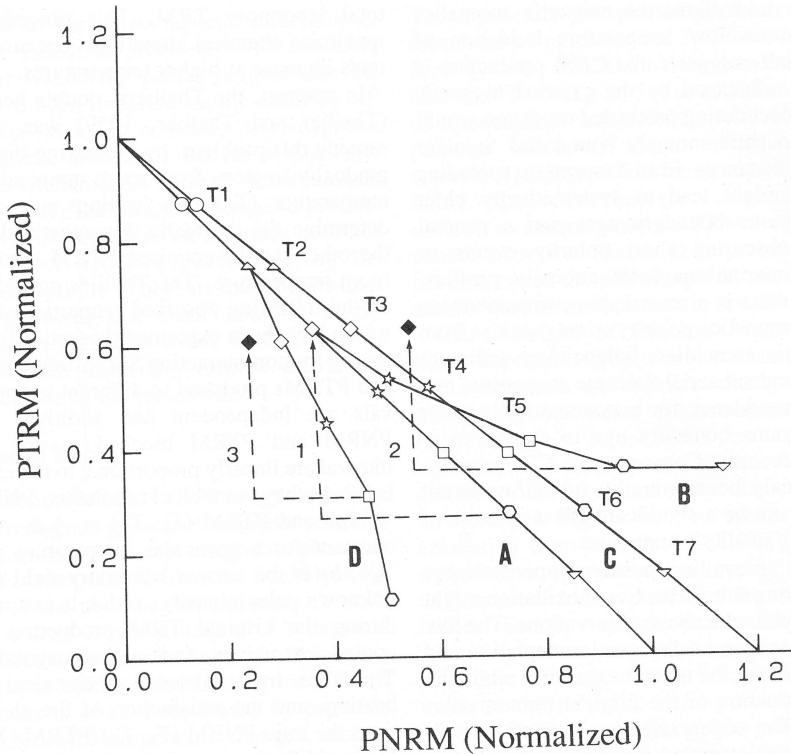
FIGURE 6. PNRM-PTRM diagram for four hypothetical Thellier paleointensity experiments A, B, C, and D, discussed in the text. Like symbols are given to identical temperatures. Dashed lines 1, 2, and 3 indicate PTRM checks between the designated temperatures, corresponding to experiments A, B, and D, respectively. Closed symbols refer to unsuccessful PTRM checks.

completely demagnetized at T_{M+1}, the next higher thermal demagnetization step. The resulting nonideal concave-up PNRM-PTRM diagram is shown in Fig. 6, curve B. A PTRM check at a lower temperature T_P will only detect CRM produced in particles with blocking temperatures $T_B \leq T_P$ (PTRM check 2, Fig. 6). In the special case where CRM is completely demagnetized at the next thermal demagnetization step at $T_{M+1} > T_M$, a linear PNRM-PTRM behavior might result (line C, Fig. 6), provided that proportionately more CRM is produced at progressively higher temperatures. However, these linear data plot above the ideal line of unit slope (line A, Fig. 6), and the calculated paleointensity would be lower than its actual value. This emphasizes that linear PNRM-PTRM data are a necessary but not sufficient condition for obtaining reliable paleointensities.

In the above discussion we considered CRM production that increases the PTRM capacity of the specimen. Such alteration may result from precipitation of new magnetic particles or from unmixing of titanomagnetite grains to a mixture comprising a more Fe-rich phase with higher saturation magnetization. Chemical modifications, which lead to higher

PTRM, usually cause the PNRM-PTRM points to lie above the ideal line, and the calculated paleointensity will be lower than the actual paleo-field. Alternatively, if the chemical modifications decrease the PTRM potential by destroying magnetic particles or by transforming them to have lower intrinsic magnetic moments, then the PNRM-PTRM points will plot below the ideal line, with higher apparent paleointensities than the actual values (e.g., curve D and PTRM check 3, Fig. 6).

Concluding Thoughts

The foregoing CRM article is not meant to be exhaustive, and it reflects some of the interests, biases, and limitations of the author. In the future as paleomagnetists tackle more difficult tectonic and geomagnetic problems, which require information from structurally more complex, metamorphosed, and older formations, it will be increasingly likely that the NRM will be partly CRM. Indeed, paleomagnetists have become more clever at isolating different remanence components by using detailed

and varied demagnetization procedures. It is usually assumed that the most resistant remanence component, whether with respect to increasing alternating fields, elevated temperatures, or a particular leaching agent is also the oldest. However, the current knowledge of CRM is so rudimentary that it is usually not known whether this assumption is correct. A better understanding of CRM is needed to assist paleomagnetists in interpreting complex, often multicomponent, remanence from rocks with probable CRM overprinting. This understanding might be accomplished through controlled field and laboratory CRM experiments for different magnetic minerals: (1) to identify the varied geochemical environments, including pressures and temperatures, necessary to form different magnetic minerals and the associated CRMs; (2) to determine the ranges of magnetic and mineralogical stabilities with respect to thermal demagnetization or with respect to a chosen solvent; (3) to discover the best methods of demagnetization to isolate a particular CRM; and (4) to develop the needed experimental procedures for ascertaining the temporal sequence of multicomponent CRMs. In short, a more thorough knowledge of CRM is required to interpret paleomagnetic records with complex geologic histories, to further the contributions of paleomagnetism to Earth magnetism and tectonic reconstructions.

Acknowledgements

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CONTINENTAL COLLISION ZONES: SEISMOTECTONICS AND CRUSTAL STRUCTURE

Continental collision zones usually develop along convergent plate boundaries when a considerable mass of continental lithosphere that is connected to a subducting oceanic lithosphere collides with an overriding continental plate. This process often results in the development of dramatic surface and subsurface geological processes including major mountain building, continental plateau uplift, and foreland basins. Continental collision episodes ultimately end in changes in the configuration of the nearby plate boundaries. The collision zones then evolve through erosion and isostatic adjustment into mature, relatively inactive orogenic belts. The whole cycle may last tens of millions of years and possibly longer.

The Himalayan and Zagros continental collision zones are often cited in the geological literature as type examples of such processes, and along with the Alpine belt (from Turkey to Spain) probably represent the most active collisional belts during the Cenozoic and Quaternary times. Of course, not all mountain belts are the result of collision between two major continental plates along convergent plate boundaries. Some of the currently most active mountain-building processes are associated with noncollisional (i.e., ocean-continent) convergent plate boundaries, such as the Andes of western South America, or are located in an intraplate setting (i.e., within a continent), such as the Rockies of western North America and the Atlas system of northwest Africa, or are even associated with an extensional tectonic setting, such as the East African rift system. This paper, however, focuses on active collisional mountain belts and specifically on the Himalayan and Zagros collisional zones. It should be emphasized that collision zones, in general, are preceded by

episodes of ocean-continent subduction, producing accretionary prisms, volcanic arcs, back-arc mobilization, and tectonism.

Any discussion of the deep structure and evolution of the Himalayas and Zagros cannot be complete without addressing the nature and evolution of the Tibetan and Iranian plateaus located behind these two collision zones, respectively. These uplifted regions appear to be intimately related to the evolution of the nearby collisional zones, and hence understanding their deep structure is an essential part of deciphering the deep structure of the collisional zones. The following includes a discussion of the seismotectonics and deep structure of the Himalayas and Zagros and a hypothesis on how these two collisional belts may represent different stages in an evolutionary cycle.

The Himalayan Collision Zone

The Himalayan system is the result of collision between the Indian subcontinent and what is now Tibet, about 50 million years ago. The initial contact is represented by the Indus-Tsangpo suture, which was the site of the plate boundary along which the Tethyan oceanic lithosphere that separated India and Tibet was subducted beneath Tibet (see Fig. 1). The Trans-Himalayan (Kangdese) plutons of southernmost Tibet, located just north of the suture, represent the core of the volcanic arc of that annihilated subduction system. Convergence between India and Tibet continued after their initial contact, up to the present (about 5 cm/yr) (Molnar and Tapponnier, 1975) and has resulted in the development of two northerly dipping new intraplate convergent zones: the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT) (Valdiya, 1980). The MCT appears to have developed since about Miocene time with minor, if any, recent movements. It separates the High Himalaya from the Lesser Himalaya. The MBT has developed since about Pliocene time and is still active. It is made up of a series of thrusts that separate the Lesser Himalaya from the Tertiary Siwalik sedimentary belt (the Sub-Himalaya belt) and the adjacent Gangetic foredeep. Thus the impressive Himalayan mountains have developed entirely within the advancing Indian subcontinent during about the last 20 million years. That is, these mountains represent an intraplate deformation located to the south of the initial contact between India and Tibet.

Though most of these surface geological structures are reasonably well investigated at the surface, the behavior of these structures at depth is to a large extent unknown. Knowledge of the architecture of these structures at depth is essential if we want to understand why the High Himalaya has attained its impressive height, and why, for example, the Lesser Himalaya has not developed into a High Himalayan type. Moreover, the estimated convergence between