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3.3 THERMAL METAMORPHISM

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Most chondrites have experienced thermal metamorphism, resulting in changes in texture, mineralogy and possibly chemical composition. The physical conditions for metamorphism range from approximately 400 to 1000° C at low lithostatic pressure. Metamorphism may have resulted from decay of short-lived radionuclides, electromagnetic induction or accretion of hot materials. Several thermal models for chondrite parent bodies have been proposed. The least metamorphosed type 3 chondrites probably carry the most information about the early solar system, but even these have been affected to some degree by thermal processing.

3.3.1. INTRODUCTION

The Van Schmus and Wood (1967) classification scheme for chondrites, already presented in Chapter 1.1 divides meteorites by chemical group and petrographic type (Van Schmus and Wood actually used the term "petrologic type"; "petrographic type" is substituted here to conform with its usage in this book). Most meteoriticists now accept that the textural and mineralogical variations summarized by petrographic types for the most part reflect the effects of thermal metamorphism, that is, the adjustment of rocks to a new set of physical conditions. However, the idea that chondrites are metamorphosed has been contested by some workers since it was first proposed by Merrill (1921). As we shall see, there may be some additional complexities that affect the metamorphic interpretation. Before chondrites can be used to infer conditions in the early solar system, the kinds of changes caused by thermal processing must be thoroughly understood.

3.3.2. TEXTURAL EVIDENCE FOR METAMORPHISM

Recrystallization during metamorphism resulted in progressive blurring of the distinctive chondritic texture, that is, integration of chondrules with matrix, as illustrated in Fig. 3.3.1. This textural change is the most obvious but certainly not the only modification that these meteorites experienced. Increasing metamorphism is also indicated by devitrification of glass in chondrules, growth of secondary feldspar, increase in the proportion of orthopyroxene relative to low-calcium clinopyroxene, and replacement of fine-grained opaque matrix by more transparent recrystallized matrix. Most metamorphic processes appear to have been nearly isochemical in terms of the major-element composition of the bulk sample. However, the compositions of major phases like olivine and pyroxene changed systematically. In general, olivines and pyroxenes tended to become more iron-rich as they underwent chemical exchange with matrix during metamorphism, and their compositional variabilities decreased. Olivines achieved homogeneity before pyroxenes because Fe-Mg diffusion is slower in the latter. Statistical measures of compositional variability for olivine and pyroxene (standard deviation or percent mean deviation) are commonly used to rank chondrites according to their metamorphic grades. This tendency toward homogenization of silicate phases is the basis for the terms "unequilibrated" and "equilibrated", used to describe petrographic types 3 and types 4 through 7, respectively.

Many chondrites are breccias, commonly containing lithic clasts of more highly equilibrated material within hosts of the same chemical group but lower petrographic type (Binns 1968; see also Chapter 3.5). This association, and the lack of mixing between groups, indicate that chondrites of various petrographic types formed within the same parent bodies and were later mixed together by impact processes. Dodd et al. (1967) and Scott et al. (1985) recognized individual chondrules with aberrant olivine compositions in some chondrites without obvious clasts; from this observation, they argued that most chondrites may be unrecognized breccias and that the Van Schmus-Wood classification system does not identify samples with more complex thermal histories. This is probably an extreme viewpoint, although recognition of events in the thermal history is certainly difficult in many cases.

Despite the problem of brecciation, it is possible to assess how wide-

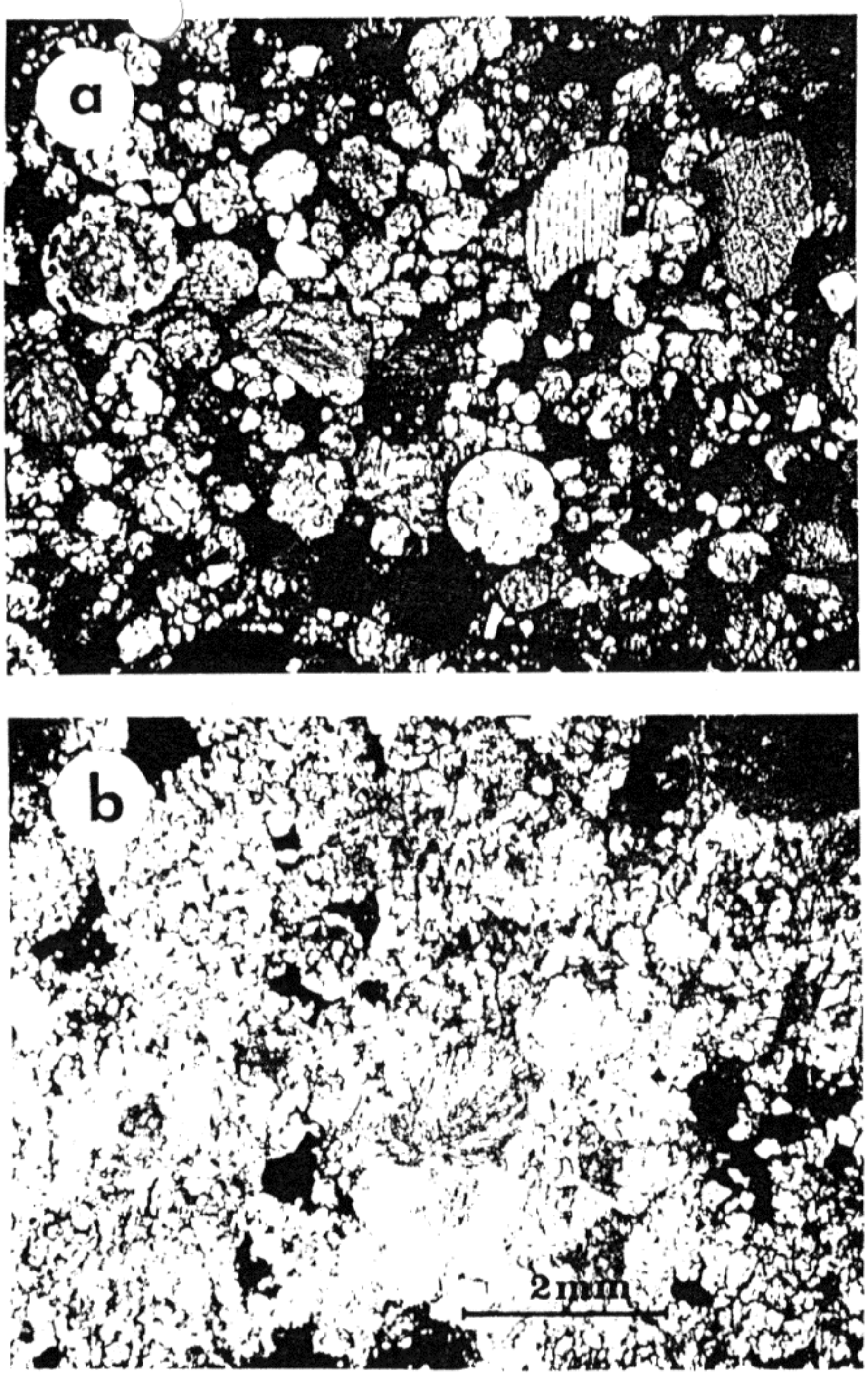

Fig. 3.3.1. Photomicrographs illustrating typical textures of (a) type 3, Tieschitz and (b) type 6, Dhurmsala ordinary chondrites. Recrystallization of type 6 chondrites has blurred the outlines of chondrules. The scale for both photographs is as shown in (b).

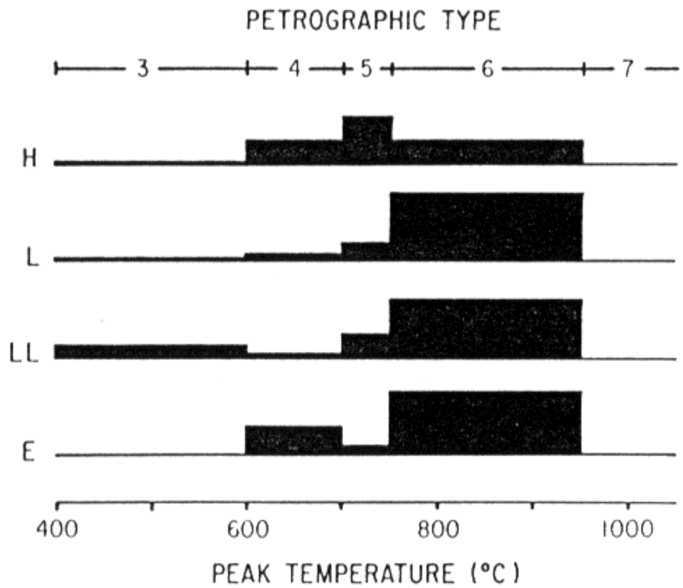

Fig. 3.3.2. The relative proportions of different petrographic types of the various chondrite groups illustrated by histograms of well-classified non-Antarctic chondrites in each category. Classification data are from Motylewski (1978); a few type 7 ordinary chondrites and E3 chondrites are now recognized, but were not included in this compilation. The width of each petrographic type is based on its estimated temperature range from Dodd (1981).

spread the effects of thermal metamorphism are among chondrites of the various chemical groups. Although some recent studies identify the range of petrographic types in chondritic breccias, earlier classifications of chondrites were based on the petrographic types of the most abundant materials. Nevertheless, these data provide at least a rough index of the proportions of unequilibrated and equilibrated chondrites. Petrographic type assignments for well-classified chondrites are summarized in Fig. 3.3.2; Antarctic chondrites are omitted from this tabulation because of uncertainties in pairings. It is clear that equilibrated samples dominate most chondrite classes. For these data to have any significance for parent-body thermal models, we must assume that falls have sampled chondrite parent bodies randomly, yielding the various petrographic types in their correct volumetric proportions, although it is uncertain that this was indeed the case.

3.3.3. TEMPERATURE OF METAMORPHISM

The physical conditions under which chondrite metamorphism occurred are difficult to quantify. Although the metamorphic trend for a group of chondrites forms a continuum, the divisions between petrographic types are arbitrarily based on certain critical petrographic observations, summarized in Chapter 1.1; see Table 1.1.4. These divisions therefore do not necessarily correspond to equal temperature intervals. Chondrite metamorphic temperatures can be bracketed from observations of metal and troilite. The absence of eutectic melting in type 6 chondrites suggests temperatures of less than 950 to 1000° C for such meteorites. Depletion of Fe and S from some type 7 chondrites, from which it has been inferred that a melt fraction was drained off, suggests temperatures at or above this range. Compositions of metal-grain interiors in the least metamorphosed type 3 chondrites suggest maximum temperatures near 400° C. The two-pyroxene geothermometer, based on the temperature-dependent partitioning of Fe and Mg between orthopyroxene and diopside, provides some of the best available estimates of metamorphic temperatures between these limits, but its application is limited by the absence of metamorphic diopside from most meteorites of low petrographic type. The partitioning of Ca between coexisting pyroxenes also varies with temperature. Analyses of equilibrated chondrites using both these thermometers have been summarized by Olsen and Bunch (1984). Phase transformations in feldspar, which can be monitored by certain characteristics of thermoluminescent emission, provide another indication of paleotemperatures (Guimon et al. 1985). While some type 3 ordinary chondrites contain feldspar predominantly in the high-temperature form, others contain predominantly the low-temperature form. Guimon et al. suggest that this boundary within the type 3 group (to which they assign a value of 3.5) coincides with the order/disorder transformation temperature (500–600° C). The distribution of ^{18}O between coexisting minerals is a function of, and has also been used to constrain estimates of temperature (Onuma et al. 1972). Other mineral-exchange geothermometers, specific to one chondrite group or another, have been formulated with mixed success. The approximate ranges for peak metamorphic temperatures for chondrites of types 3 to 7 are summarized in Fig. 3.3.2. Dodd (1981) provides detailed information on the application of geothermometers to chondrites and their uncertainties.

3.3.4. PRESSURES OF METAMORPHISM

Lithostatic pressures during thermal metamorphism, inferred from mineralogy, were invariably low. Although some chondrites show deformation due to stress (see, e.g., Cain et al. 1986), such effects do not appear to correlate with petrographic type (Dodd 1965). Pressures even at the centers of asteroids are less than 2 kbar, and very limited pressure-sensitive chemical substitutions in chondritic pyroxenes are consistent with this interpretation. Pyroxene components measured by Heyse (1978) are very close to analytical uncertainties and more work of this kind is needed. Heyse argued nonetheless that systematic variations in such substitutions with increasing temperature in LL-group chondrites indicate that metamorphic intensity increased with depth in the parent body. In this model, petrographic type should be inversely correlated with cooling rate, because deeply buried rocks would cool more slowly than those near the surface. Meteorite cooling rates can be inferred from the retention of fission tracks in different minerals (see, e.g., Pellas and Storzer 1977) or the zoning profiles of Ni in metal grains (Wood 1967). In the case of LL-group chondrites, cooling rates based on fission tracks agree with Heyse's conclusion, but metallographic cooling rates do not. From a synthesis of cooling rates based on metallographic data, Scott and Rajan (1981) suggested that metamorphic intensities are not related in any straightforward way to burial depths within parent bodies. The issue is clouded further by the problem that cooling rates determined by the metallographic and fission track techniques do not agree with those that appear to be required by K-Ar and ^{40}Ar-^{39}Ar isotopic dating (Wood 1979). The relationship, if any, between temperature and pressure in chondrite parent bodies remains an unsolved problem, though an important one because of its implications for asteroid thermal models.

3.3.5. LACK OF METAMORPHIC FLUIDS

The persistence of many of the same minerals in chondrites throughout the metamorphic sequence is very different from the terrestrial metamorphic experience and can be explained by the virtual absence of fluids (H_2O and CO_2). This in turn may explain why type 6 chondrites contain some relict textures. Equilibrated chondrites contain no hydrous or carbonated phases, and earlier accounts of fluid inclusions contained in them have now been discounted (Rudnick et al. 1985). The apparent absence of fluids from ordinary and enstatite chondrites is consistent with their very low measured or calculated oxygen fugacities. Carbonaceous chondrites might be expected to have contained a fluid phase during metamorphism because some of them contain hydrated phyllosilicates and carbonates at low grade, but the properties of type 4 carbonaceous chondrites are very similar to those of the anhydrous classes (Scott and Taylor 1985). Fluids undoubtedly played a role in altering some chondrites at very low temperatures (see Chapter 3.4), but they must have been largely driven off at or below the onset of thermal metamorphism.

3.3.6. METAMORPHIC HEAT SOURCES

The source of heat for chondrite parent body metamorphism is still controversial. The most commonly held view is that initially cool material accreted to form parent bodies and was subsequently heated. Peak temperatures were obtained within a few tens of millions of years. Similar Rb-Sr ages for equilibrated and unequilibrated chondrites constrain metamorphism to have occurred soon after chondrite formation, because these ages are reset by thermal effects. Decay of short-lived radionuclides such as ^{26}Al (Lee et al. 1976) is a plausible heating mechanism, although external heat sources such as electromagnetic induction by a massive solar wind (Sonett et al. 1970) have also been suggested. Note that a body heated internally by radioactivity should show an increase in metamorphic intensity with depth, whereas an object externally heated by induction may show the opposite trend. An alternative view to these heating mechanisms for asteroidal parent bodies after they are assembled is that small, rapidly accreted clumps of chondritic material were metamorphosed by residual heat from condensation; Larimer and Anders (1967) suggested that accretion at varying temperatures would explain the different petrographic types. This kind of model can also be adapted to larger parent bodies. For example, Heyse (1978) favored continuous accretion of hot material onto a progressively cooling body of asteroidal size. One test that might distinguish among some of these models would be to establish whether oxygen fugacity varied systematically with petrographic type. If metamorphism was caused by accretion during condensation, more oxidizing conditions would have obtained as the temperature fell. Another test involves determining the relationship, if any, between temperature and pressure during metamorphism (Heyse 1978).

3.3.7. PARENT-BODY THERMAL STRUCTURES

Thermal models for several chondrite parent bodies have now been formulated based on information concerning heat sources, peak metamorphic temperatures, and the relative proportions of various petrographic types. From the discussion above, it should be clear that these models are highly speculative because of gross uncertainties in all of these input parameters. The orthodox view of chondrite parent bodies is the "onion-shell" model, in which internal heating has produced a succession of concentric layers of different petrographic type grading from equilibrated material in the interior to unequilibrated at or near the surface. Miyamoto et al. (1981) constructed onion-shell models for ordinary chondrite parent bodies, one of which is illustrated in Fig. 3.3.3a. A feature of this model is that the volume fraction of each petrographic type matches very closely the distribution of petrographic types among classified falls; this, of course, assumes random sampling of chondrite parent bodies.

In order to explain the absence of a correlation between petrographic type and metallographic cooling rate, Scott and Rajan (1981) formulated an entirely different kind of parent body model, called the "rubble-pile". They hypothesized that peak metamorphic temperatures were reached during, rather than after, accretion, so that metamorphism occurred in small planetesimals. These were subsequently assembled into composite asteroid-sized bodies in which the metallographic cooling rates were controlled by burial depth. A sketch of a rubble-pile parent body is given in Fig. 3.3.3b. Wood (1979) attempted to circumvent the problem of lack of correlation between the metallographic cooling rate and that seemingly required by ^{40}Ar-based age

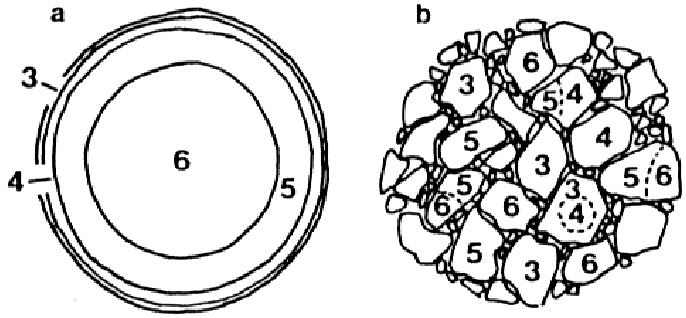

Fig. 3.3.3. Thermal models for ordinary chondrite parent bodies: (a) an onion-shell model for the H chondrite parent body calculated by Miyamoto et al. (1981), with concentric shells of petrographic types; (b) sketch of a rubble-pile parent body advocated by Scott and Rajan (1981).

dating by invoking parent bodies coated with thermally insulating particulate matter. In this model, cooling to the temperature for Ar isotopic diffusion to cease occurred rapidly in small planetesimals; these were then accreted into larger, insulated bodies for further cooling through the temperature at which metallographic cooling rates were set. Grimm (1985) concluded that rubble-pile models are only applicable to highly insulating, ^{26}Al-rich planetesimals that can accrete without being shattered by impact. He advocated a hybrid model in which onion-shell parent bodies were collisionally fragmented during metamorphism and then gravitationally reassembled on a short time scale.

3.3.8. METAMORPHIC REDISTRIBUTION OF VOLATILES

Recognition of the effects of thermal metamorphism in chondrites has some important implications for our ability to decipher the information carried in these meteorites. As one example, the concentrations of trace elements with different volatilities can, in principle, provide important constraints on the condensation process in the early solar system; however, many of these elements are thermally mobile so that their abundances may have been changed during metamorphism (see Chapter 7.6). Gas permeabilities of some chondrite classes are high enough that volatile elements within them may have exhibited open-system behavior (Sugiura et al. 1984). Inverse correlations between abundances of the noble gases and petrographic type are now firmly established. Larimer and Anders (1967) argued that the volatile-element distributions were established during condensation and are unrelated to metamorphism. However, Dreibus and Wänke (1980) suggested that such elements may have been mobilized from parent-body interiors and ultimately deposited in the cooler exterior regions.

Differences in the carbon contents and oxygen isotopic compositions of unequilibrated and equilibrated ordinary chondrites have been explained by oxidation and subsequent loss of C in the form of CO during metamorphism (Clayton et al. 1981). Calculations suggest that it may also be possible to transport other elements like bismuth, thalium and indium, known to be inversely correlated with petrographic type (Sugiura et al. 1985), but uncertainties in the thermodynamic data used in such calculations limit their usefulness. Ikramuddin et al. (1977) attempted to distinguish between volatile (in the sense of condensation) and mobile (in the sense of metamorphism) trace elements experimentally. These kinds of behavior are different, in that volatility is calculated from thermodynamics and mobility is a kinetic process that is measured empirically. The order of some element mobilities suggested by heating experiments (summarized more fully in Chapter 7.6) is Te < Bi < In < Zn < Tl < Cd; the comparable volatility sequence is Te < Zn < Cd < Bi < Tl < In (Chapter 7.6). Apart from Cd, the most mobile (but not most volatile) elements appear to be correlated with petrographic type (Lipschutz et al. 1983), and temperatures in the uppermost parent body regions may simply have been too high for Cd redeposition. Supercosmic abundances of some highly mobile elements in type 3 chondrites (Lipschutz et al. 1983) may also be evidence that at least some elements have been redistributed during parent-body heating. No definitive conclusions can be made concerning the mobilization of elements during metamorphism, but it remains an intriguing possibility.

3.3.9. METAMORPHISM IN UNEQUILIBRATED CHONDRITES

Because of potential changes in the petrography, chemical composition and isotopic systems of chondrites during thermal metamorphism, it is of obvious importance to identify and concentrate our efforts on the least altered meteorites. However, even type 3 chondrites have experienced various degrees of mild thermal processing. Dodd et al. (1967) used the dispersion of olivine compositions in unequilibrated ordinary chondrites as a criterion for metamorphic ranking of these meteorites. Huss et al. (1981) proposed subdivisions for these chondrites based on changes in matrix, and Afiattalab and Wasson (1980) offered a subclassification based on metal compositions. McSween (1977) identified a metamorphic sequence within one class of type 3 carbonaceous chondrites (CO3), based on systematic changes in metal and matrix compositions and subtle textural blurring. At present, the most useful scale for assessing the degree of metamorphism within type 3 ordinary chondrites is based on changes in thermoluminescence (TL) discovered by Sears et al. (1980). TL sensitivity for ordinary chondrites increases markedly with petrographic type, and type 3 chondrites exhibit an especially large range, as shown in Fig. 3.3.4. This behavior reflects the formation of secondary feldspar, which acts as a TL phosphor, during metamorphism at modest temperatures. Based on the excellent correlations between TL sensitivity and olivine compositions, metal compositions, degree of matrix recrystallization, and

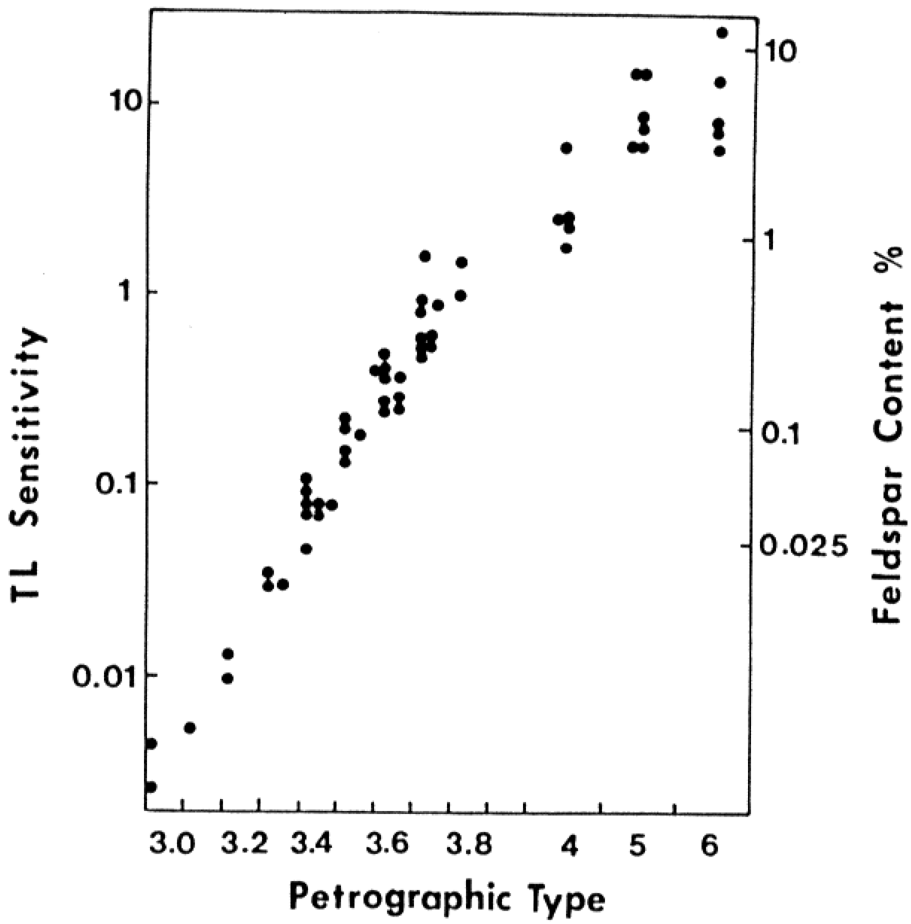

Fig. 3.3.4. Plot of thermoluminescence (TL) sensitivity (relative to that of Dhajala = 1) vs petrographic type for ordinary chondrites, after Sears et al. (1980). The large TL range exhibited by type 3 chondrites provides a means of subdividing them according to their thermal histories. TL sensitivity is a function of devitrification of glass to form feldspar, as illustrated by the right-hand axis of this diagram.

carbon and noble gas contents, Sears et al. (1980) assigned type 3 ordinary chondrites to ranks of 3.0 to 3.9 with increasing metamorphism. Complications in TL patterns, introduced by aqueous alteration or shock, make the classification of some chondrites ambiguous. The TL sensitivity is more complex in carbonaceous chondrites than in ordinary chondrites, but Keck and Sears (1985) also found systematic changes within the CO3 group that correlate with McSween's (1977) proposed sequence. Enstatite chondrites of petrographic type 3 are so uncommon that an analogous study has not yet been done for this group. It would be desirable to be able to subdivide equilibrated chondrites into finer subdivisions as well (using, for example, feldspar grain size), but little work of this type has been done.

3.3.10. SUMMARY

The metamorphic process in chondrite parent bodies is not well understood, but it is of crucial importance that its effects be recognized and quantified. Important problems yet to be solved include determining whether chondrite metamorphism occurred in a closed or open system, and quantifying pressure effects and possible correlations with temperature. The present classification system based on discrete petrographic types is serviceable, but it should be replaced by one that recognizes the gradational nature of the metamorphic process, such as a continuous scale based on maximum temperature attained. The apparent lack of correlation between cooling rates and petrographic type must be investigated further, and its implications understood. Finally, more refined thermal models for asteroids are needed. Without an appreciation of chondrite metamorphism, the usefulness of these meteorites as probes of early solar system processes and events is very limited.

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