

Do

N86-23499

**PRIMORDIAL MATERIAL IN METEORITES**

John F. Kerridge  
Institute of Geophysics  
University of California  
Los Angeles  
California 90024

**PRECEDING PAGE BLANK NOT FILMED**

**PAGE 70 INTENTIONALLY BLANK**

Introduction

"Primordial" is a term which we apply here to material that entered the solar system early and became incorporated into a meteorite without totally losing its identity. Identification of such material surviving in meteorites has so far been solely through recognition of anomalous isotopic compositions of generally macroscopic entities (e.g. inclusions) contained within those meteorites. Those entities are inferred to have incorporated some fraction of primordial particles but the particles themselves may well have been altered beyond present recognition. In the majority of cases, the actual primordial particles have not, in fact, been convincingly identified. In some cases the primordial material was a gas which escaped homogenization with protosolar gas and whose isotopic composition was inherited by a surviving solid phase.

The search for primordial material is therefore the search for isotopic anomalies in meteorites. Isotopic anomalies are, by definition, isotopic compositions which differ from the canonical "solar system abundances" in ways which cannot be explained in terms of local (i.e. solar system) processes such as mass-dependent fractionation, cosmic-ray-induced spallation or decay of radionuclides.

A comprehensive account of isotopic anomalies is impractical here, so it is necessary to be selective. A useful approach seems to be to focus on issues which are potentially addressable through the study of such primordial material. Those issues will be illustrated with specific, but not exhaustive, examples.

Note: Many of the extant anomalies were not originally sought as such but emerged in the course of other investigations. Also, in addition to recognizing an anomaly and identifying, where possible, its host phase, it is generally necessary to consider possible perturbation of the record by secondary alteration processes and to assess the possibility of the isotopic effect having been produced by a purely local process.

### Carbonaceous Chondrites

Most isotopic anomalies observed so far have been found in meteorites known as carbonaceous chondrites. The chemical compositions of those meteorites are minimally altered away from our best estimate of "solar system elemental abundances" [Anders and Ebihara, 1982]. The idea has therefore developed that many of the lithic constituents of those meteorites are themselves more or less pristine surviving nebular condensates. (The meteoritic record is generally interpreted in terms of an initially hot and vaporized inner solar system which subsequently cooled permitting nucleation and growth of solid particles that eventually accreted into planetesimals, the meteorite parent bodies, currently identifiable as asteroids.) However, for relatively few of the macroscopic constituents of carbonaceous chondrites is identification as a pristine nebular condensate convincing, the evidence seeming in most cases to favor a relatively complex evolution.

Carbonaceous chondrites are, in fact, breccias, i.e. disequilibrium mixtures of lithic, and organic, components which may have experienced a variety of primary and secondary processing, such as aqueous alteration and/or thermal

metamorphism, prior to final compaction in their parent body regoliths [Kerridge and Bunch, 1979; McSween, 1979; Bunch and Chang, 1980]. Coexistence now of two entities in such a meteorite is no guarantee of any common history before final compaction.

Crystallization of several mineral phases in carbonaceous chondrites, including some formed by aqueous alteration, occurred very close to solar system formation at 4.55Gy ago [Gray et al., 1973; Tatsumoto et al., 1976; Macdougall et al., 1984]. Compaction of carbonaceous chondrites into their current configuration apparently took place over an interval from 4.5 to 4.3Gy ago [Macdougall and Kothari, 1976].

We now consider five issues which may be studied via isotopic anomalies in carbonaceous chondrites.

#### Nebular Inhomogeneity

This issue is addressed using the isotopic composition of oxygen and titanium in certain types of meteorite, their inclusions and minerals. Oxygen data for a suite of calcium-aluminum-rich inclusions (CAIs, described below) from the Allende meteorite are shown in Figure 1 [Clayton et al., 1985]. Mass-dependent fractionation, as in most chemical and physical processes, acting on nominally "solar system" oxygen can only generate isotopic compositions which lie along the dashed line with a slope close to 0.52 [Matsuhisa et al., 1978]. Therefore, deviation of the CAI data from that line constitutes evidence for isotopic inhomogeneity in the solar system at the time these

meteoritic samples achieved their present composition. Before showing that these data imply existence of at least three isotopically distinct reservoirs of oxygen in the early solar system, two of them gaseous, we must briefly describe the CAIs, in which so many isotopic anomalies have been observed.

#### Calcium-Aluminum-rich Inclusions

CAIs are light-colored mm- to cm-sized inclusions embedded in the dark, volatile-rich matrix of certain carbonaceous chondrites. They are enriched in elements, such as Ca, Al, Ti and the Rare Earths, which are believed to have behaved as refractory lithophiles in the early solar system [Grossman, 1980]. For several years they were interpreted as some of the earliest material to have condensed during cooling of an initially vaporized solar nebula [e.g. Grossman and Larimer, 1974]. More recent work, however, has indicated greater complexity than an origin by simple equilibrium condensation from a gas of solar composition [e.g. Wark and Lovering, 1982; Stolper, 1982; Meeker et al., 1983; Kornacki and Wood, 1984; Clayton et al., 1985].

The CAI oxygen data define a trend which can only be produced by either non-mass-dependent fractionation (discussed later) or mixing of nucleogenetically distinct reservoirs (the currently preferred interpretation). That mixing is most likely to have been caused by isotope exchange between inclusion material and an external gaseous reservoir characterized by a different isotopic composition. The individual minerals within a CAI frequently exhibit a spread in isotopic values even greater than that of the inclusions themselves, see Figure 2a. Minerals such as melilite, which are known to

exchange oxygen readily with a gas, are found to be  $^{16}\text{O}$ -poor relative to those, such as pyroxene or spinel, which are more resistant to exchange. Exchange is therefore inferred to have been between an  $^{16}\text{O}$ -rich solid and an  $^{16}\text{O}$ -depleted gas, as illustrated in Figure 2b. The locations of the end-members along the trend line are inferred from various lines of evidence [Clayton et al., 1985].

In contrast to oxygen, the major cations, silicon, magnesium and calcium, in CAIs reveal evidence for mass-dependent fractionation [Niederer and Papanastassiou, 1984; Clayton et al., 1985], as illustrated in Figure 3 for Si. The fractionation trends for the different elements do not generally correlate and imply a complex series of evaporation and/or condensation episodes during the evolution of the CAIs. Those episodes must have disturbed the oxygen isotopic composition, and therefore presumably preceded the isotope exchange episode, described above, because oxygen currently shows no evidence for such mass-fractionation. Thus, it seems likely that the prevalent  $^{16}\text{O}$ -rich solid, identified above, was produced by exchange with the ambient gas during the evaporation/condensation episodes. At the high temperature implied by the cation fractionation, close approach to the isotopic composition of the gas seems likely so that existence of a gaseous reservoir close to that marked 1 in Figure 2b seems probable [Clayton et al., 1985].

In addition to the two gaseous reservoirs implied by the CAI data, one further reservoir, apparently a solid phase, may be inferred from the oxygen data for chondrules from primitive meteorites. Chondrules are spheroidal particles, generally polymineralic and with diameters usually in the range a

tenth to one mm, which are prevalent in most chondritic meteorites. Their textures reveal that they were at least partially molten and their compositions show that their precursor materials had experienced little, if any, elemental fractionation from solar abundances for the condensible elements. Although the exact heating mechanism is still unclear, it is generally believed that chondrules were made by localized melting of small solid particles, of either nebular or primordial origin, in the early solar system, probably before substantial accretion of planetesimals [King, 1984].

Chondrules from ordinary and carbonaceous (CV) chondrites show different trends on an oxygen three-isotope plot, as illustrated in Figure 4 [Clayton et al., 1985]. Both apparently define mixing lines, presumably reflecting greater or lesser degrees of exchange between the molten chondrule and its gaseous environment. For CV chondrules, those whose petrography shows that they were only partially molten are more  $^{16}\text{O}$ -rich than those which were completely melted, indicating that initially  $^{16}\text{O}$ -rich solids, designated 4' in Figure 2c, were heated while embedded in an  $^{16}\text{O}$ -depleted gas, 2 in Figure 2c. Similar arguments for ordinary chondrites suggest that their chondrules were made by heating, in the same gas, solids which were yet more depleted in  $^{16}\text{O}$ , 3 in Figure 2c. Chondrules from a third group of meteorites, the enstatite chondrites, also define the same gaseous reservoir [Clayton and Mayeda, 1985]. It seems logical to relate reservoirs 2 and 2' to each other, and to terrestrial oxygen, by mass-dependent fractionation. The precursor material for the CV chondrules, 4' in Figure 2c, can be identified with material lying on the CAI mixing line and does not, therefore, require a third discrete reservoir, but the chondrule trend line for ordinary chondrites requires existence of a

third, solid, reservoir, depleted in  $^{16}\text{O}$  relative to the others, 3 in Figure 2c.

In conclusion, the oxygen data seem to require existence of a minimum of one solid and two gaseous reservoirs in the early solar system, Figure 2d. Whether these all coexisted or whether they represent successive additions to the solar neighborhood is not known, nor is the chemical identity of any of the reservoirs.

In addition to interpretation of the oxygen data in terms of discrete nucleogenetic components, it has been suggested that the data may reflect non-mass-dependent isotopic fractionation in the early solar system. Evidence in support of this view has come from experimental studies of ozone synthesis by a spark discharge acting on molecular oxygen [Thiemens and Heidenreich, 1983]. The isotopic compositions of the product ozone and the residual oxygen are shown in Figure 5, and reveal a trend line with a slope of unity, not the mass-dependent slope of 0.52. The reaction pathways involved in ozone production are quite complex and the actual mechanism responsible for the non-linear fractionation is not fully clear. The fractionating step is apparently neither the initial dissociation of the oxygen molecule nor the (partial) decomposition of the product ozone, but probably involves some metastable intermediate species and may be related to the longer lifetime of heteronuclear species relative to the symmetric homonuclear species [Heidenreich and Thiemens, 1985].

Although the experimental observations are certainly real, their relevance to meteoritic data is less clearcut. The existence of a suitably fractionat-



ing environment in the early solar system has not been demonstrated, nor has a mechanism for efficient trapping of the fractionated products. However, it would be premature to rule out such an interpretation.

Anomalous Ti isotopic compositions are ubiquitous among Allende CAIs and also present in some other meteoritic samples. The dominant anomaly is an excess of  $^{50}\text{Ti}$ , up to 28 parts in  $10^4$ , but more subtle effects are also apparent, including deficits in  $^{47}\text{Ti}$  and, in some chondrules from unequili- brated ordinary chondrites, in  $^{50}\text{Ti}$  [Niemeyer and Lugmair, 1984]. At least four isotopic components are needed to account for the Ti data, though the nature of those components in the early solar system cannot yet be specified. Preservation of the anomalous components as a "chemical memory" in presolar grains [Clayton, 1982] seems to be indicated [Niemeyer and Lugmair, 1984].

#### Nucleosynthetic Time Scales

Isotopic anomalies generated by decay of now-extinct radionuclides can be used both to resolve small time differences between events in the early solar system, and to define the time interval,  $\Delta$  in Figure 6, between the end of an episode of nucleosynthesis and the formation of solid objects within the solar system itself. We consider here two examples of the latter application.

The first utilizes several very short-lived radionuclides to place limits on when a "last gasp" of intermediate mass nuclides was produced. A lower limit on that  $\Delta$  may be derived from an apparent lack of  $^{41}\text{Ca}$  in the early solar system. A search in K-poor, Ca-rich minerals from apparently ancient

CAIs in Allende revealed a hint of radiogenic  $^{41}\text{K}^*$ , possibly correlated with Ca/K ratio, but it was deemed not statistically significant and is currently interpreted as corresponding to an upper limit on  $^{41}\text{K}^*/^{40}\text{Ca}$  of  $8 \times 10^{-9}$  [Hutcheon et al., 1984]. This would yield a lower limit to  $\Delta$  of  $1.8 \times 10^6$  years.

A model-dependent upper limit on  $\Delta$  may be inferred from evidence for  $^{26}\text{Mg}$  excesses apparently derived from decay of  $^{26}\text{Al}$ . For many, but not all, CAIs from Allende and similar meteorites, those excesses correlate with Al/Mg ratios to give an apparent  $^{26}\text{Al}/^{27}\text{Al}$  ratio of  $5 \times 10^{-5}$ , see Figure 7 [Wasserburg, 1985]. Some inclusions yield other values for the  $^{26}\text{Al}/^{27}\text{Al}$  ratio, including a few which give a null value, within error. It is not clear whether different values reflect time differences or heterogeneous distribution of  $^{26}\text{Al}$ .

If it is assumed that the  $^{26}\text{Al}$  was synthesized in a single event close to the birth of the solar system, the  $5 \times 10^{-5}$  value, if characteristic of a significant fraction of solar system material, leads to a probable upper limit for  $\Delta$  of  $3 \times 10^6$  years, given a production ratio for  $^{26}\text{Al}/^{27}\text{Al}$  of about  $10^{-3}$ . Support for this assumption has been inferred from the apparent association of two other radionuclides with  $^{26}\text{Al}$  in the early solar system [Wasserburg, 1985]. Many iron meteorites, apparently formed in the cores of several small differentiated asteroids, reveal evidence of excesses of  $^{107}\text{Ag}^*$  which correlate with Pd content, indicating that they were derived from decay of  $^{107}\text{Pd}$  [Kelly and Wasserburg, 1978]. A value of  $2 \times 10^{-4}$  for  $^{107}\text{Pd}/^{108}\text{Pd}$  is commonly observed. A similar value, from 0.7 to  $1.7 \times 10^{-4}$ , is calculated for

the ratio  $^{129}\text{I}/^{127}\text{I}$  in many meteoritic materials, based on their contents of radiogenic  $^{129}\text{Xe}^*$  which correlate with I content [e.g. Niemeyer, 1979; Jordan et al., 1980; Hohenberg et al., 1981].

From the similar fractional abundances of these three radionuclides with very different mean lives, it is inferred that their production and injection into the early solar system were closely related, and that they represent a "last gasp" addition amounting to about 0.01% of the mass of the solar system [Wasserburg, 1985]. However, other explanations for the  $^{26}\text{Mg}^*$  excess have been proposed. One involves a "chemical memory" due to presolar decay of  $^{26}\text{Al}$  in Al-rich circum- or interstellar grains which were subsequently incorporated into the meteorites [e.g. Clayton, 1982]. Alternatively, there is evidence [Mahoney et al., 1984] for a significant steady-state level of  $^{26}\text{Al}$  in the interstellar medium, apparently nova-produced, which, if incorporated promptly into the protosolar-system, might explain the meteoritic data [Clayton, 1984; 1985].

The second example uses two relatively long-lived extinct actinides to place limits on  $\Delta$  for the last substantial addition of real r-process material to the early solar system. The lower limit is supplied by the failure, so far, to find evidence for the existence of live  $^{247}\text{Cm}$  in meteoritic material. The decay chain of  $^{247}\text{Cm}$  passes through  $^{235}\text{U}$ , so that the former presence of  $^{247}\text{Cm}$  would be manifested by an anomalously high value of  $^{235}\text{U}/^{238}\text{U}$ . Despite occasional reports of such  $^{235}\text{U}$  excesses, a conservative interpretation of the extant data places an upper limit on  $^{247}\text{Cm}/^{235}\text{U}$  of  $4 \times 10^{-3}$ , corresponding to a lower limit to  $\Delta$  of about  $10^8$  years [Chen and Wasserburg, 1981].

The upper limit on  $\Delta$  comes from abundant evidence for the presence of live  $^{244}\text{Pu}$  in the early solar system. Decay of this nuclide produces fission tracks in minerals and also xenon with a characteristic isotopic spectrum. Both phenomena have been observed, either individually or correlated in the same samples, in a wide variety of meteoritic material. Precise calculation of the actual  $^{244}\text{Pu}$  abundance at the moment of formation of the solar system is made difficult by the lack of another, extant, Pu isotope and the fact that Pu has been chemically fractionated during formation of most, if not all, of the samples analyzed to date. Nonetheless, there is reason to believe that the ratio  $^{244}\text{Pu}/^{238}\text{U}$  was about  $10^{-2}$  at 4.6 Gy ago. This leads to an upper limit on  $\Delta$  of about  $5 \times 10^8$  years and indicates that the final injection of pure r-process material, amounting to a few percent of the ambient medium, took place between 1 and  $5 \times 10^8$  y before solar system formation [Wasserburg, 1985].

### Nucleosynthetic Details

Laboratory analysis of a component believed to have a specific nucleosynthetic origin can, through its superior precision, illuminate details of that nucleosynthesis which would not be accessible to either astronomical measurement or astrophysical calculation. Two examples will illustrate this approach.

The first example involves analysis of two petrographically unexceptional but isotopically unusual CAIs, known as EK 1-4-1 and C-1, respectively. Figure 8 shows the isotopic compositions of two Rare Earth elements, neodymium

and samarium, for these inclusions [McCullough and Wasserburg, 1978a,b; Lugmair et al., 1978]. Substantial deviation from normal solar system values is evidenced by EK 1-4-1, with C-1 showing only a monoisotopic excess at  $^{144}\text{Sm}$ . By normalizing to the two s-process nuclides  $^{148,150}\text{Sm}$ , the EK 1-4-1 data can be seen to consist of enrichment of p-process  $^{144}\text{Sm}$  and of a series of r-unshielded nuclides the distribution of which closely matches that of average solar system r-process material, see Figure 9 [Lugmair et al., 1978]. The conclusion is therefore that EK 1-4-1 contains an above-average concentration of canonical r-process nuclides, and that both EK 1-4-1 and C-1 contain a p-process excess. Coincidence of r- and p-process excesses in one inclusion and a sole p-process enrichment in the other shows that the two processes are not necessarily coupled. Note that the physical/chemical form in which the alien material entered the solar system has not been revealed by analyses to date.

The second example involves analysis of constituents of carbonaceous chondrites quite different from the CAIs which have dominated discussion so far. When these meteorites, and also some unequilibrated ordinary chondrites, are largely demineralized by dissolving the bulk of their lithic fabric in HF/HCl, a tiny residue is left which contains a very high proportion of the primordial noble gas inventory of the meteorite. By a variety of procedures, this noble gas population can be separated into a number of isotopically distinct components, some of which are mundane but others of which reveal isotopic compositions which are believed to be of nucleogenetic origin. The main solid species comprising such an acid-resistant residue are organic matter, elemental carbon, spinel and chromite. We consider here a C component, apparently

emanating from a red giant star, which tells us something about nucleosynthesis in at least one star of that type, and in the next section we discuss what that and other components can reveal about condensation processes in various astrophysical environments.

During stepwise release of Xe from an acid-resistant residue from the Murchison carbonaceous chondrite, a very small fraction of gas revealed an isotopic composition quite distinct from any previously found, Figure 10 [Srinivasan and Anders, 1978]. In every detail it matched very closely the composition of Xe calculated to be produced by the s-process in a red giant [Clayton and Ward, 1978]. Its probable host phase appeared to be elemental C with an unusual isotopic composition ( $^{12}\text{C}/^{13}\text{C} = 42$  [Swart et al., 1983]) which was also consistent with origin in a red giant, thus making such an origin seem very likely. The anomalous Xe in this component was accompanied by krypton which was also anomalous,  $^{86}\text{Kr}$  being distinctly enriched over the normal solar system value [Matsuda et al., 1980]. This is of interest because the s-process precursor of  $^{86}\text{Kr}$  is radioactive  $^{85}\text{Kr}$  with a mean life of about 15 years. Persistence of  $^{85}\text{Kr}$  to an extent capable of building up  $^{86}\text{Kr}$  implies a mean time between successive neutron captures which was of the same order as the mean life, i.e. 5 to 100 years [Matsuda et al., 1980]. Whether or not this is characteristic of red giants in general, it nicely illustrates the kind of information obtainable from laboratory analysis of "astrophysical" material.

Note that in this case, the physical/chemical nature of the host phase is consistent with the putative astrophysical origin, i.e. condensation in the

atmosphere of a red giant, though more elaborate, if less likely, scenarios, could be envisaged.

### Condensation in Astrophysical Environments

For only a few anomalies has the actual presolar carrier phase been reliably identified. Note that identification is influenced by such factors as the ability of the grain to survive throughout an arduous existence, and presence of some distinctive feature during microscopic examination of the sample. Note also that the carrier cannot be assumed to be pristine; alteration is possible at any stage, up to and including preparation of the sample for analysis.

Five host phases are listed in Table 1 for three well established anomalous noble gas components. The nature of Xe-s was considered in the previous section. The isotopic spectrum of Xe-HL is shown in Figure 11 [Lewis and Anders, 1983]; note enrichment of both heavy and light isotopes, which have been attributed to r-process and p-process zones, respectively, of a supernova [Manuel et al., 1972; Black, 1975; Ott et al., 1981]. Xe-HL is apparently associated with nitrogen which is highly enriched in  $^{14}\text{N}$  [Lewis et al., 1983]. Its host phase is reasonably securely identified as elemental carbon with a grain size in the range 20 to 90 Å [Lewis and Anders, 1983].

The final component, Ne-E, is essentially pure  $^{22}\text{Ne}$ , Figure 12, [Eberhardt et al., 1981], probably formed by decay of  $^{22}\text{Na}$  with a 2.6 year half-life. A nova source seems likely for the  $^{22}\text{Na}$ , consistent with identification of two

of its host phases as C and spinel [Lewis and Anders, 1983]. However, one of the host phases for Ne-E is apatite [Eberhardt et al., 1981], a mineral which is clearly of secondary solar system origin. How, when and where this mineral became associated with Ne-E is unknown.

Another point worth making is that the 2.6 year half-life of  $^{22}\text{Na}$  places severe constraints on the time interval between nucleosynthesis and condensation of the solid phases capable of retaining Ne. Such observations will undoubtedly shed much light on condensation processes in stellar envelopes.

#### Thermal History of Solar Material

Survival of a presolar isotopic anomaly implies that its host was never heated to a sufficiently high temperature to permit isotopic equilibration with its surrounding medium. Because of major difficulties in placing individual meteoritic components at specific times and locations within the early solar system, existing data do not serve as useful constraints on models of the thermal evolution of the solar nebula, so that this exploitation of isotopic anomalies is largely hypothetical at the present time. However, it is useful to make two comments relevant to this topic.

First, there is very little cosmochemical evidence for nebula-wide high temperatures, i.e. those capable of vaporizing lithic material. There are abundant signs of high temperatures, e.g. presence of chondrules and fractionation patterns involving refractory elements, but it is possible, and even likely, that they reflect processing on a local scale. The best evidence for



large-scale vaporization of the protosolar system used to be the observed lack of isotopic anomalies in meteorites but clearly that argument no longer applies, at least strictly. There is evidence that some meteoritic materials formed by condensation from a gas, e.g. Rare Earth Element patterns for some refractory inclusions [Boynton, 1985], which are consistent with production during cooling of a gas of solar composition, but the scale and location of that event are not rigorously constrained.

Secondly, much of the organic material in primitive meteorites is so highly enriched in deuterium that an origin by ion-molecule reactions in interstellar clouds is widely inferred, [Geiss and Reeves, 1981; Kerridge, 1983]. Besides holding the promise of eventually clarifying some details of molecular cloud chemistry, survival of such material implies that it was never heated above about 600K, though uncertainty about when and where this material entered the solar system inhibits use of this conclusion to constrain conditions in the early solar system.

#### Local Production ?

For most of the anomalies considered so far, a local, solar system origin is inconceivable because of the extreme conditions needed for synthesis, e.g. the high neutron flux needed for the r-process. For three anomalies, however, such an origin has been proposed, though the flux requirements for production of Ne-E in the solar system seem prohibitive and it will not be considered here.

Both the remaining anomalies also require high proton fluxes in the early solar system. Production of  $^{26}\text{Al}$  by p,n reactions on  $^{26}\text{Mg}$  requires  $10^{21} \text{ cm}^{-2}$ , while  $10^{25} \text{ cm}^{-2}$  are needed to generate the  $^{16}\text{O}$  excess by destruction of  $^{17,18}\text{O}$  through p,o reactions [Lee, 1978]. Note also that the presence of radiogenic  $^{26}\text{Mg}^*$  from extinct  $^{26}\text{Al}$  does not rigorously correlate with enrichment in  $^{16}\text{O}$ , though a loose association may exist. In neither case could irradiation of the entire nebular mass have been involved, the most plausible scenario being irradiation of grain or planetesimal surfaces by an early active sun. If, indeed, the  $^{26}\text{Al}$  were associated with  $^{107}\text{Pd}$  and  $^{129}\text{I}$ , as inferred earlier, a local irradiation origin seems precluded [Wasserburg, 1985]. In summary, local production cannot plausibly be responsible for all the currently observed anomalies and, where not immediately implausible, leads to quite contrived conditions. Nonetheless, such scenarios require further study before they can be ruled out.

### Epilogue

It must be reemphasized that the work cited above represents only a small fraction of recent studies into isotopic anomalies. The reader's attention is drawn in particular to the substantial body of work on the isotopic systems of Ca [e.g. Lee et al., 1978; Niederer and Papanastassiou, 1984; Jungck et al., 1984] and Ti [e.g. Niederer et al., 1981; Niemeyer and Lugmair, 1984].

### Acknowledgements

Support by NASA through grants NAGW-347 and NAG-9-27 is gratefully acknowledged.

## References

- Anders, E. (1981) Proc. Roy. Soc., A374, 207.
- Anders, E. and Ebihara, M. (1982) Geochim. Cosmochim. Acta, 40, 2363.
- Black, D. C. (1975) Nature, 253, 417.
- Boynton, W. V. (1985) In: Protostars and Planets 2 (Univ. Arizona) in press.
- Bunch, T. E. and Chang, S. (1980) Geochim. Cosmochim. Acta, 44, 1543.
- Chen, J. H. and Wasserburg (1981) Earth Planet Sci. Lett., 52, 1.
- Clayton, D. D. (1982) Q. J. R. Astron. Soc., 23, 174.
- Clayton, D. D. (1984) Astrophys. J., 280, 144.
- Clayton, D. D. (1985) Geophys. Res. Lett., submitted.
- Clayton, D. D. and Ward, R. A. (1978) Astrophys. J., 244, 1000.
- Clayton, R. N. and Mayeda, T. K. (1985) Lunar Planet. Sci. XVI, 142.
- Clayton, R. N., Mayeda, T. K. and Molini-Velsko, C. A. (1985) In: Protostars and Planets 2 (Univ. Arizona) in press.
- Eberhardt, P., Jungck, M. H. A., Meier, F. O. and Niederer, F. R. (1981) Geochim. Cosmochim. Acta, 45, 1515.
- Geiss J. and Reeves, H. (1981) Astron. Astrophys., 93, 189.
- Gray, C. M., Papanastassiou, D. A. and Wasserburg, G. J. (1973) Icarus, 20, 213.
- Grossman, L. (1980) Ann. Rev. Earth Planet. Sci., 8, 559.
- Grossman, L. and Larimer, J. W. (1974) Rev. Geophys. Space Phys., 12, 71.
- Heidenreich, J. E. and Thiemens, M. H. (1985) Lunar Planet. Sci. XVI, 335.
- Hohenberg, C. M., Hudson, B., Kennedy, B. M. and Podosek, F. A. (1981) Geochim. Cosmochim. Acta, 45, 535.

- Hutcheon, I. D., Armstrong, J. T., and Wasserburg, G. J. (1984) Lunar Planet. Sci. XV, 387.
- Jordan, J., Kirsten, T., and Richter, H. (1980) Z. Naturforsch., 35A, 145.
- Kelly, W. R. and Wasserburg, G. J. (1978) Geophys. Res. Lett., 5, 1079.
- Kerridge, J. F. (1983) Earth Planet. Sci. Lett., 64, 186.
- Kerridge, J. F. and Bunch, T. E. (1979) In: Asteroids (Univ. Arizona) 745.
- King, E. A. (1983) Chondrules and Their Origins (LPI).
- Kornacki, A. S. and Wood, J. A. (1984) Geochim. Cosmochim. Acta, 48, 1663.
- Lee, T. (1978) Astrophys. J., 224, 217.
- Lee, T., Papanastassiou, D. A. and Wasserburg, G. J. (1977) Astrophys. J., 211, L107.
- Lewis, R. S. and Anders, E. (1983) Sci. Amer., 249, 66.
- Lewis, R. S., Anders, E., Wright, I. P., Norris, S. J. and Pillinger, C. T. (1983) Nature, 305, 767.
- Lugmair, G. W., Marti, K. and Scheinin, N. B. (1978) Lunar Planet. Sci. IX, 672.
- Macdougall, J. D. and Kothari, B. K. (1976) Earth Planet. Sci. Lett., 33, 36.
- Macdougall, J. D., Lugmair, G. W. and Kerridge, J. F. (1984) Nature, 307, 249.
- Mahoney, W. A., Ling, J. C., Wheaton, W. A. and Jacobson, S. (1984) Astrophys. J., 286, 578.
- Manuel, O. K., Hennecke, E. W. and Sabu, D. D. (1972) Nature, 240, 99.
- Matsuda, J. I., Lewis, R. S. and Anders, E. (1980) Astrophys. J., 237, L21.
- Matsuhisa, Y., Goldsmith, J. R. and Clayton, R. N. (1978) Geochim. Cosmochim. Acta, 42, 173.
- McCullough, M. T. and Wasserburg, G. J. (1978a) Astrophys. J., 220, L15.
- McCullough, M. T. and Wasserburg, G. J. (1978b) Geophys. Res. Lett., 5, 599.

- McSween, H. Y. (1979) Rev. Geophys. Space Phys., 17, 1059.
- Niederer, F. R. and Papanastassiou, D. A. (1984) Geochim. Cosmochim. Acta, 48, 1279.
- Niemeyer, S. (1979) Geochim. Cosmochim. Acta, 43, 843.
- Niemeyer, S. and Lugmair, G. W. (1984) Geochim. Cosmochim. Acta, 48, 1401.
- Ott, U., Mack, R. and Chang, S. (1981) Geochim. Cosmochim. Acta, 45, 1751.
- Srinivasan, B. and Anders, E. (1978) Science, 201, 51.
- Stolper, E. (1982) Geochim. Cosmochim. Acta, 46, 2159.
- Swart, P. K., Grady, M. M., Pillinger, C. T., Lewis, R. S. and Anders, E. (1983) Science, 220, 406.
- Tatsumoto, M., Unruch, D. M. and Desborough, G. A. (1976) Geochim. Cosmochim. Acta, 40, 617.
- Thiemens, M. H. and Heidenreich, J. E. (1983) Science, 219, 1073.
- Wark, D. A. and Lovering, J. F. (1982) Geochim. Cosmochim. Acta, 46, 2581.
- Wasserburg, G. J. (1985) In: Protostars and Planets 2 (Univ. Arizona) in press.
- Wasserburg, G. J., Papanastassiou, D. A. and Lee, T. (1979) In: Les Elements et Leurs Isotopes Dans l'Univers (Liege) 203.

## Figure Captions

Figure 1. Oxygen isotopic compositions of a suite of calcium-aluminum-rich inclusions from the Allende meteorite. The ordinate shows variations in  $^{17}\text{O}/^{16}\text{O}$  ratios in parts in  $10^3$  relative to the terrestrial ocean water standard; the abscissa shows variations in  $^{18}\text{O}/^{16}\text{O}$  ratios. The dashed line corresponds to mass-dependent fractionation. The Allende data define a mixing line, apparently produced by isotopic exchange between distinct components, probably of nucleosynthetic origin. From Clayton et al. [1985].

Figure 2. (a) Oxygen isotopic compositions of individual minerals separated from Allende CAIs. Spinel and pyroxene undergo isotopic exchange less readily than melilite, suggesting that their compositions more closely reflect that of the solid which subsequently exchanged with nebular gas to produce the observed mixing line. This exchange is shown schematically in (b), in which composition #1 is that of the solid and #2' that of the gaseous reservoir. (c) Schematic representation of the data in Figure 4. Allende chondrules, initially with compositions close to #4', and ordinary chondrules, at #3, apparently both exchanged with a gaseous reservoir at #2. (d) Summary of minimal population of oxygen isotopic reservoirs in the early solar system, identified so far. An apostrophe denotes a composition readily derivable, either by mixing or fractionation, from established reservoirs.

Figure 3. Silicon isotopic compositions of a suite of Allende CAIs, analogous to Figure 1 for oxygen. Note that the data closely define a line with a slope of 0.5, indicative of mass-dependent fractionation. From Clayton et al. [1985].

Figure 4. Oxygen isotope plot, like Figure 1, for individual chondrules separated from Allende and some ordinary chondrites. Note that for Allende, porphyritic chondrules, which were not totally molten, are more  $^{16}\text{O}$ -rich than barred chondrules which were completely melted. From Clayton et al. [1985].

Figure 5. Oxygen isotopic compositions generated during spark-discharge production of ozone from molecular oxygen. Square symbols represent compositions of ozone samples; round symbols those of residual oxygen. Note that the data fall on a line with a slope of unity, not on the mass-fractionation trend line (dashed). From Thiemens and Heidenreich [1983].

Figure 6. Schematic representation of the time interval between nucleosynthesis of an element and its incorporation into solid objects during solar-system formation. Elements produced by different nucleosynthetic schemes would be characterized by different values of  $\Delta$ . After Wasserburg [1985].

Figure 7. Magnesium isotopic compositions of individual minerals separated from an Allende CAI, as a function of Al/Mg ratio. The strong positive correlation indicates that the observed  $^{26}\text{Mg}$  excesses resulted from decay of extinct  $^{26}\text{Al}$ . After Lee et al. [1977].

Figure 8. Isotopic compositions of neodymium and samarium in two unusual Allende CAIs, plotted as deviations, in parts in  $10^4$  relative to terrestrial values. The nucleosynthetic production mechanisms believed to be responsible for each nuclide are identified. After Wasserburg et al. [1979].

Figure 9. (a) Isotopic excesses in Nd and Sm observed in Allende inclusion EK 1-4-1. Absolute excesses in atoms are plotted versus atomic mass. Note the smooth curves for even- and odd neutron nuclides. (b) Calculated "average solar-system" abundances of the nuclides depicted in (a). Note striking congruency between the curves in (a) and in (b). After Lugmair et al. [1978].

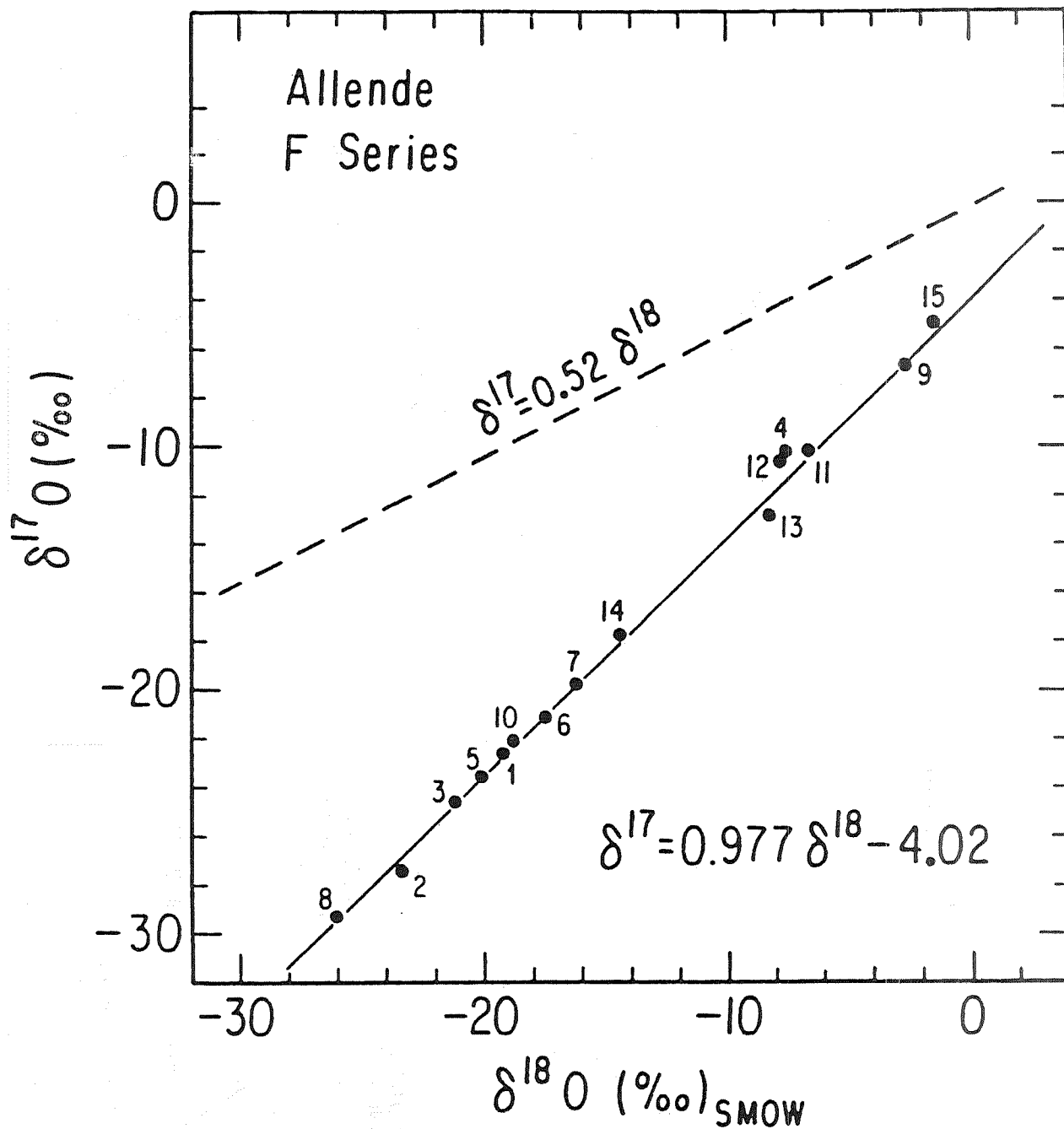
Figure 10. Relative abundances of the xenon isotopes in a small fraction of gas released from the Murchison and Orgueil meteorites. Note the excellent agreement with the xenon composition calculated by Clayton and Ward [1978] to be produced by the s-process in red giants. From Anders [1981].

Figure 11. Isotopic composition of a xenon component extracted from Allende. Note enrichment in both Heavy and Light isotopes relative to "normal" Xe, leading to its designation as Xe-HL. A supernova origin is inferred for this component, see text. From Lewis and Anders [1983].

Figure 12. Isotopic compositions of neon components identified in primitive meteorites. The component known as Ne-E, consisting of essentially pure  $^{22}\text{Ne}$ , is dramatically different from the more common components and is believed to be of nova origin. After Eberhardt et al. [1981].



Figure 1



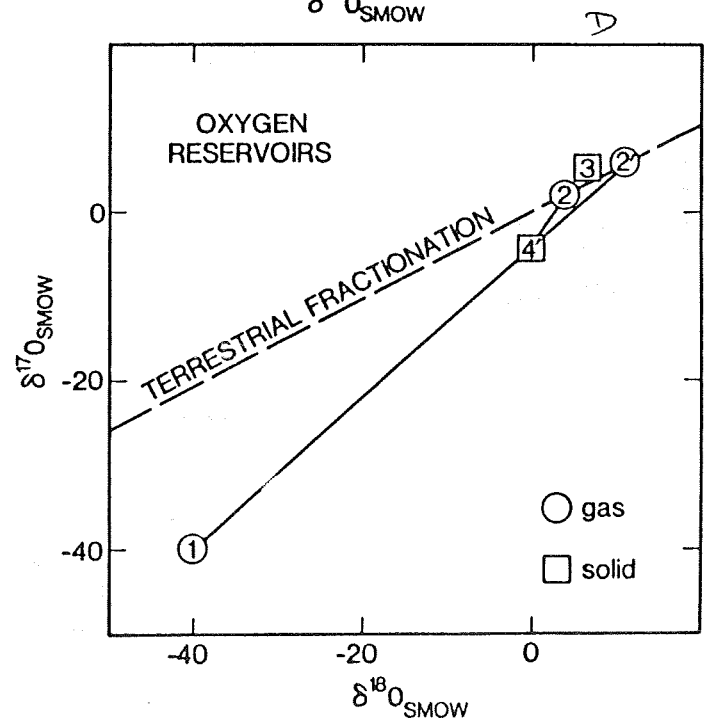
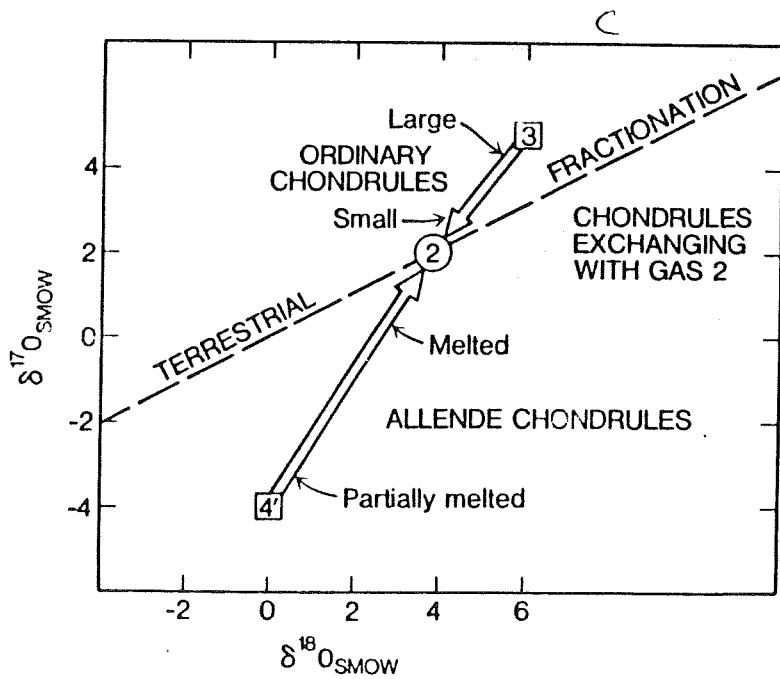
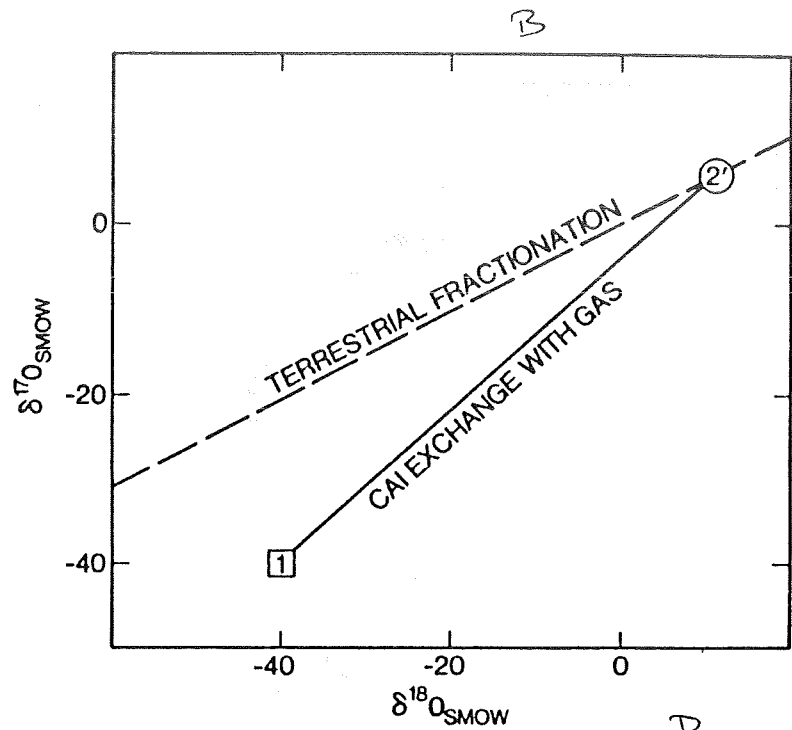
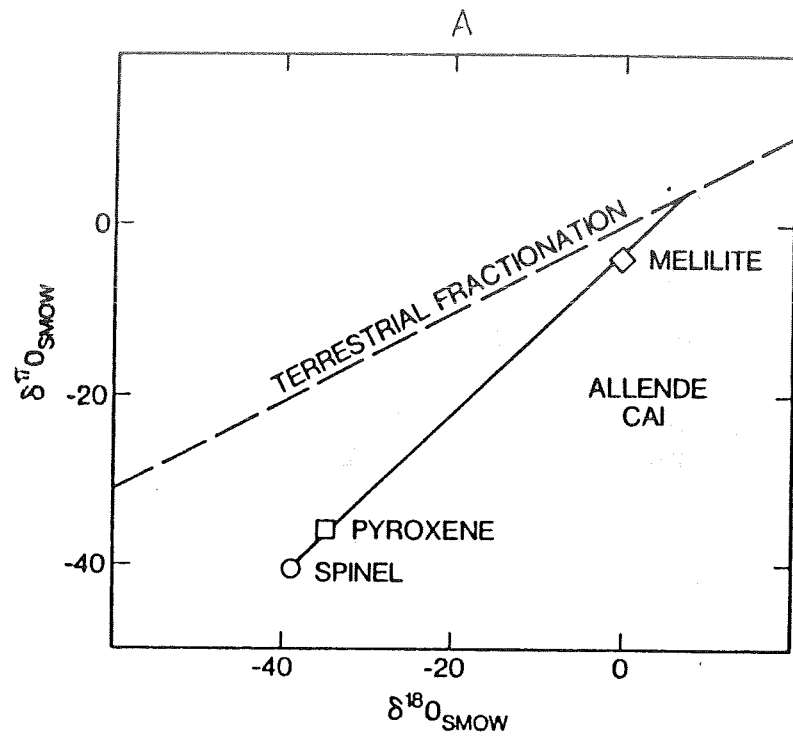


Figure 2

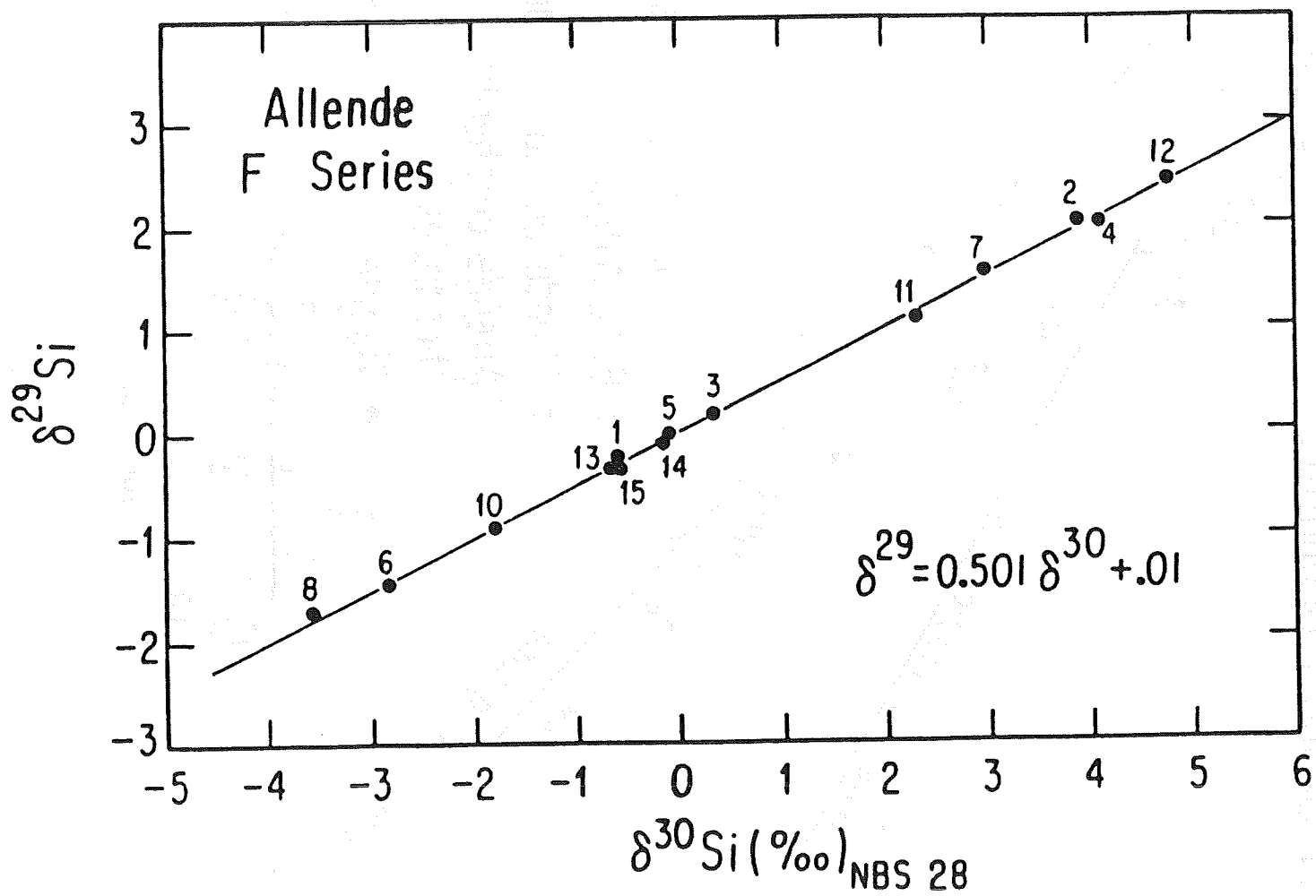
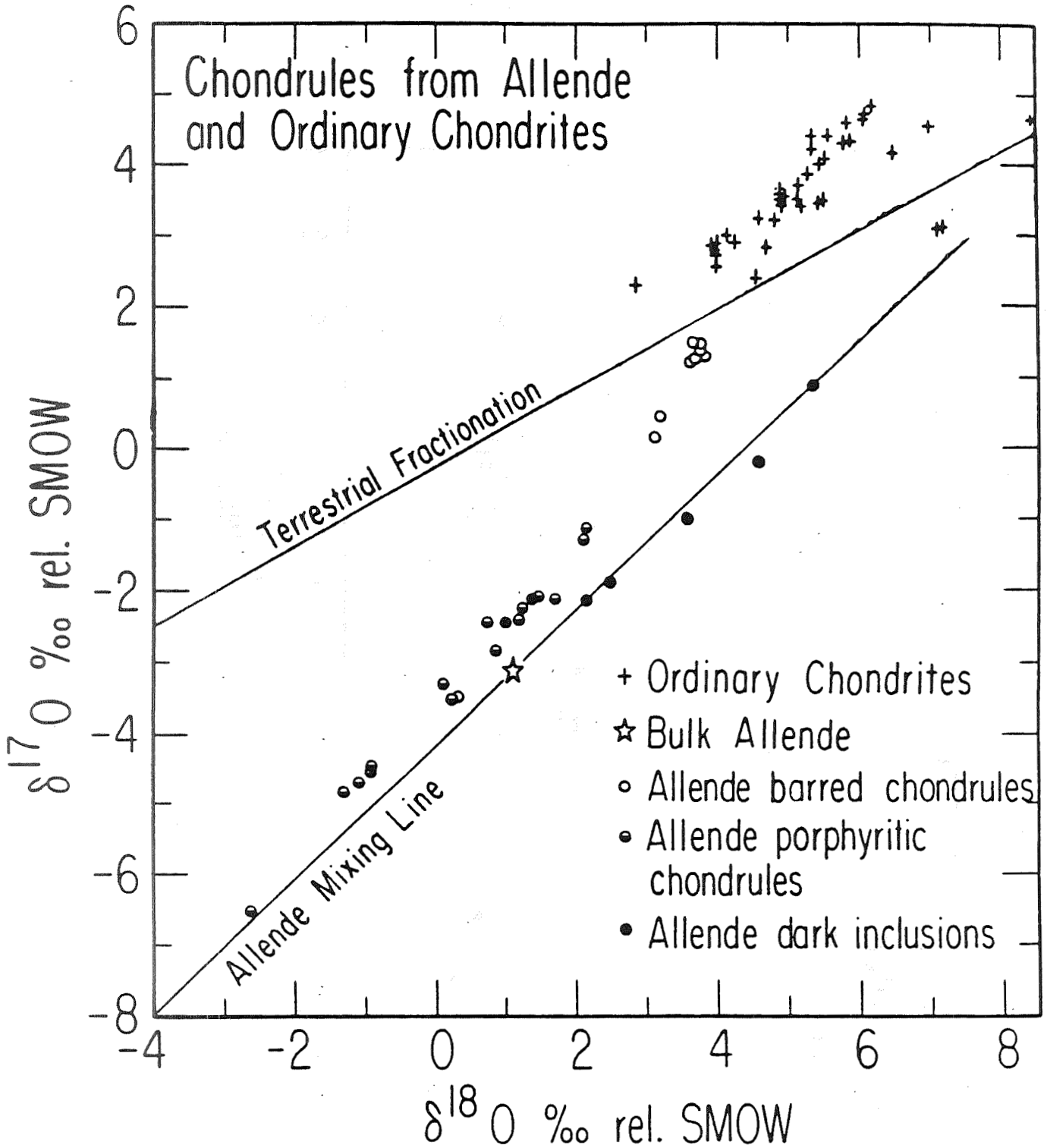


Figure 3

Figure 4



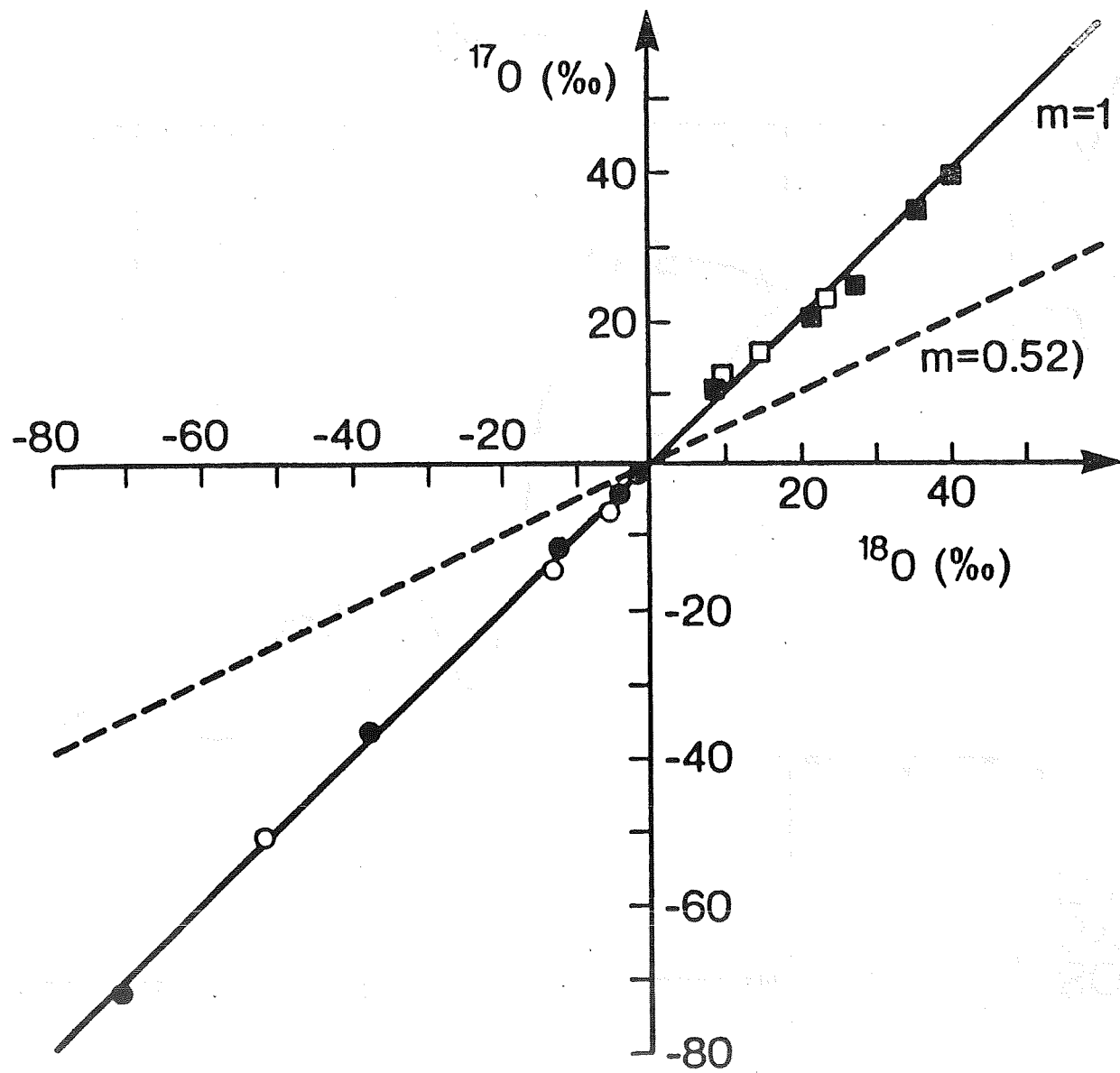


Figure 5

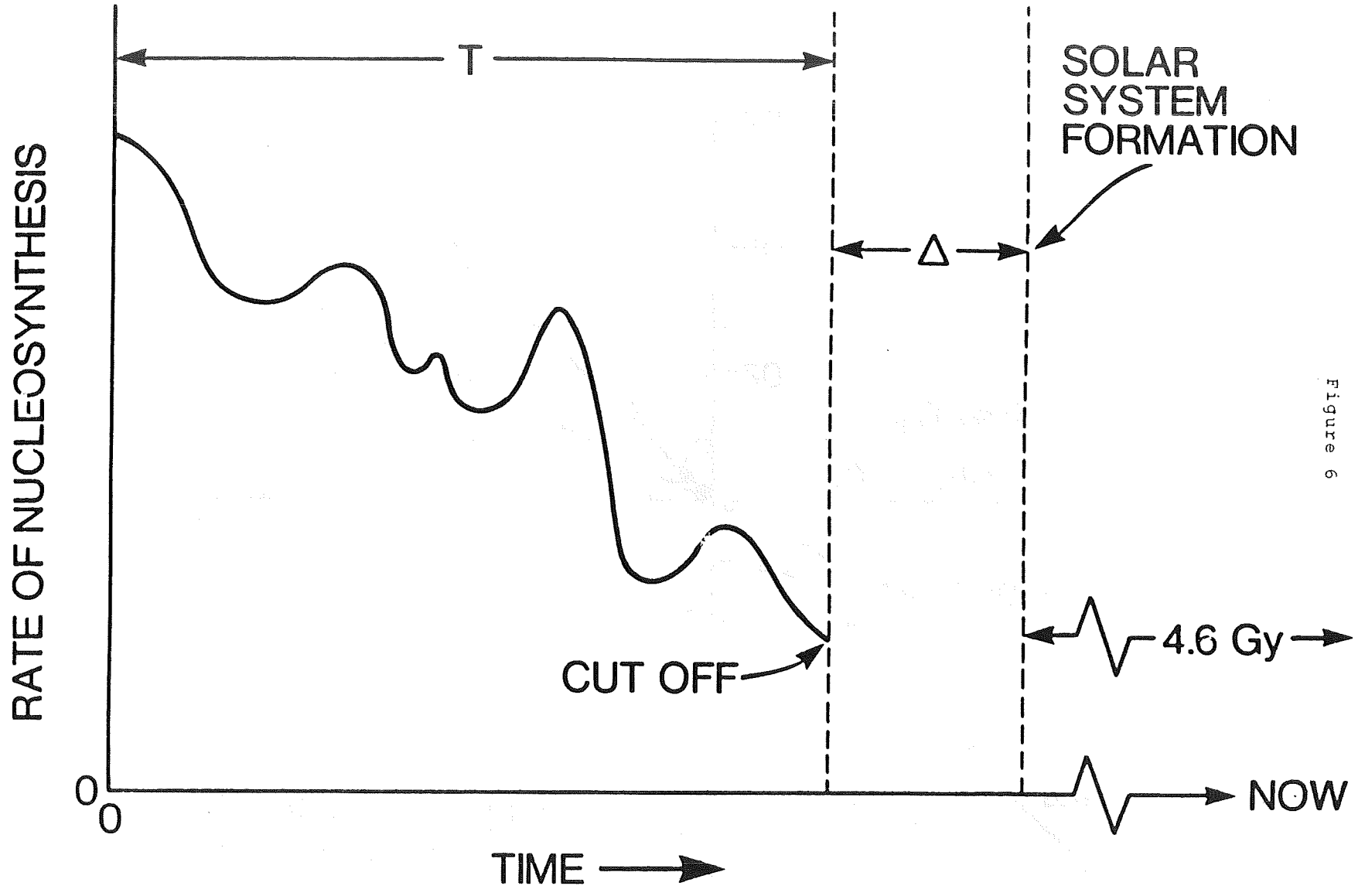


Figure 6

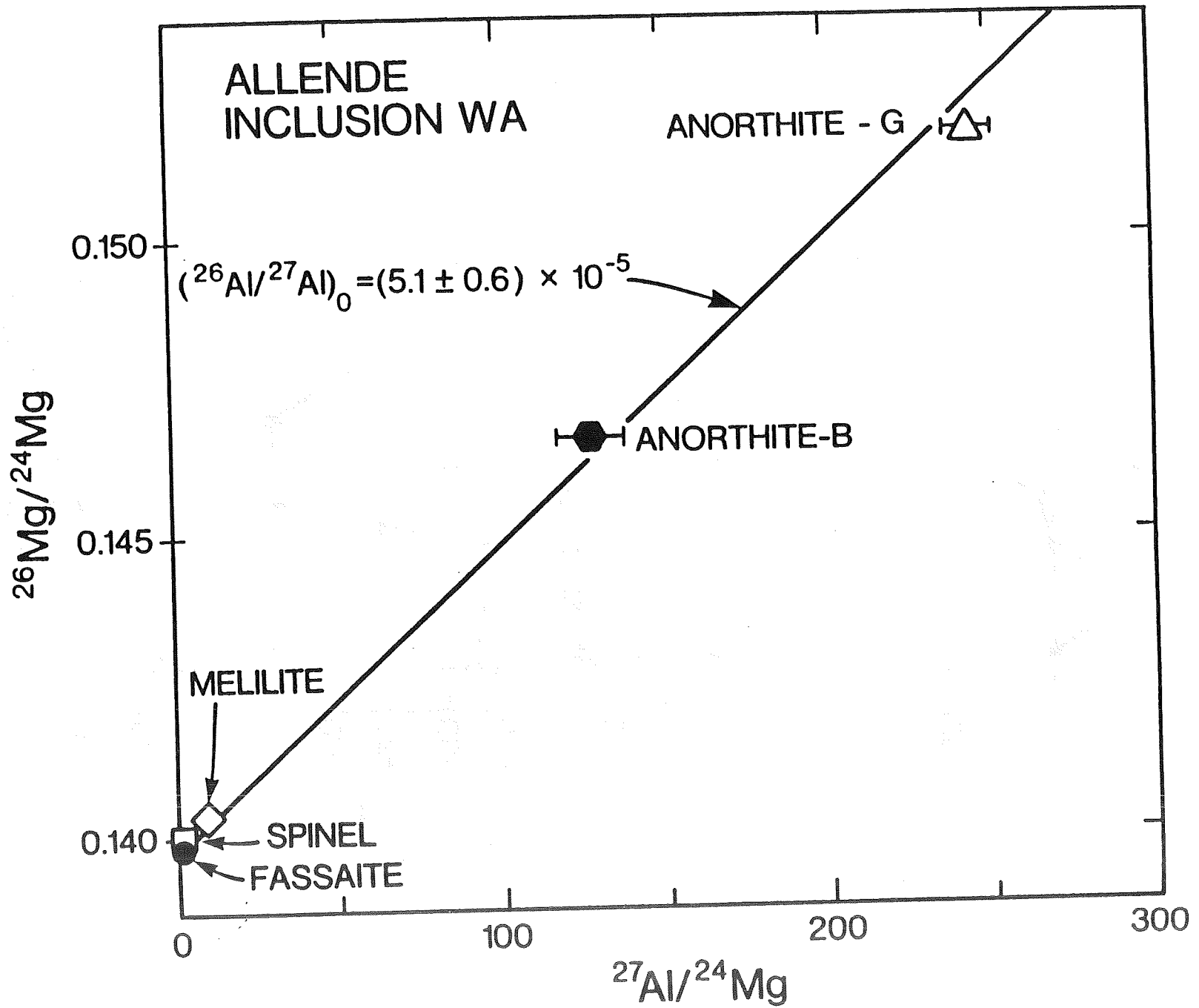


Figure 7

Figure 8

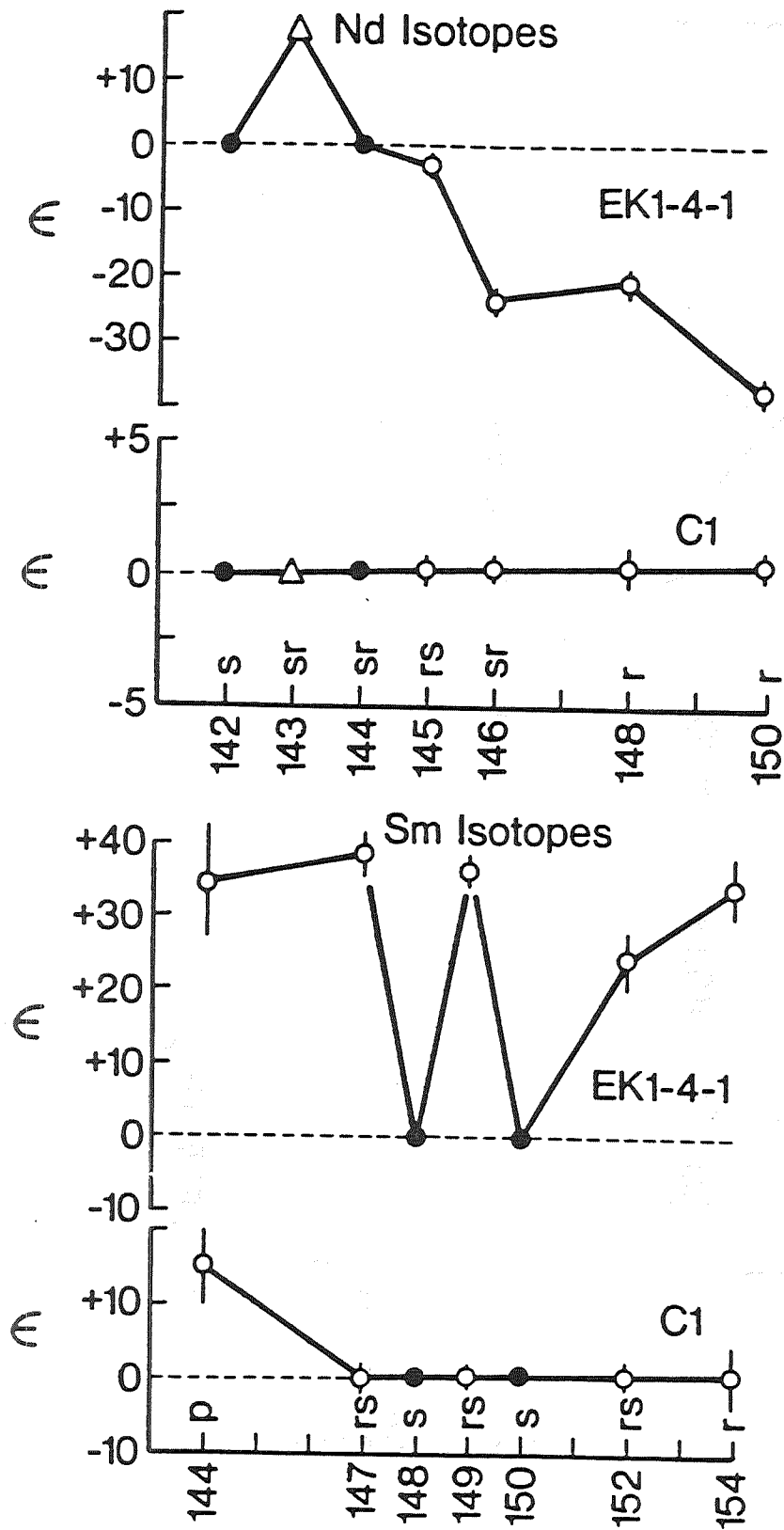




Figure 9

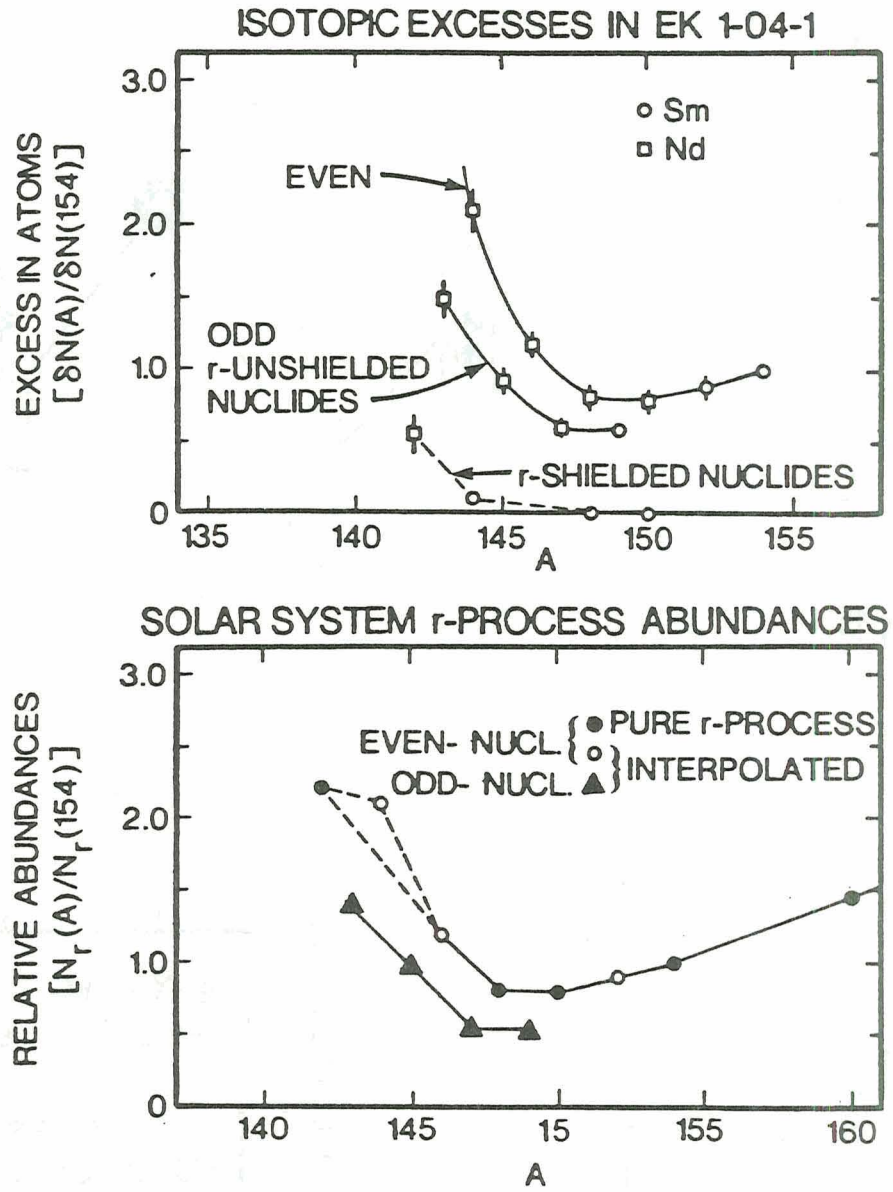


Figure 10

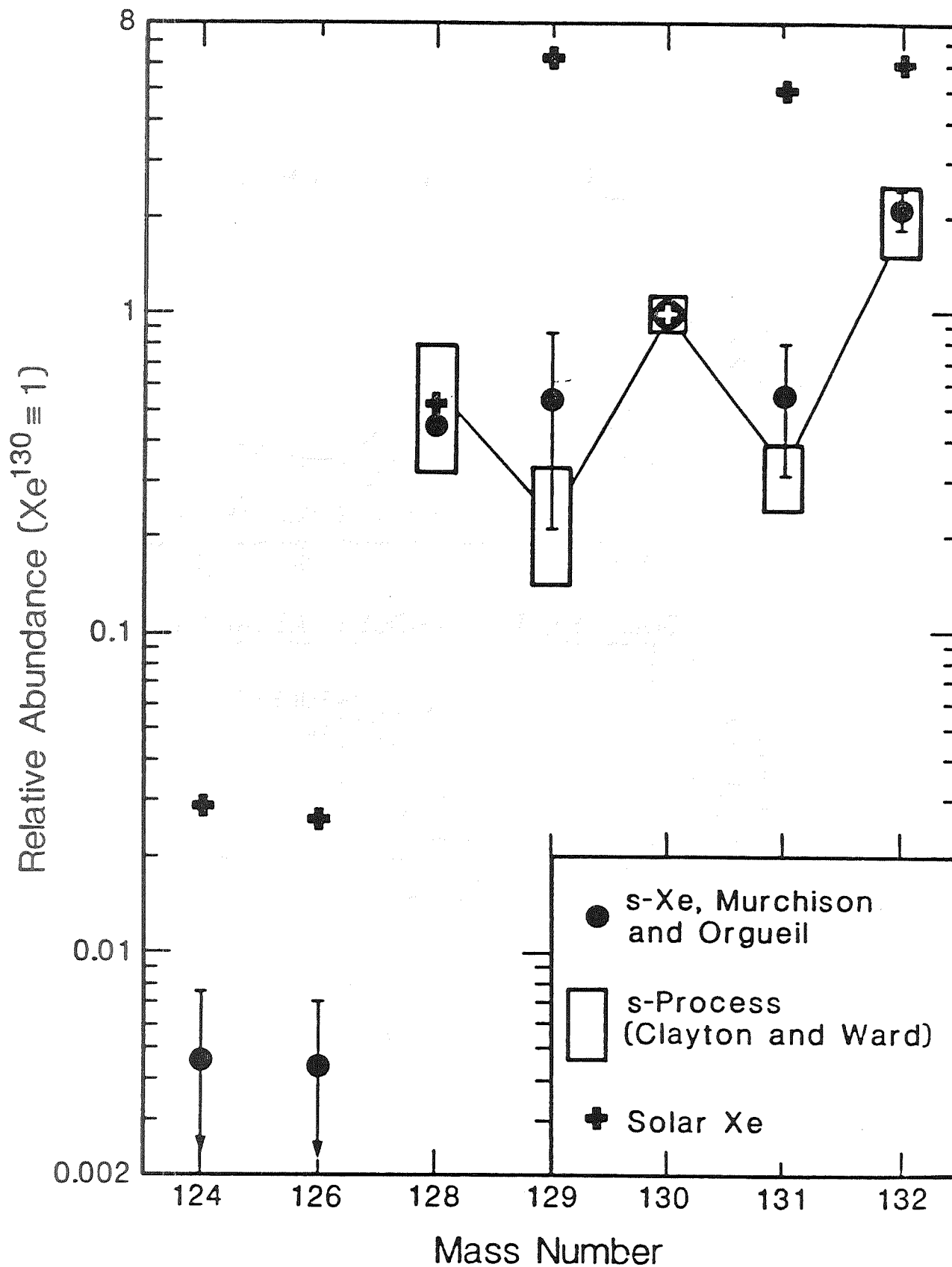


Figure 11

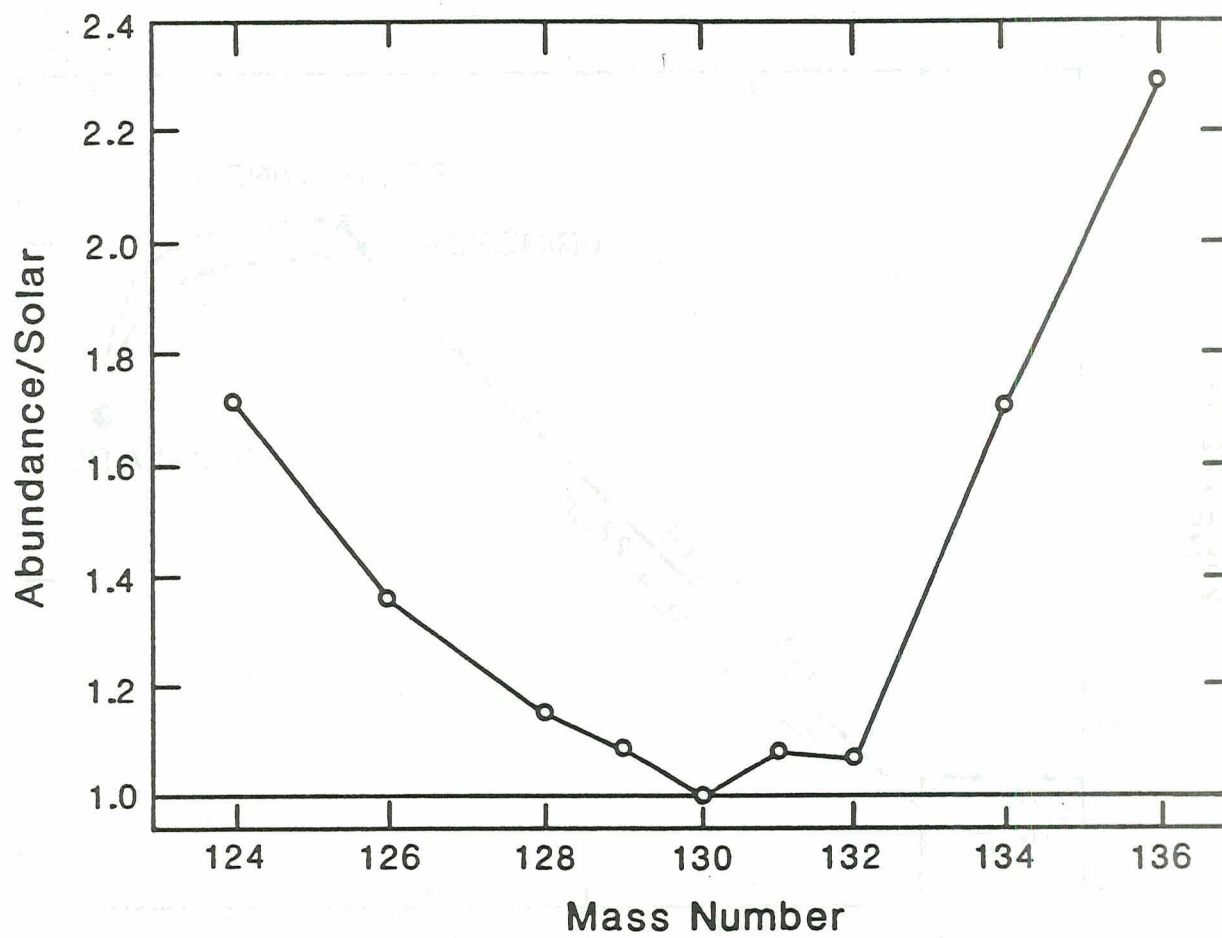
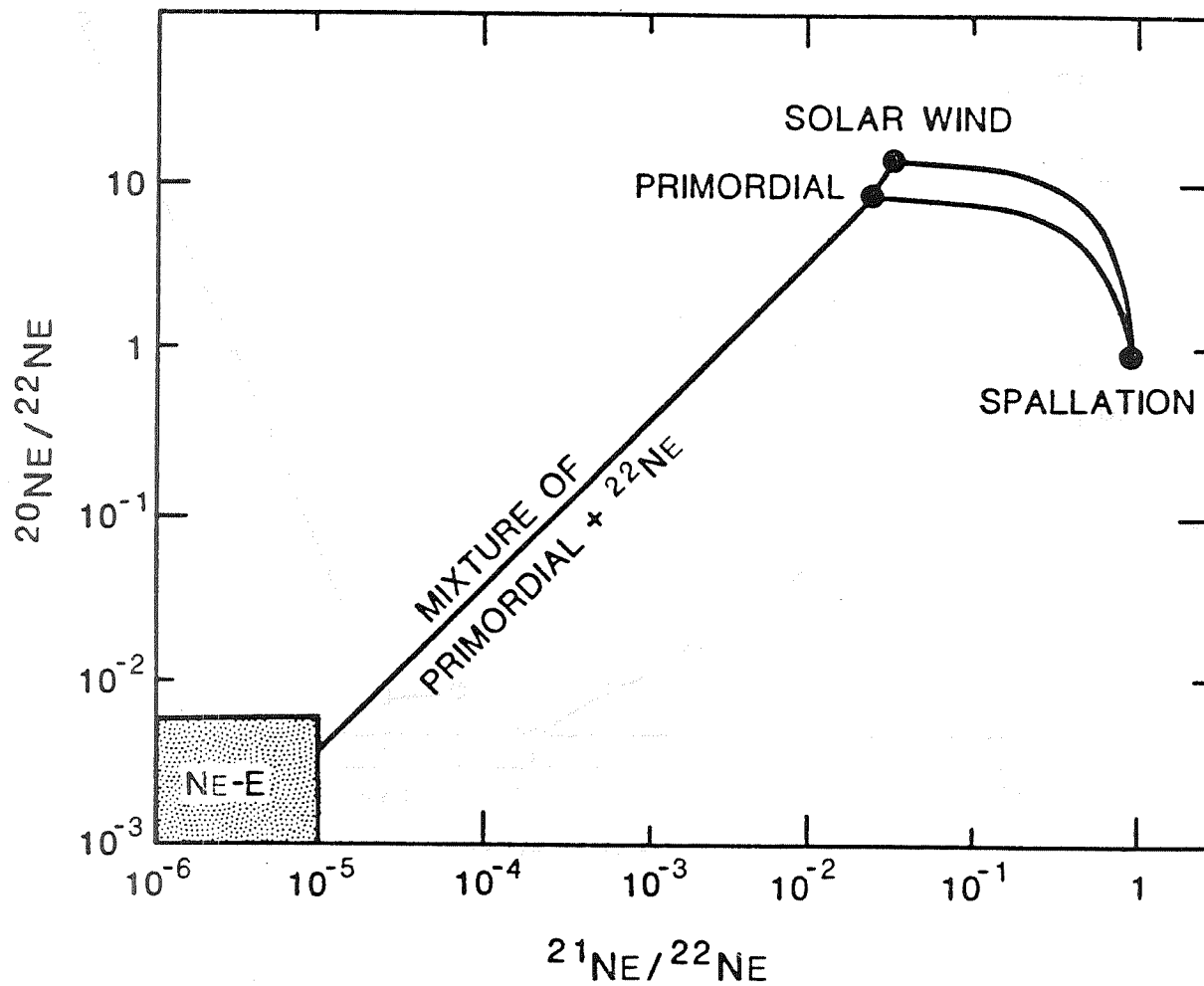


Figure 12



HOST PHASES OF ALIEN NOBLE GASES

SUMMARY

Component	Xe-S	Xe-HL	Ne-E(L)	Ne-E(H)	
Material	carbon C	carbon C	carbon C	spinel MgAl <sub>2</sub> O <sub>4</sub>	apatite Ca <sub>2</sub> PO <sub>4</sub> (OH,F)
Release T°C	1400	1000	600	1100	1100
Grain size	0.1-3 μm	~ 20 Å	1-10 μm		
Source	red giant	supernova	nova	nova	??????????????