

Diagnosis: The head is short with a prominent cervical furrow. The eyes are sessile and extend out in front of the anterior surface of the head. Each thoracic segment bears an anterior and posterior ridge; the prominence of the ridges is less marked on the posterior segments. The coxa of the anterior thoracopod appears to be fused to the thoracic pleura but is free on the remaining thoracopods. The expanded bases are two to three times as long as the coxae. The ischium, merus, carpus, propodus, and dactylus each average about half the length of the basis. The dactylus and propodus do not form a subchela on the second thoracopod. The transition in size from thoracic to abdominal segments is not marked. The fifth abdominal segment is inflated. The pleotelson is large and pointed posteriorly.

The taxonomic position of *Hesslerella* within a family is ambiguous. *Hesslerella* possesses characteristics of both the Paleophreatoicidae and the Amphisopidae, both families known from fossils in the Permian. The short head, the possible fusion of some of the thoracic coxae to the pleuron, and the general characteristics of the thoracic endopods, especially the expanded basis, are shared with the amphisopids. The protrusion of the eyes anteriorly, the unfused posterior thoracic coxae, the enlarged fifth abdominal segment, and the posterior projection of the pleotelson are shared with the paleophreatoicids. It appears that *Hesslerella* occupies a transitional position between the paleophreatoicids and the amphisopids. The segmentation and general body plan remain like those of the paleophreatoicids, while alterations are made in the structure of the appendages (and probably in locomotor efficiency) toward that exhibited by the amphisopids.

The discovery of this isopod in the Middle Pennsylvanian extends the range of the isopods back some 50 million years from the Late Permian and raises some questions about eumalacostracan evolution. The exact phyletic position of the Phreatoicea within the Isopoda is still a matter of conjecture. Some workers consider that the phreatoicids are specialized and not primitive forms. *Hesslerella* would imply a previously unsuspected, rather extensive peracarid and isopod radiation in or before the Middle Pennsylvanian, whose origins must extend back into Mississippian times or earlier. According to the ideas of Siewing (4) on the phyletic relationships within the Peracarida, it now seems likely that peracarid origins may be closely allied with the origin and early radiation of the Eumalacostraca as a whole in the Middle or Early Devonian. The fact that we have practically no record

of this Paleozoic peracarid radiation is undoubtedly due to Paleozoic Peracarida having not lived in environments conducive to fossilization. It appears that future speculations concerning the Late Paleozoic radiation of the Eumalacostraca must now take into account the Peracarida (5).

FREDERICK R. SCHRAM
Department of Zoology, Eastern
Illinois University, Charleston 61920

Lunar Spectral Reflectivity (0.30 to 2.50 Microns) and Implications for Remote Mineralogical Analysis

Abstract. *The spectral reflectivity (0.30 to 2.50 microns) of several lunar areas was measured with ground-based telescopes. A narrow absorption band centered at 0.95 micron was revealed for the first time. No other absorption bands appear in the spectrum. The reflectivity continues to rise at longer wavelengths throughout the spectral region studied. A comparison of the telescope measurements of an area 15 kilometers in diameter that includes Tranquillity Base with laboratory measurements of Apollo 11 soil samples reveals remarkable agreement, an indication that properties determined for fairly large lunar areas are relevant to local conditions. The spectra are interpretable in terms of surface mineralogy. The absorption band varies in both depth and shape and the overall slope of the curve changes with lunar area, an indication of differences in the composition and opacity of surface material. However, the lack of variety in the band position suggests there are no major differences (say, from mostly pyroxenes to mostly olivines) in the mineralogy at those sites studied.*

The use of reflection spectroscopy to perform remote compositional mapping and mineralogical analysis of the lunar surface has been suggested and discussed (1, 2). Electronic absorption bands are present in the diffuse reflection spectrum of most minerals and their powders. These bands are produced by transition elements, notably iron, in various valence and coordination states. Band frequencies are sensitive to distortion of *d*-orbital shells of transition metals by neighboring ions. Because metal-oxygen distances differ for most minerals, the frequencies of the absorption bands can be used to identify minerals that exhibit bands. If such absorption bands appear in lunar spectra and there is variety in the bands across the lunar surface, the techniques of telescopic reflection spectroscopy can be applied (to remote mapping and mineralogical analysis). We have conducted a ground-based observational study designed to provide the information necessary to perform such an analysis.

In our past studies we have measured relative spectral reflectivity (0.4 to 1.1 μ) of various areas of the lunar surface. The relative reflectivity is defined as the ratio of the reflectivities for two

References and Notes

1. R. G. Johnson and E. S. Richardson, Jr., *J. Geol.* **74**, 626 (1966).
2. F. R. Schram, *Feldiana Geol.* **12**, 14 (1969).
3. I am pleased to honor an outstanding student of the modern Isopoda, Dr. Robert R. Hessler, who has been of invaluable assistance to me in my work, and Levi Sherman, the serious collector who generously made the specimen available for study.
4. R. Siewing, *Zool. Jahrb. Anat. Ontog. Tiere* **75**, 39 (1956).
5. A detailed report of this animal is in preparation.

26 June 1970

lunar areas. These studies have shown that structure exists in the spectral reflectivity curves in the spectral region from 0.4 to 1.1 μ . In particular, spectral features in the relative reflectivity curves in the spectral region from 0.9 to 1.0 μ were noted. We suggested (3) that this structure indicates the existence of an absorption band in the spectrum between 0.95 and 1.0 μ for some lunar areas. This absorption feature was found to change with lunar area and to correlate with lunar morphology. It was argued that this structure must be indicative of the surface composition and mineralogy, and that changes in the relative spectral features with lunar area suggest variations in surface composition and mineralogy.

Our recent efforts have been directed toward extending our relative reflectivity curves to 2.5 μ (4), and determining the spectral reflectivity of our lunar standard area in Mare Serenitatis. With the reflectivity of the standard area determined, all ratios can be applied to determine the reflectivity for all other areas for which relative curves are known.

As in our earlier work, we have used a set of narrow-band interference filters, this time a set of 52 filters cover-

ing the spectral region from 0.3 to 2.5 μ , and the double-beam photometer (5). Both photomultiplier tubes and lead sulfide detectors were used. The observations were made with the 60-inch (152 cm) telescope of the Cerro Tololo Inter-American Observatory, and supplemental work was done with

the Mount Wilson 24-inch (61 cm) and 60-inch instruments.

The spectral reflectivity of our standard lunar area in Mare Serenitatis (18°7'N, 21.4°E) as determined by us is shown by the points in Fig. 1 for the spectral region from 0.3 to 1.1 μ . An area 15 km in diameter was observed.

We obtained these points by measuring the flux from the lunar area through each of the narrow-band filters and using standard stars to calibrate the instrument and atmosphere. Star measurements were made many times during the same night on which the flux from the moon was measured and ex-

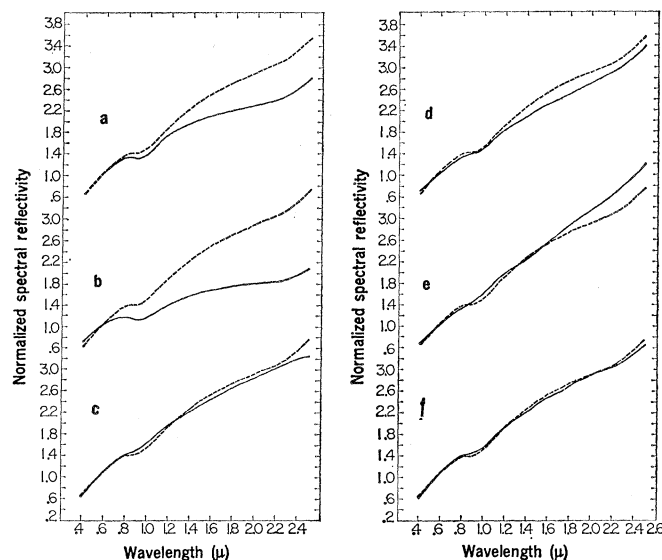
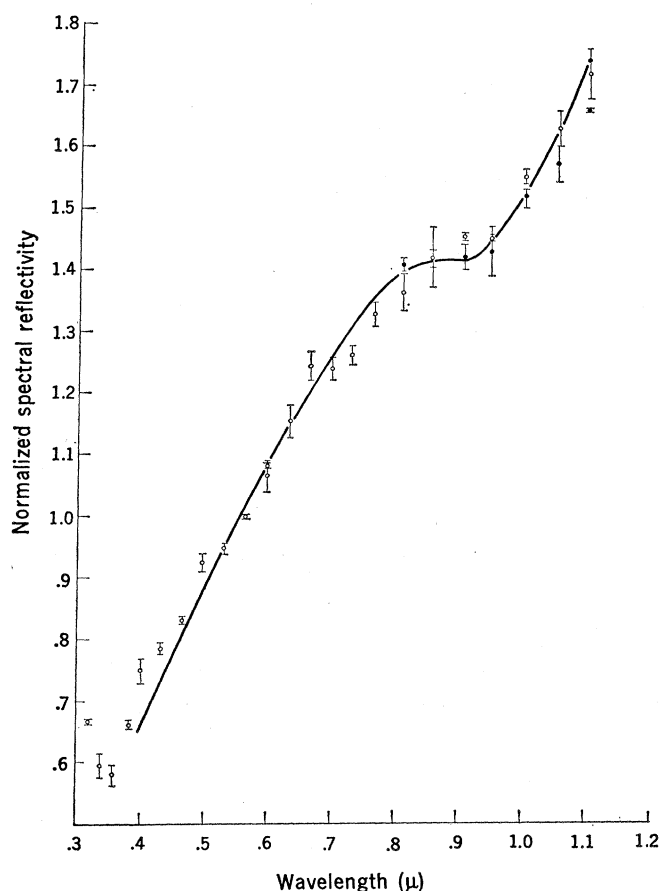


Fig. 1 (above left). Spectral reflectivity of a small area in Mare Serenitatis scaled to unity at 0.56 μ . We derived the line from laboratory measurements of Apollo 11 soil samples (11) with data for the Apollo 11 landing site converted to the corresponding values for the Mare Serenitatis standard area by use of the measured ratio of the reflectivity of Mare Serenitatis 2 to that of the Apollo 11 site (12). The solid circles were obtained by use of a PbS detector and the open circles are the result of measurements with a photomultiplier tube.

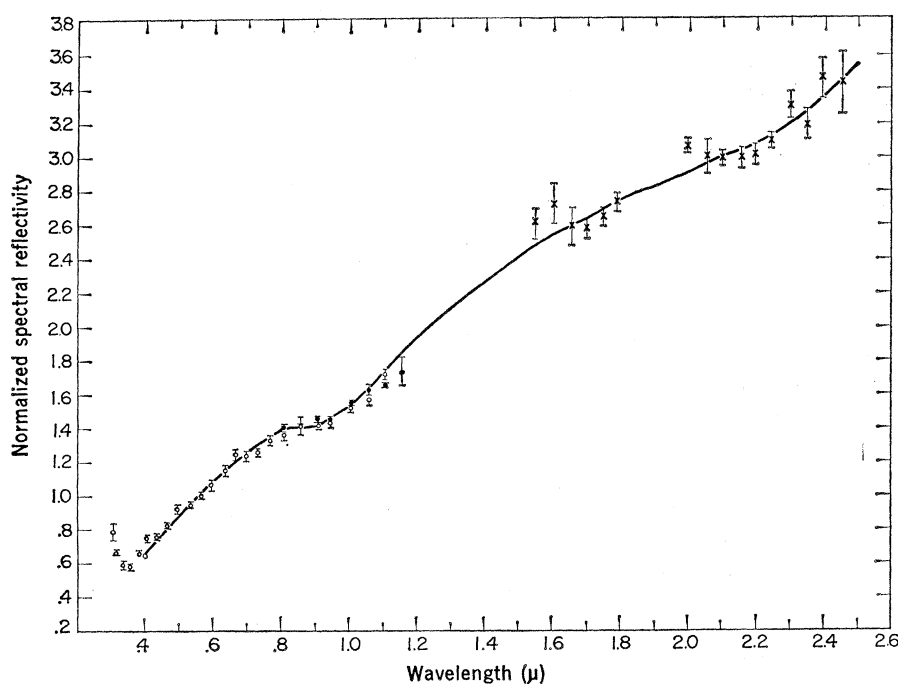


Fig. 2 (left). Spectral reflectivity of a small area in Mare Serenitatis with the spectral region extended to 2.5 μ . The infrared points, plotted as x's, are derived from telescope observations of Mare Serenitatis and α Bootes and from the spectral fluxes for α Bootes and the sun. Certain spectral regions are blank because of a lack of stellar flux data.

Fig. 3 (above right). Spectral reflectivity for six lunar areas relative to the curve for Mare Serenitatis: (a) Kepler; (b) Aristarchus; (c) Uplands; (d) Mare Tranquillitatis (Apollo 11 sample); (e) Littrow; (f) Plato C. We derived the curves from the curve of Fig. 2 and measurements of the reflectivity of Mare Serenitatis (dashed line) relative to that of the other area (Kepler, for example) (solid line) (4).

tinction corrections were made. The ratio of the flux from the moon to the flux from the star was calculated. This ratio was multiplied by the ratio of the flux from the star to the flux from the sun with stellar fluxes taken from the work of Oke (6) and Oke and Schild (7) and solar fluxes taken from the work of Labs and Neckel (8). The resulting quantity is the spectral reflectivity multiplied by a constant. This reflectivity was scaled to unity at 0.56μ .

The two most important features in the curves are: (i) the steep increase in reflectivity from blue to red, and (ii) the absorption band centered at 0.95μ . This band has not been reported previously, although it has been suggested by our earlier relative reflectivity studies (3). Notably absent is the band at 1.0μ reported by several earlier workers (9). Cruikshank (10) has recently reported a band at 0.9μ in the reflectivities of some lunar areas. This may be the same band as the one at 0.95μ shown here, which was incompletely resolved in the six spectral points taken by Cruikshank. The upturn of our curve in the ultraviolet region is striking but is highly suspect. The curve of solar flux is quite uncertain in this spectral region and could easily create such an effect. However, careful analysis of existing data on the solar spectral energy distribution does not rule out the indicated ultraviolet upturn.

Also shown in Fig. 1 is the spectral reflectivity of the lunar soil returned in the Apollo 11 mission (11); we have converted these data from their values at the Apollo 11 landing site to the corresponding values at the Mare Serenitatis standard area by using the measured ratio of the reflectivity at Mare Serenitatis 2 to the reflectivity at the Apollo 11 site (12). The agreement is remarkable and indicates quite clearly that from earth-based observations of relatively large lunar surface areas ($\sim 100 \text{ km}^2$) one can determine surface soil properties relevant to local conditions (a few square meters). O'Leary and Briggs (13) have come to the same conclusion on the basis of a comparison of the photometric properties of the Apollo 11 samples with earth-based and Lunar Orbiter observations of the Tranquillity Base region. This is an important point for future ground-based studies of planetary objects. Given a few lunar ground samples for analysis, it seems quite possible to extend the interpretation of these samples to the entire front side of the

moon on the basis of ground-based observations. The telescope measurements are in agreement with laboratory spectra of the lunar soil. The reflectivity of the soil is different from that of some of the individual rocks returned in the Apollo 11 sample.

The extensions of the spectral reflectivity measurements for Mare Serenitatis farther into the infrared region are very difficult because of the lack of spectral flux data for standard stars. A recent determination of the flux for α Bootes in the spectral regions from 1.55 to 1.80μ and from 2.00 to 2.45μ (between the absorption bands for water) by Hyland and Neugebauer (14) and the observations made on the basis of the flux ratios of Mare Serenitatis and α Bootes enabled us to obtain the infrared points shown in Fig. 2. No further accurate reduction of our infrared data is possible until standard star fluxes become available. The points in Fig. 1 are repeated in Fig. 2.

Also shown in Fig. 2 is the complete reflectance curve for the Apollo 11 soil samples, with the data again converted to the corresponding values at Mare Serenitatis, as in Fig. 1. The agreement between telescope measurements and laboratory data is very good. The upturn at the blue end of both segments of points in the infrared region seems to be due to errors in the fluxes for α Bootes. Because the telescope and laboratory reflectivity measurements are in such good agreement in the spectral regions where telescope data can be reduced, we propose that the laboratory data be considered the standard curve to which telescope measurements would converge if they could be made as precisely as laboratory measurements.

The curve for the standard area shows no absorption bands other than the band at 0.95μ . Two important features in the infrared curve are: (i) the continual rise in reflectivity to at least 2.5μ , and (ii) the upturn in the curve beyond 2.3μ . The latter feature could be due to contamination of the reflected solar radiation by emitted thermal radiation. However, laboratory measurements of Apollo 11 samples (15) indicate that the reflectivity may actually increase, as the curve in Fig. 2 shows.

A mineralogical interpretation can be made of the overall shape of the spectral reflectivity curves and especially of the band at 0.95μ on the basis of laboratory data for terrestrial materials (16). A predominance of py-

roxenes is indicated because the absorption exists below 1.0μ ; the analysis of Apollo 11 soil samples is in agreement with this result (11). Remote sensing of surface mineralogy by reflection spectroscopy seems to be a workable method. A detailed analysis of the mineralogical interpretation of the curve presented here will appear elsewhere (2).

On the basis of the curve for the standard area in Mare Serenitatis (Figs. 1 and 2) and our measurements of other areas on the moon relative to the standard area (ratio of reflectivity for other areas to that for the standard area), it is now possible to calculate reflectivity curves for other lunar areas. Figure 3 shows the reflectivity curves, calculated in this way, for several lunar areas. Significant variations in the curves are seen from place to place on the moon. The band at 0.95μ is completely lacking at the Littrow region, and there is a strong band at the craters Kepler and Aristarchus. The slope of the curve also changes from place to place.

None of the sites studied shows significant absorption bands beyond 1.0μ . Recent studies of differential curves by Cruikshank (10) suggest the existence of absorption bands at wavelengths longer than 1.5μ in the spectra of Aristarchus and Kepler. Although the differential curves reported by Cruikshank cannot be directly compared with reflectivity curves (Cruikshank's curves are differences, not ratios), it appears that differences in slope between the reflectivities of Aristarchus and Kepler and Cruikshank's standard area, Plato, rather than absorption bands, are responsible for the features beyond 1.0μ in the differential curves.

The differences between the curves in Fig. 3 indicate differences in the composition and opacity of the surface material (2, 11). However, the lack of variety in the band position and the absence of other bands in any of the curves suggest that there are no major differences in the mineralogy (say, from mostly pyroxenes to mostly olivines) at those sites studied. The seven samples in Fig. 3 suggest the limit of mineralogical heterogeneity that exists across the lunar surface.

THOMAS B. MCCORD
TORRENCE V. JOHNSON

*Planetary Astronomy Laboratory,
Department of Earth and Planetary
Sciences, Massachusetts Institute of
Technology, Cambridge 02139*

References and Notes

1. J. B. Adams, *Science* **159**, 1453 (1968); T. B. McCord, *J. Geophys. Res.* **74**, 3131 (1969).
2. J. B. Adams and T. B. McCord, *Geochim. Cosmochim. Acta*, in press.
3. T. B. McCord and T. Johnson, *J. Geophys. Res.* **74**, 4395 (1969).
4. ———, *Icarus*, in preparation.
5. T. B. McCord, *Appl. Opt.* **7**, 475 (1968).
6. J. B. Oke, *Astrophys. J.* **140**, 689 (1964).
7. ——— and R. Schild, in preparation.
8. G. Labs and H. Neckel, *Z. Astrophys.* **69**, 1 (1968).
9. R. G. Tull, *Icarus* **5**, 505 (1966); V. I. Moroz, *Soviet Astron. AJ Engl. Transl.* **9**, 999 (1966).
10. D. P. Cruikshank, *Science* **166**, 215 (1969).
11. J. B. Adams and R. L. Jones, *Science* **167**, 737 (1970).
12. T. B. McCord, T. V. Johnson, H. H. Kieffer, *J. Geophys. Res.* **74**, 4385 (1969).
13. B. O'Leary and F. Briggs, *ibid.*, in press.
14. A. R. Hyland and G. Neugebauer, in preparation.
15. J. B. Adams, personal communication.
16. ——— and A. L. Filice, *J. Geophys. Res.* **72**, 5705 (1967).
17. We thank J. B. Adams and L. T. Silver for helpful conversations, and Drs. A. R. Hyland and G. Neugebauer and Drs. J. B. Oke and R. Schild for making their data available before publication. Supported by NASA grant NGR-22-009-350. Contribution No. 6 from the Planetary Astronomy Laboratory.
- 18 March 1970

Hematite: Intrinsic and Defect Ferromagnetism

Abstract. *Both intrinsic (spin-canted) ferromagnetism and defect ferromagnetism occur in hematite. Because defect ferromagnetism is sensitive to structure, it is altered by stress or heating and could give spurious paleomagnetic information. Annealing experiments now suggest that the defect remanence of fine-grain hematites and red sediments, unlike that of single crystals, is magnetically softer than the spin-canted remanence and can be erased by partial demagnetization.*

Red sediments are widely used in paleomagnetism because their natural remanent magnetization (NRM) is magnetically extremely stable. The explanation of this stability undoubtedly lies in the high remanent coercivities of the fine hematite grains carrying NRM, but the origin of these high coercivities remains puzzling.

In the temperature range of interest in rock magnetism, between room temperature and the ferromagnetic Curie point of 680°C, the spin sublattices of hematite lie in the basal plane (1). Microwave resonance data for single crystals (2) suggest that the basal plane is practically isotropic. Direct measurements of the basal plane anisotropy of natural crystals (3) have revealed variable, generally small, two-, four-, and sixfold anisotropies, but these can account for coercivities of a few hundred oersteds at most. Yet the NRM of red sediments is frequently only slightly demagnetized by alternating fields of 2000 or 3000 oersteds!

The parasitic ferromagnetism of antiferromagnetic hematite is thought to contain two components. The first, a fundamental moment due to canting (4) of the spin sublattices, is observed only between the Morin (5) transition (at -20°C) and 680°C. The second, of variable intensity, is observable below -20°C (6) and between 680°C and the Néel point of 725°C (7, 8); it apparently originates in the interaction between the antiferromagnetism and lattice defects (9) or impurities (10). Smith and Fuller (7) report, for natural single crystals, that the defect

moment has remanent coercivities in the range of 1 to 3 kilooersteds, whereas the spin-canted moment is relatively soft. The implications for paleomagnetism are serious: the magnetically hardest component of NRM would be sensitive to changes in internal stress and could be remagnetized by geological stresses or heating.

In measurements of saturation magnetization that I made on synthetic hematite powders having grain sizes just above the superparamagnetic limit, I observed behavior opposite to that of Smith and Fuller's crystals. The spin-canted moment is *harder* than the structure-sensitive moment in these fine grains. If similarity of grain size and coercivity are reliable criteria, the same result should apply to red beds. Partial demagnetization of the NRM would then serve to isolate the paleomagnetically reliable spin-canted remanence.

The coercivity of the spin-canted moment alone was first investigated. At the University of Tokyo, I used a magnetic balance to measure hysteresis loops of a synthetic powder (grain size 0.2 to 0.7 μm , preannealed for 3 hours at 900°C) at temperatures ranging from -196° to 710°C. I estimated the antiferromagnetic susceptibility from the descending branch of the magnetization curve between 8 and 10 kilooersteds and subtracted the antiferromagnetic component from the results to derive the ferromagnetic hysteresis curve. Figure 1 shows σ_s , the "saturation" magnetization, and H_c , the coercive force, as functions of tempera-

ture. It is clear that 10 kilooersteds is not a saturating field at most temperatures; the 20°C saturation data are from a later experiment in which higher fields were used.

Below the Morin transition and above 680°C, I found no ferromagnetism. The defect moment, if present, is less than 2 percent of the spin-canted moment. The 20°C spectrum of remanent coercivities evidently extends well above 10 kilooersteds, and the coercive force versus temperature data show that coercivities of 100 oersteds or so—sufficient to ensure stability of spin-canted remanence in the earth's field of 0.5 oersted—persist up to 660°C. Similar information is given by partial thermoremanence measurements (11) on the same sample, which indicate blocking temperatures distributed between 630° and 670°C with a maximum at about 645°C. Spin-canted remanence is thus very resistant to thermal as well as to alternating-field demagnetization.

The relative stability of spin-canted and defect moments was investigated at the University of Paris. By using a 20-kilooersted electromagnet and a ballistic magnetometer, I measured the buildup of isothermal remanence σ_r , with fields H of increasing strength, for the Tokyo sample and for six new powders whose average grain sizes ranged from 0.5 to 5 μm . To enhance the spin-canted moment, I annealed the samples from 1 to 3 hours at temperatures between 650° and 950°C; I remeasured the σ_r versus H curve after each stage of heat treatment.

As Fig. 2 shows, the σ_r versus H curve becomes progressively harder (that is, a larger H is needed to produce a given σ_r) after successive anneals at increasingly high temperatures. This trend was common to all samples, although the amount of hardening varied from extreme (as in Fig. 2) to slight. Quenching, however, had little effect.

Enhancement of a hard spin-canted moment as the stress-sensitive moment anneals out is the preferred explanation, but not the only possible one. Grain growth probably occurs during heat treatment, but it is difficult to explain all the observations on this basis. If superparamagnetic grains ($<0.1 \mu\text{m}$) are growing to stable single-domain size, the low h_{cr} part of the remanent coercivity spectrum (the derivative of the σ_r versus H curve) should remain relatively constant; the inset in Fig. 2 demonstrates, however, that it is