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MAGNETIC REMANENCE IN THE WESTERN ATLANTIC SPINY LOBSTER, *PANULIRUS ARGUS*

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SUMMARY

The magnetic characteristics of 15 western Atlantic spiny lobsters (*Panulirus argus*) were analysed with a superconducting cryogenic magnetometer. Each specimen possessed a significant natural remanent magnetization (NRM) and isothermal remanent magnetization (IRM), indicating that ferromagnetic material is present. Analyses of the distribution of total remanence and mass-specific remanence indicate that magnetic material is concentrated in the cephalothorax, particularly in tissue associated with the fused thoracic ganglia. Mass-specific remanence and the total quantity of magnetic material in the cephalothorax and abdomen both increase as functions of carapace length.

The NRM is significantly orientated in at least four regions of the body. The NRM of the left half of the posterior cephalothorax is directed posteriorly, while that of the right half is orientated anteriorly. In addition, the NRM of the middle cephalothorax is orientated toward the right side of the animal; the NRM of the telson-uropods region is directed toward the left. The functional significance of these regions of orientated remanence is not known, but such a pattern could result from the ordered alignment of permanently magnetic particles comprising a magnetoreceptor system.

INTRODUCTION

The magnetic field of the earth influences the orientation of organisms ranging from unicellular algae (Lins de Barros, Esquivel, Danon & De Oliveira, 1981) and bacteria (Blakemore, 1975; Blakemore, Frankel & Kalmijn, 1980) to birds (e.g. Walcott, 1977; Gould, 1982) and mammals (Mather & Baker, 1981). Although behavioural data imply the existence of transduction mechanisms for coupling magnetic field stimuli to nervous systems (Kirschvink, 1982), magnetic field detection is clearly understood only in elasmobranch fish (Kalmijn, 1978) and magnetotactic bacteria (Kalmijn & Blakemore, 1978; Blakemore & Frankel, 1981). The discovery of magnetic remanence in honey bees (Gould, Kirschvink & Deffeyes, 1978), pigeons (Walcott, Gould & Kirschvink, 1979), dolphins (Zoeger, Dunn & Fuller, 1981), monarch

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bufferflies (Jones & MacFadden, 1982) and other animals has provided support for the hypothesis that tiny ferromagnets function as receptors for the magnetic sense in a number of organisms. Such particles could function literally as compass needles, exerting torque on secondary receptors as the magnets attempt to twist into alignment with the geomagnetic field (Yorke, 1979; Presti & Pettigrew, 1980).

The western Atlantic spiny lobster, *Panulirus argus*, undergoes an autumn migration characterized by the unremitting directional movement of thousands of lobsters in single-file head to tail processions (Herrnkind & Kanciruk, 1978). A striking feature of the migration is the uniformity of the directional bearings followed by lobster queues in the same geographic area (Herrnkind, Kanciruk, Halusky & McLean, 1973). The mechanisms underlying this precise orientation have not been established. Walton & Herrnkind (1977) demonstrated that *P. argus* can utilize wave surge and unidirectional currents as orientation guideposts. However, the migration persists in regions where hydrodynamic cues are altered by uneven underwater topography or irregular currents and when visual guideposts are obscured by overcast skies, murky water or darkness (Herrnkind, 1970; Herrnkind & McLean, 1971).

The lack of an apparent pervasive underwater guidepost and the directional specificity of the migratory queues suggest that spiny lobsters may derive directional information from one or more additional sources. As a first step toward determining if *P. argus* can detect the geomagnetic field, the magnetic parameters of spiny lobsters were systematically analysed with a superconducting cryogenic magnetometer. The results indicate that there is a non-random pattern of natural remanence in at least four regions of the body, thus implying the presence of an orderly array of magnetic particles which could comprise a magnetoreceptor system.

MATERIALS AND METHODS

Animals

Spiny lobsters were captured in the Florida Keys by trapping near Marathon Key and by diving near Woman Key. Specimens were maintained in plastic tubs with filtered flow-through sea water until needed. The carapace length of each lobster, defined as the distance from between the supra-orbital spines to the posterior edge of the cephalothorax (Kanciruk & Herrnkind, 1978), was measured with plastic calipers.

Eliminating magnetic contamination

Eliminating ambient magnetic contamination is a pervasive problem in biomagnetic studies (Jones & MacFadden, 1982; Quinn, Merrill & Brannon, 1981; R. E. Buskirk & W. P. O'Brien, in preparation). Several studies suggest that gut contents can contribute significantly to measurements of magnetic remanence (e.g. Quinn *et al.* 1981; R. E. Buskirk & W. P. O'Brien, in preparation). Although the diet of the lobsters was not controlled, 9 of the 15 lobsters examined had undergone ecdysis less than 3 days before they were analysed. It is thus unlikely that the digestive tracts of these moult stage A specimens contained food since spiny lobsters cease feeding several days prior to ecdysis and do not resume until several days after (Lipcius & Herrnkind, 1982). In addition, the foregut and hindgut of the lobsters are lined with

uncalcified chitin that is shed during moulting (Phillips, Cobb & George, 1980). Despite these factors, there were no discernible differences in magnetic parameters between lobsters which had undergone ecdysis within 3 days of analysis and those which had not (see 'Results').

All cleaning and dissection procedures were performed in a sterile, dust-free room, and all dissecting instruments used were first carefully washed in glass double-distilled, deionized water. Since metallic dissecting instruments can contaminate tissue with trails of magnetic particles (Kirschvink, 1980), only plastic implements were used.

To ensure that the lobsters did not acquire magnetic contamination from the sea water in which they were kept, six 100-ml water samples from the lobster tanks were analysed with the magnetometer. Two samples were placed into plastic sandwich bags; the other four were frozen in liquid nitrogen. The natural remanent magnetization (NRM) and isothermal remanent magnetization (IRM) of each sample were measured using the same procedure employed to analyse lobster tissue (see 'Measurement procedure'). None of the samples had any detectable remanence. Six samples of double-distilled, deionized water treated in the same way also did not have a detectable NRM or IRM.

Cleaning and dissection

Specimens were induced to autotomize all walking legs by pinching each appendage with plastic haemostats. The antennae, antennules, and third pair of maxillipeds were removed. Each lobster was then meticulously washed in a clean plastic tub filled with double-distilled, deionized water. The first phase of the washing procedure consisted of repeatedly submerging the lobster and swirling and shaking it vigorously underwater.

Preliminary experiments indicated that scrubbing the exterior surfaces of hard-shelled lobsters occasionally resulted in a slight reduction in NRM and/or IRM measurements. In the second phase of the washing procedure, all exposed surfaces of each specimen were thus vigorously and meticulously scrubbed with a toothbrush. The 45–60 min of scrubbing were interspersed with frequent rinsings with double-distilled, deionized water. At the conclusion of the scrubbing session, each specimen was again submerged repeatedly and shaken vigorously in fresh, double-distilled, deionized water.

The lobsters were dissected using plastic knives; a new knife was used to make each cut. Nine of the final eleven specimens analysed were cut into 11 pieces (Fig. 1). The two remaining lobsters had particularly wide posterior cephalothoraxes which had to be cut into four pieces rather than the usual two before they could be analysed in the magnetometer. After each piece had been severed from the body of the lobster, it was picked up with plastic haemostats and carefully wrapped in pieces of Saran wrap or plastic sandwich bags. The wrapped pieces were placed into clean, airtight, plastic containers and transported to the magnetometer.

Measurement procedure

All magnetic measurements were made with the Superconducting Technology cryogenic magnetometer at the University of Florida. This instrument employs a superconducting quantum interference device (SQUID) sensor cooled to liquid helium temperature (4 °K) and is capable of detecting magnetic fields down to about

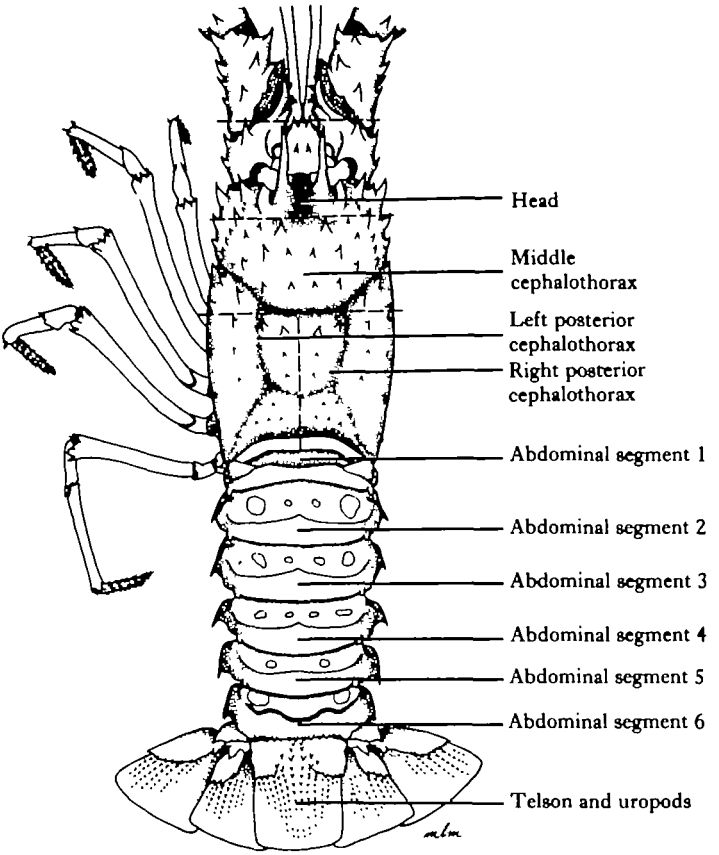

Fig. 1. The cephalothorax of each lobster was divided into four pieces by cutting along the dashed lines shown. The abdomen was then severed into six abdominal segments and a seventh piece consisting of the telson and uropods. (The first abdominal segment is partially obscured by the posterior edge of the cephalothorax. During analysis the uropods were collapsed toward the longitudinal body axis rather than extended laterally as shown.)

2×10^{-11} Am^2. Goree & Fuller (1976) present a detailed description of the design and applications of this instrument.

The measurement procedure closely followed the methodology described by Jones & MacFadden (1982). In the present study, however, plastic sandwich bags were attached to a mylar tube with Scotch® tape and used to support the samples in the magnetometer. To begin the measurement procedure, the sandwich bag and mylar tube were lowered into the magnetometer and analysed for possible contamination. If the magnetic moment was less than 2×10^{-11} Am^2 (i.e. less than the background noise of the magnetometer), the bag was used in the subsequent measurement. Occasionally a bag possessed an NRM greater than background noise and was discarded.

The pieces of each lobster were analysed in random order. When a satisfactory bag had been obtained, a sample was placed inside and manoeuvred into the appropriate orientation by bracing it against the bottom of the mylar tube. It was then lowered into the magnetometer for analysis. Five measurements were taken in the x, y and z axes

These values were used to calculate a mean vector for each axis. The resulting vectors were used to calculate the intensity and direction of the total NRM.

The tissue sample was then removed from the holding bag with plastic haemostats. The bag was remeasured in the magnetometer to ensure that the NRM had not changed. The lobster sample was transported across the laboratory and placed 1 cm away from a 3000 Oe magnet; the tissue was always orientated so that its most anterior end faced the magnet directly. After 10 s the sample was removed from the magnet, replaced in the holding bag, and remeasured in the magnetometer. The IRM was computed from the mean values of five measurements in each axis. When the magnetic measurements had been completed, the samples were weighed on a Mettler digital balance. Using these procedures, about 16–22 h of magnetometer time were required completely to analyse the body of each lobster.

RESULTS

All of the 15 lobsters examined possessed a significant NRM and IRM in at least some tissue samples. The first four lobsters analysed, however, were not cut into precisely the same pieces as the final 11 specimens. It is thus difficult to compare the two groups quantitatively. The data presented in Table 1 are for the final 11 specimens for which the dissection procedure was standardized as shown in Fig. 1. Additional measurements are reported by Lohmann (1983).

The NRM accurately reflects the total amount of magnetic material present only if all sources of remanence are aligned in the same direction so that individual magnetic moments do not cancel each other. The IRM is thus typically a better indicator of the total quantity of magnetic material present since the strong ambient field usually forces individual moments into alignment. In this study an occasional sample had a NRM slightly (usually <9 %) higher than the IRM. Preliminary experiments suggest that this result may be attributable to a remanence carrier with relatively high coercivity, since some tissue samples were stable when subjected to an ambient field of about 500 Oe (Table 2). The higher of the two measurements (NRM or IRM) for each

Table 1. *Summary of NRM, IRM and mass-specific remanence (MSR) data*

Piece	*N*	Mean NRM	S.D.	Mean IRM	S.D.	Mean MSR	S.D.
Head	11	111·6	175	127·5	144	66·6	60
Middle cephalothorax	11	149·0	222	247·4	218	118·8	181
Left posterior cephalothorax	11	241·6	359	248·5	339	108·0	107
Right posterior cephalothorax	11	228·9	414	275·2	387	88·0	88
Abdominal segment 1	11	97·3	181	97·5	173	52·8	82
Abdominal segment 2	11	50·4	82	55·0	81	47·1	63
Abdominal segment 3	11	42·9	67	60·5	85	51·8	64
Abdominal segment 4	11	33·8	62	37·2	61	36·7	41
Abdominal segment 5	11	9·6	10	11·6	8	21·8	12
Abdominal segment 6	11	11·2	20	23·6	35	46·8	53
Telson and uropods	11	8·2	10	17·0	8	42·1	38

All measurements pertaining to intensity of the NRM and IRM are ($\times 10^{-11}$ Am^2). The background noise of the magnetometer is 2–3 $\times 10^{-11}$ Am^2. Measurements pertaining to the mass-specific remanence are ($\times 10^{-8}$ Am^2 kg^{-1} tissue wet weight).

Table 2. *Preliminary data suggesting the presence of highly coercive magnetic material in* Panulirus argus

Sample	Direction 500 Oe field applied from	DEC	INC
Middle cephalothorax			
NRM	—	130°	−8°
IRM	0°	110°	−23°
IRM	90°	92°	−1°
IRM	Top	135°	−21°
Posterior cephalothorax (both halves together)			
NRM	—	131°	68°
IRM	Top	88°	−2°
IRM	0°	95°	6°
IRM	90°	82°	35°
IRM	180°	110°	−3°
IRM	270°	167°	−49°

Two tissue samples from the cephalothorax of a small spiny lobster were analysed with the magnetometer to determine the orientation of the NRM.

Orientation of remanent magnetization is described by declination (direction within the horizontal plane) and inclination (vertical component or dip, where positive inclination is defined as downward and +90° is directly down). The samples were exposed to a 500 Oe field for 10 s and remeasured with the magnetometer. The process was repeated several times with the samples orientated in different directions relative to the magnetic field. The resulting IRMs did not track the applied field very closely. In each case the IRM declination remained within 50° of the original NRM declination, regardless of the direction from which the ambient field was applied and despite repeated exposures to the 500 Oe field. These data suggest that there is a component of remanence along a preferred direction that is stable at ambient fields of about 500 Oe. Because of the difficulty associated with reproducibly aligning samples in the magnetometer, the margin of error is estimated at 15° for the declinations (DEC) and 20° for the inclinations (INC).

sample was thus used for an estimate of the total amount of magnetic material present, although such estimates are likely to be slightly low in some cases. Mass-specific remanence was calculated by dividing this quantity by the gram wet weight of each piece.

There was considerable individual variation in the amount of magnetic material present (Table 1), but the relative distribution of magnetic material in different animals was similar. There were no detectable differences in the data between the sexes, between lobsters which had recently undergone ecdysis and those which had not, or between specimens from the different geographic locations (Wilcoxon ranked signs tests and *t*-tests). However, the small sample sizes could obscure such differences. In this initial study all 11 lobsters were grouped together for the statistical analyses.

Distribution of magnetic material

An analysis of the maximum remanence values indicated that the distribution of magnetic material is not uniform throughout the body (Friedman two-way analysis of variance; $Xr^2 = 70{\cdot}4$, $P << 0{\cdot}001$). The measurements of the four cephalothorax pieces were added together to obtain a total remanent magnetization measure of th

cephalothorax. This value was compared with the sum of the maximum remanence values of the seven pieces of the abdomen in each lobster. The results indicate that the total remanent magnetization of the cephalothorax is significantly higher than that of the abdomen (Wilcoxon ranked signs test; $z = -2{\cdot}93$; $P = 0{\cdot}003$). The more massive cephalothorax also contained significantly more magnetic remanence per kg than did the abdomen (Wilcoxon ranked signs test; $z = -2{\cdot}85$; $P = 0{\cdot}004$).

The four pieces of the cephalothorax do not contain equivalent amounts of magnetic material (Friedman two-way analysis of variance; $Xr^2 = 15{\cdot}5$; $P = 0{\cdot}001$). Wilcoxon ranked signs tests indicate that the left posterior cephalothorax contains significantly more magnetic material than does the head ($z = 2{\cdot}00$; $P = 0{\cdot}043$). The difference between the measurements of the head and middle cephalothorax and between the head and the right posterior cephalothorax approach significance ($z = 1{\cdot}87$; $P = 0{\cdot}059$ in both cases). There was no difference between the measurements of the middle cephalothorax and those of the left and right posterior cephalothorax regions.

The distribution of magnetic material in the abdomen is also not uniform (Friedman two-way analysis of variance; $Xr^2 = 15{\cdot}8$, $0{\cdot}01 < P < 0{\cdot}02$). The fifth abdominal segment possessed significantly less remanence than the first, second, third and fourth abdominal segments ($P \leqslant 0{\cdot}027$ for all cases). There were no significant differences in values between any of the other regions of the abdomen.

An analysis of the mass-specific measurements indicated that there is no significant difference between the remanence per kg in different pieces of the cephalothorax. Similarly, there is no difference between the mass-specific measurements in different pieces of the abdomen.

The posterior cephalothorax of one specimen was systematically dissected and remeasured in the magnetometer in an attempt to localize the magnetic material in this region. The source of about 85 % of the NRM was tissue located between the arches formed by the mesophragma of the endosternites and the fused sternal plates. The muscle lying dorsal to this region was markedly non-magnetic. The tissue sample containing most of the remanence surrounds and includes the fused thoracic ganglia (George, Reuben & Muthe, 1955).

Orientation of NRM

The orientation of the NRM measurements in each piece of the lobster was analysed with Fisher statistics. The results indicate that 4 of the 11 pieces possess significantly orientated natural remanence (Figs 2, 3).

Magnetic parameters and body size

A preliminary examination of the relationship between the size of each animal and the magnitude of the magnetic parameters was made using carapace length as an indicator of size (Kanciruk & Herrnkind, 1978; Phillips, Cobb & George, 1980). Correlations were calculated for the four possible pairings between total cephalothorax remanence, carapace length and the natural log-transformed value of each (Fig. 4A). Similar calculations were computed for total abdomen remanence (Fig. 4B) and for mass-specific measurements in both the abdomen and cephalothorax (Fig. 5).

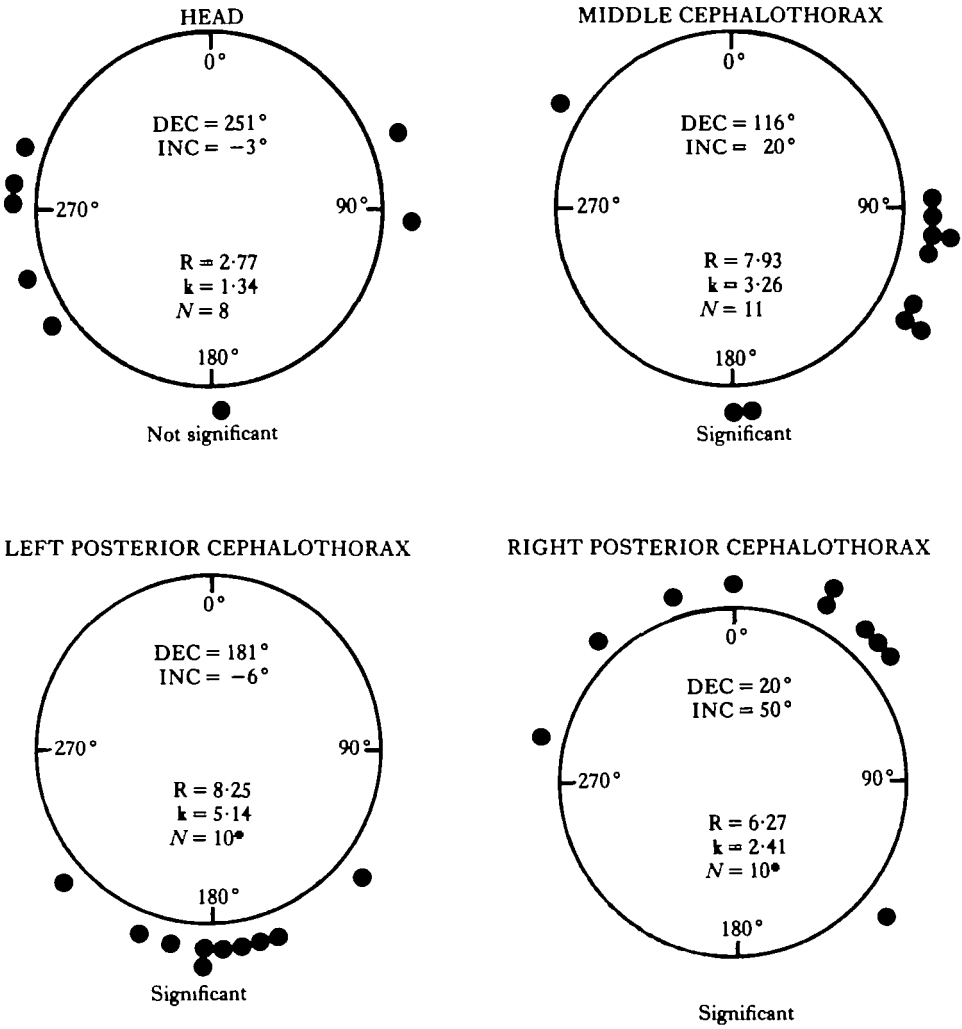

Fig. 2. The declination measurements of the NRM in the four pieces of the cephalothorax. A declination of 0° indicates that the net natural field is directed anteriorly within the horizontal plane; a declination of 90° is orientated toward the right side of the animal, 180° is directed posteriorly, and 270° toward the left of the lobster. Inclination data for each lobster are not shown but were used in the analysis of NRM orientation. The orientation of the NRM in three dimensions was analysed and statistically tested using the Fisher directional distribution on a sphere. Only NRM measurements exceeding 4×10^{-11} Am^2 (those clearly above the background noise of the magnetometer) were used. N = the number of specimens out of 11* with an NRM $> 4 \times 10^{-11}$ Am^2, k = Fisher precision parameter, DEC = Fisher declination, INC = Fisher inclination, and R = the sum of the individual vectors in the mean direction. 'Significant' indicates that the NRM is significantly orientated using a confidence level of 95 %. * The data presented for the two halves of the posterior cephalothorax do not include the two specimens in which this region was severed into four pieces. However, the posterior cephalothorax of an additional animal was examined and the data involving orientation of the NRM are included. Thus, the data for the two halves of the posterior cephalothorax are for 10 lobsters instead of 11.

Fig. 3. The NRM declinations in the seven pieces of the abdomen. N is the number of specimens (out of 11) with an NRM $> 4 \times 10^{-11}$ Am^2, k = Fisher precision parameter, DEC = Fisher declination, INC = Fisher inclination, R = sum of the individual vectors in the mean direction, and 'Significant' indicates that the NRM is significantly orientated using a confidence level of 95 %.

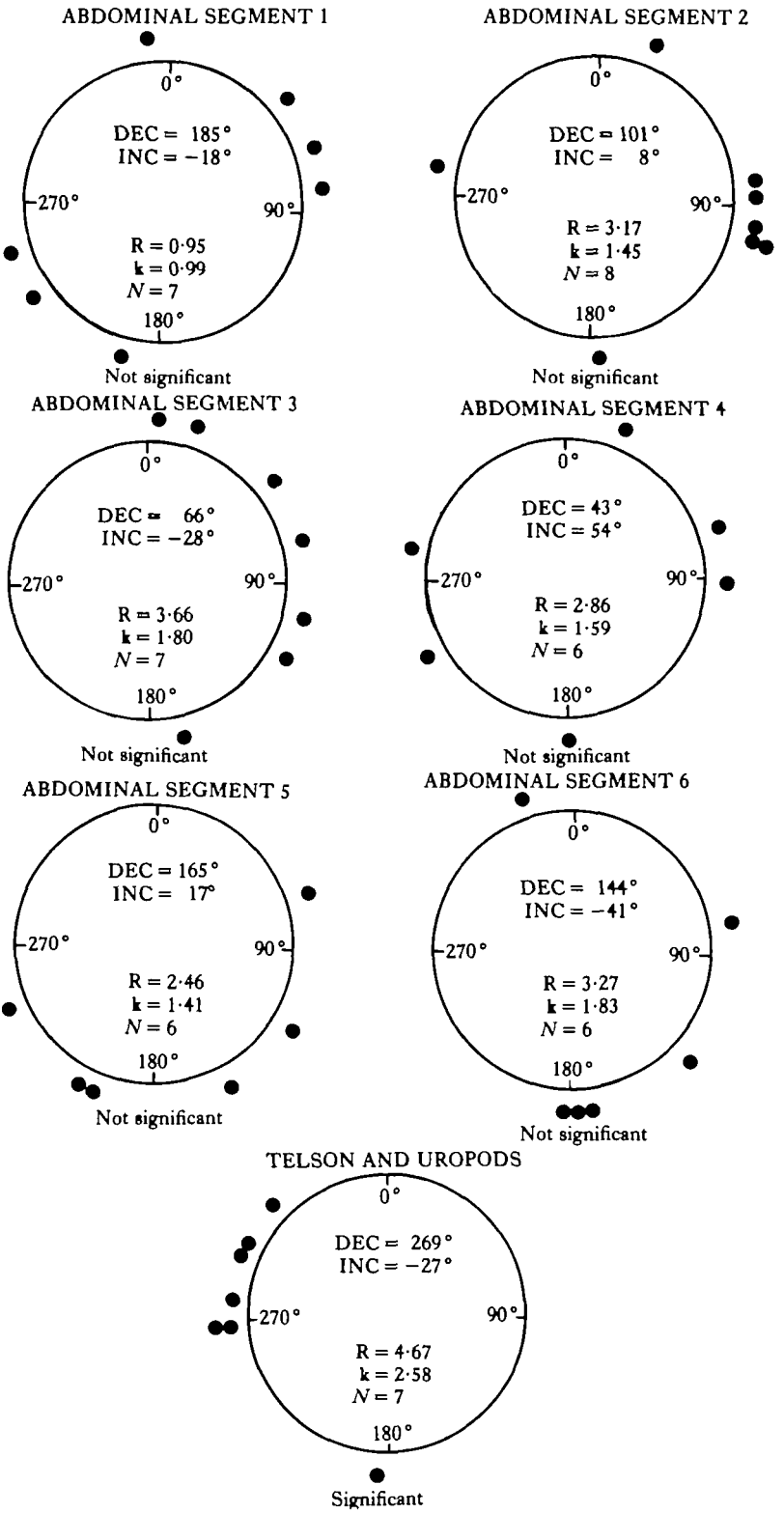
ABDOMINAL SEGMENT 1
0°
DEC = 185°
INC = −18°
270°
90°
R = 0·95
k = 0·99
N = 7
180°
Not significant
ABDOMINAL SEGMENT 2
0°
DEC = 101°
INC = 8°
270°
90°
R = 3·17
k = 1·45
N = 8
180°
Not significant
ABDOMINAL SEGMENT 3
0°
DEC = 66°
INC = −28°
270°
90°
R = 3·66
k = 1·80
N = 7
180°
Not significant
ABDOMINAL SEGMENT 4
0°
DEC = 43°
INC = 54°
270°
90°
R = 2·86
k = 1·59
N = 6
180°
Not significant
ABDOMINAL SEGMENT 5
0°
DEC = 165°
INC = 17°
270°
90°
R = 2·46
k = 1·41
N = 6
180°
Not significant
ABDOMINAL SEGMENT 6
0°
DEC = 144°
INC = −41°
270°
90°
R = 3·27
k = 1·83
N = 6
180°
Not significant
TELSON AND UROPODS
0°
DEC = 269°
INC = −27°
270°
90°
R = 4·67
k = 2·58
N = 7
180°
Significant

Fig. 3

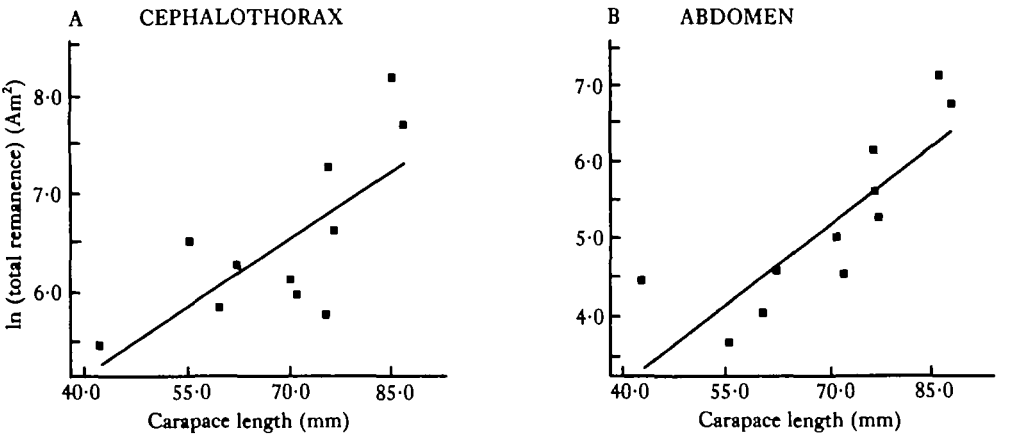

Fig. 4. (A) The natural log-transformed total remanence of the cephalothorax as a function of carapace length. The regression equation is $Y = 0{\cdot}046X + 3{\cdot}22$; $r = 0{\cdot}713$, $P = 0{\cdot}013$. Other correlations calculated were: carapace length (CL) *vs* total cephalothorax remanence (TCR), $r = 0{\cdot}653$; ln(CL) *vs* ln(TCR), $r = 0{\cdot}674$; ln(CL) *vs* TCR, $r = 0{\cdot}597$. (B) The natural log-transformed total remanence of the abdomen as a function of carapace length. The regression equation is $Y = 0{\cdot}070X + 0{\cdot}28$; $r = 0{\cdot}824$, $P = 0{\cdot}002$. Other correlations calculated were: CL *vs* total abdomen remanence (TAR), $r = 0{\cdot}720$; ln(CL) *vs* ln(TAR), $r = 0{\cdot}765$; ln(CL) *vs* TAR, $r = 0{\cdot}656$.

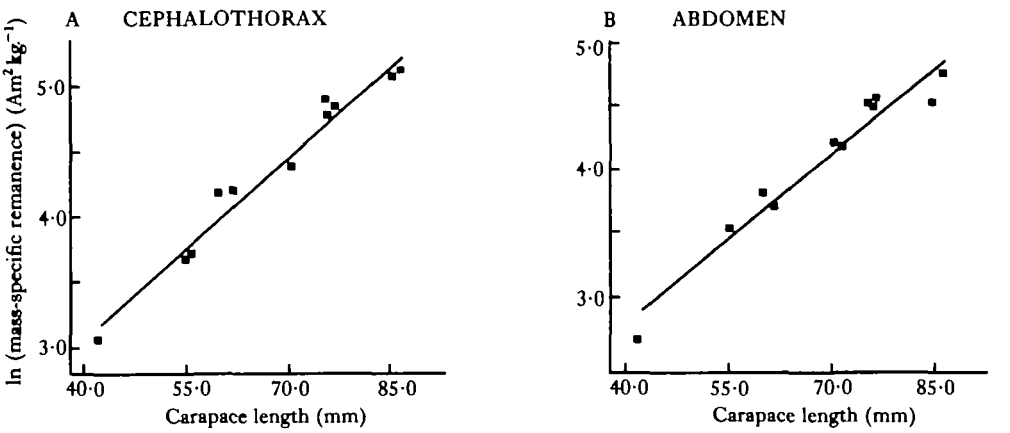

Fig. 5. (A) The natural log-transformed mass specific remanence of the cephalothorax as a function of carapace length. The regression equation is $Y = 0{\cdot}047X + 1{\cdot}12$; $r = 0{\cdot}981$, $P < 0{\cdot}001$. Other correlations calculated were: CL *vs* mass-specific cephalothorax remanence (MCR), $r = 0{\cdot}964$; ln(CL) *vs* ln(MCR), $r = 0{\cdot}987$; ln(CL) *vs* MCR, $r = 0{\cdot}938$. (B) The natural log-transformed mass-specific remanence of the abdomen as a function of carapace length. The regression equation is $Y = 0{\cdot}044X + 0{\cdot}93$, $r = 0{\cdot}966$, $P < 0{\cdot}001$. Other correlations calculated were: CL *vs* mass-specific abdomen remanence (MAR), $r = 0{\cdot}958$; ln(CL) *vs* ln(MAR), $r = 0{\cdot}981$; ln(CL) *vs* MAR, $r = 0{\cdot}943$.

Appendages and mandibles

The antennae, antennules and legs of the lobsters were not systematically examined in this study. However, four antennae and five antennules from three lobsters were analysed in detail. These appendages characteristically had little ($\leq 1 \times 10^{-10}$ Am^2) or no magnetization (either NRM or IRM), and that present could usually be removed with meticulous washing. The statocysts at the base of the antennules did not possess a detectable NRM or IRM. The legs of one specimen were scanned by

lowering them slowly past the SQUID sensors. The NRM and IRM measurements were comparable in magnitude to the antennae. While it would be premature to dismiss the limited remanence of these appendages as ambient contamination, these data suggest that magnetic material is not concentrated in these regions.

The mandibles of three lobsters were also analysed. The magnetic mineral magnetite (Fe_3O_4) occurs on the denticle cappings of chitons (Mollusca, Polyplacophora) and is believed to function in scraping algae from rocks as the animals feed (Lowenstam, 1962). Since magnetite is the hardest mineral known to be synthesized biologically (Kirschvink, 1982), it could conceivably fulfil a grinding function in lobster feeding. However, none of the mandibles analysed possessed a detectable NRM or IRM.

DISCUSSION

The presence of a significant NRM and IRM in each of the 15 specimens indicates that magnetic material is present in *P. argus*. The precautions taken against contamination from external sources make it unlikely that the magnetic remanence is attributable to substances in the digestive tract or to contaminants on the external surfaces of the lobsters.

The statistical analyses indicate that the cephalothorax contains both significantly more magnetic material and significantly more magnetic material per unit mass than does the abdomen. Magnetic material in *P. argus* is thus concentrated in the cephalothorax. In 10 of the 11 specimens the highest total remanence measurements were obtained from the middle or posterior cephalothorax. These regions all contain tissue surrounding and including the fused thoracic ganglia.

The three pieces of the cephalothorax containing parts of the fused thoracic ganglia all possess significantly orientated natural remanence (Fig. 2). The Fisher mean declination for the middle cephalothorax is 116°, while that of the left posterior cephalothorax is 181° and that of the right posterior cephalothorax is 20°. This pattern of orientated remanence is unlikely to be an artifact of the cleaning or dissection procedures for several reasons. First, although these processes were carried out in the geomagnetic field, most of the specimens died from osmotic shock during the washing procedure while being constantly rotated, rinsed and scrubbed. The NRM pattern is thus unlikely to have resulted from similarities in the position of the specimens relative to magnetic north at the time of death. Similarly, variations in the orientation of lobsters after washing and during the dissection process make it improbable that the observed pattern arose from interactions between the geomagnetic field and endogenous magnetic particles after the animals died. Thirdly, individual pieces were placed randomly into plastic containers after they were severed from the bodies of the lobsters, and the containers were rotated frequently while being transported to the paleomagnetic laboratory. Lastly, the final pieces of the cephalothorax to be separated in the dissection were always the two halves of the posterior cephalothorax; these pieces have virtually antipodal declinations (Fig. 2). Since it is difficult to explain the orientated natural remanence as an artifact, it is likely that the remanence carrier is consistently orientated in the same direction in corresponding regions of different individuals.

The pattern of NRM declinations in the four regions of the body with orientated natural remanence is striking. The mean NRM declination in the left posterior cephalothorax is reasonably close to 180°, indicating that the remanence carrier in this region is aligned so that the resulting magnetic field is directed posteriorly. In contrast, the mean declination of 20° in the right half of the posterior cephalothorax indicates a net field directed more or less anteriorly. The NRM of the middle cephalothorax is orientated toward the right side of the animal, while that of the telson-uropods region is significantly orientated toward the left (although only 7 of the 11 telson-uropod samples possessed an NRM $> 4\times10^{-11}$ Am^2). The functional significance of these regions of orientated NRM is not known, but such a pattern could result from the ordered alignment of ferromagnetic particles comprising a magnetoreceptor system.

If the magnetic material functions as a transducer for a magnetic sense, it seems unlikely that the divisions of the body arbitrarily used in this study correspond to functional units of magnetoreceptors. The orientation of natural remanence within subdivisions of the tissue samples was not examined, but it seems possible that other regions of orientated NRM exist within the boundaries of the samples or were divided in the dissection.

Relationships between body size and biomagnetic parameters have not previously been examined in any animal. The preliminary data presented here are inadequate to determine the precise nature of the relationships between carapace length and the various magnetic measurements. However, the data suggest that the quantity of magnetic material in the cephalothorax and abdomen is an increasing non-linear function of carapace length (Fig. 4). A similar relationship exists between mass-specific data and carapace length (Fig. 5). Additional research is needed because of the restricted size range of the lobsters examined (carapace length = 43–87 mm) and the small sample size. Nevertheless, it appears evident that body size significantly influences at least some biomagnetic parameters in *P. argus*.

The data obtained in this study indicate that magnetic material occurs in *P. argus*, that it is concentrated in the cephalothorax, and that it is orientated non-randomly in some regions of the body. There is currently no evidence that this magnetic material functions as a transducer for a magnetic sense. Behavioural studies are needed to determine if spiny lobsters can detect magnetic fields and if the geomagnetic field functions as a guidepost in migratory navigation. The underwater habitat and presence of multiple orientation cues along the migratory routes (Walton & Herrnkind, 1977) will make this a challenging undertaking.

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