USE OF PALEOMAGNETIC EVIDENCES FOR SOME TECTONIC IMPLICATIONS OF AQRA LIMESTONE OUTCROPS NORTHEASTERN IRAQ

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Abstract

Maastrichtian Aqra limestone Formation at Maukaba and Zardabe localities were sampled for paleomagnetic investigations. 80 oriented limestone drill cores were collected from these localities, which are situated at the northeast part of Iraq. Following stepwise thermal demagnetization procedures, two main magnetic components were determined، a low-temperature component at (20-200)ºC that is regarded as overprint secondary unstable magnetic component with magnetic direction around the present Earth's field; and medium - high temperature component at (250-600)ºC which is carried by high coercivity magnetic grains. It shows stable magnetic component. IRM reveals that the remanent magnetization in the Aqra limestone Formation is of a depositional origin and carried by a detrital magnetite grains. Rock magnetic analysis indicates that the primary magnetite is the dominant remanence carrying minerals observed in Maukaba and Zardabe specimens. Both of these rocks show stable and reverse paleomagnetic directions. There is a clear difference in the declinations between these two localities, which is probably due to the existed transverse faults and local tectonic movements. These movements usually indicated by the divergence of fold axis of Azmar anticline. By removing of these paleo movements It is clearly indicated that the folding and the divergence in the fold axis happened after Aqra Limestones rocks acquired their primary magnetic directions.

It seems that the Neotethys Ocean to the north and northeast of studied area was still there during Maastrichtian age. The closure of this ocean apparently happened sometime between the Maastrichtian and Lower Tertiary. The rotational movement of Afro-Arabian plate towards the northeast part of Iraq causing the closing of the ocean and then the collision with Iranian and Turkish micro plates. This movement caused the Arabian plate to move about 20 degrees in latitude.

أستخدام أدلة المغناطيسية القديمة لبعض التطبيقات التكتونية في مكاشف تكوين عقرة الجيري شمال شرق العراق

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الخلاصة

تم دراسة المغناطيسية القديمة لمكاشف تكوين عقرة الجيري (الماسترختيان) في موقعي موكيبه وزردبي وذلك من خلال جمع (٨٠) نموذج لباب موجه من الموقعين أعلاه الواقعة في شمال شرق العراق . بأتباع خطوات عملية التنظيف الحراري تم تحديد مركبتين مغناطيسيتين رئيسيتين ، مركبة تم نزعها عند درجة حرارة منخفضة (٢٠-٢٠٠) درجة مئوية والتي تعد مركبة مغناطيسية ثانوية مطبوعة غير مستقرة ذات أتجاه قريب من أتجاه المجال المغناطيسي الأرضي الحالي ، ومركبة تم عزلها عند درجة حرارة (متوسطة–عالية) (٢٥٠-٦٠٠) درجة مئوية والمحمولة من قبل حبيبات مغناطيسية ذات قوة ممانعة عالية وهي مركبة مغناطيسية مستقرة . أظهرت نتائج تقنية التحليلات الحرارية للمغناطيسية المتبقية بأن المغناطيسية المتبقية المتواجدة في صخور تكوين عقرة الجيري تمثل مغناطيسية ذات أصل ترسيبي محمولة بواسطة حبيبات معدن المكنتايت المتفتت والذي دلت عليه نتائج تحليل مركبات العينة ، حيث تبين أنها تمثل المعدن السائد الحامل للمغناطيسية المتبقية في عينات الموقعين أعلاه ، وتبين أن صخور كلا الموقعين تحمل أتجاهات مغناطيسية مستقرة ومقلوبة. يوجد اختلاف واضح في قيم زوايا الأنحراف بين هذين الموقعين وهذا ممكن أن يحصل بفعل حدوث الفوالق المستعرضة والحركات التكتونية المحلية. أن هذه الحركات عادة ما يستدل عليها من خلال ملاحظة أنحراف محور طية أزمر. وعند أرجاع محور طية أزمر الى موقعه السابق في موقعي موكيبه وزردبي، فأنه من الملاحظ بأن الأتجاهات المغناطيسية لهذين الموقعين سيتطابقان ليشكلان أتجاه خطي واحد يمثل محور طية أزمر قبل الأنحراف ، مما يدل على أن عمليتي الطي والأنحراف في طية أزمر قد حدثتا بعد أن أكتسبت صخور تكوين عقرة الجيري أتجاهاتها المغناطيسية الأولية.

أن محيط التثس القديم الواقع في شمال وشمال شرق منطقة الدراسة كان موجودا خلال عصر الماسترختيان وأن أنغلاق هذا المحيط محتمل أنه قد حدث في الفترة ما بين الماسترختيان والعصر الثلاثي الأسفل . أن الحركة الدورانية للصفيحة الأفريقية–العربية بأتجاه شمال شرق العراق قد أدت الى أنغلاق المحيط ثم أصطدامها مع الصفيحتين الثانويتين الأيرانية والتركية ، الأمر الذي جعل الصفيحة العربية تتحرك بحدود (٢٠) درجة خط عرض.

Introduction

The studied area is located at the north of Sulaimaniya governorate, northeastern Iraq. It is covered by high mountains trending northwest-southeast especially Azmar mountain. (1 and 2) (Figure.1). The structure and the tectonic evolution of the study area are strongly influenced by the location of the Arabian part of the African platform and the Asian branches of the Alpine geosyncline in addition to the opening and closing of the Paleotethys and Neotethys (3). The Arabian part of the African platform can be divided into two units; they are the stable and the unstable shelves. However, NE boundary of the unstable shelf is not yet precisely ascertained throughout the area. The reason is partly the insufficient geological data. The unstable shelf can be divided into three zones: Mesopotamian zone, foothill zone and the high folded zone (4). The studied area is situated within the high folded zone. The lower contact of Aqra Formation with Tanjero Formation is gradational and where the conglomerate wedges out tongues laterally into Tanjero marl and shale member. It is greyyellowish well bedded bioclastic calcareous, calcareous sandstone and silty shale.

Unfortunately, there are very few paleomagnetic studies achieved in Iraq. Hijab 5 has performed his paleomagnetic investigations about the Jurassic sediments in Iraq. He concluded that the NE part of the country (Alpine geosynclinal belt) was a part of the Iranian plate during the Upper Jurassic. Moreover, Turkey, Iran, central Afghanistan and Baluchistan were parts of the Arabian plate during Late Precambrian and Paleozoic times. However, 6 have been re-evaluated the paleopole geography of the Arab homeland (including Iraq) and the adjacent countries like Turkey and Iran using performed paleomagnetic information. He also demonstrated a possible review and theoretical approach to the tectonics of these countries.

In this study, Carbonate (Aqra Formation) is considered as very good rocks for paleomagnetic studies, because they recorded the paleomagnetic directions and kept them through the geologic times. Therefore, this formation was chosen as a good target for paleomagnetic investigations. So, the first aim of this research is to make paleomagnetic study for the sedimentary Aqra limestone Formation which outcrops NE part of Iraq. It could be of great help in the tectonic evolution of this area. Location of the paleoposition of the studied area during the geological times is the second aim.

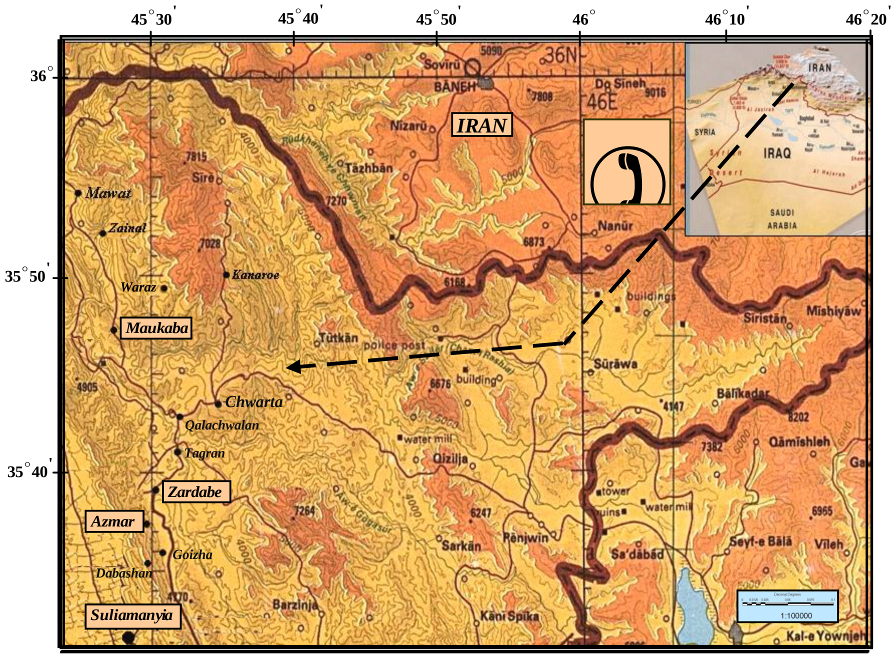

Figure 1: Location map of the studied area (modified from internet, 2006)

Field and laboratory work

In spite of the rugged topography, complicated structures and scarps existing in the whole area, a systematic fieldwork was precisely made. The samples investigated in this study were extracted from Maukaba and Zardabe locations on approximately three weeks. We drilled typically at least six cores per site from an area of (0.15) m2. Attitude (strike and true dip) of the beds were recorded more than once at each sampling locality, so that the direction of magnetization can be related to the paleohorizontal (7). Consequently, during May and Jun/2005, (80) core samples were collected from (14) sites distributed in the region as illustrated in (Table 1).

Table 1: Paleomagnetic information about core samples which collected from the area understudy

Locality	*Coordinates*		*Elevation m. (asl)*	*Bed attitude*		*No. of sites*	*No. of core samples*	*Sampling date*
	Latitude	*Longitude*		*Strike*	*Dip*			
Zardabe Village	35° 37′ 44″	45° 24′ 32″	917	N 17º E	30º NW	8	46	15-24/5/2005
Maukaba Village	35° 47′ 50″	45° 21′ 10″	817	N 23º W	65º NE	6	34	26/5-2/6/2005

Noise level

Due to the lack of paleomagnetic laboratory in Baghdad University, an attempt was made to locate a suitable place with less noise effect. Hence, three NRM measurements for more than (35) specimens were accomplished using Spinner Magnetometer, in order to identify the influence of the associated noise caused by magnetic materials existed surrounding the above instrument. One specimen was chosen from every site to conduct this process, and on the other hand, another sample from the same site might properly replace the selected one in case of abnormal results. In one place (within Geology Department) it appears that only (18) samples relatively gave close magnetic intensities; declinations and inclinations. Standard deviations of declination, inclination and intensity which calculated for these samples are varying from (1.9º-5.3º), (2º-4.3º) and (1.7-7.2) mAm-1 respectively (Table-2), while the remaining specimens have high standard deviations. On this ground, the suitable place for measurements was chosen and it is decided to repeat the measurements twice (at least) in order to reduce noise effect.

Table 2: Three NRM measurements and standard deviations for detecting noise effect purposes

Sample No.	1^{St} NRM Measurements			2^{nd} NRM Measurements			3^{rd} NRM Measurements			Standard deviation of the mean value		
	Dec°	Inc°	Int. mAm^{-1}	Dec°	Inc°	Int. mAm^{-1}	Dec°	Inc°	Int. mAm^{-1}	Dec°	Inc°	Int. mAm^{-1}
Ch 1.3	15.6	58.1	0.0435	13.4	54.4	0.0524	11.8	51.2	0.0568	1.9	3.5	7.2
Ch 2.6	297.3	-25.8	0.0377	295	-24	0.0368	300.6	-28.9	0.0471	2.8	2.5	5.7
Ch 3.4	22.5	-34.9	0.0549	18.9	-31.6	0.0626	15.7	-29.5	0.0638	3.4	2.7	4.8
Ma 7.3	121.7	-83.9	0.0523	118.3	-80.1	0.0409	115.9	-78.5	0.0387	2.9	2.8	7.2
Ma 8.4	115.9	-88.4	0.0489	112.3	-85.2	0.0405	113.8	-87.3	0.0453	2.5	2.6	4.2
Ma 9.3	271.2	-80	0.0391	274.3	-84.2	0.0415	280.5	-87.5	0.0466	4.7	3.8	5.2
Ma 11.4	121.2	-80.2	0.0483	113.1	-74.7	0.0436	116.4	-77.1	0.0476	4.1	2.8	2.5
K 13.4	217.6	52.1	133.874	223.4	59.9	133.882	220.1	56	133.880	2.9	4	4.2
Z 15.2	136.7	55.4	0.0682	126.1	46.8	0.0666	131	50	0.0606	5.3	4.3	4
Z 16.3	274.1	75.1	0.0761	269.2	70.4	0.0684	267.5	69.2	0.0633	3.4	3.1	6.7
Z 18.4	310.1	-17	0.0796	312.2	-18.6	0.0754	316	-20.9	0.0806	3	2	2.7
Zr 21.3	254.3	-79.9	1.010	251.4	-76.6	1.002	248.2	-73.7	0.0998	3.1	3.1	6.1
Zr 24.2	153.3	-80.3	0.1259	155.5	-83.9	0.1261	149.1	-78.6	0.1254	3.3	2.7	3.6
Zr 25.1	218.1	-76.9	0.8318	221.5	-79.2	0.8359	225.3	-83.3	0.8374	3.6	3.2	2.8
Zr 26.3	236.9	-66.3	0.1647	239.2	-68.8	0.1624	244	-73.6	0.1658	3.6	3.7	1.7
Az 28.5	159.4	60	0.0804	157.1	56.6	0.0754	155.2	53.3	0.0688	2.1	3.4	5.8
Az 31.5	229.6	19.4	0.0799	225	16.9	0.0764	221.4	14.3	0.0748	4.1	2.5	2.6
W 35.1	1.5	31.4	3.648	2.3	33.7	3.653	5.5	37.5	3.655	2.8	3.1	3.6

Paleomagnetic Measurements and Results

Measurements of the natural remnant magnetization (NRM) of samples were done using Spinner Magnetometer Model SSM-1A (existed in University of Baghdad-Iraq) and a 2G Enterprises horizontal DC SQUID cryogenic Magnetometer (existed in Oklahoma University-USA). In order to come to an understanding of the nature of the stable magnetic components existed in the samples, and the nature of the magnetic minerals which carry the remnant magnetization, thermal and alternating field demagnetizations were applied for (16) pilot specimens representing (8) sites out of (14) sites. Pilot specimens usually chosen randomly from the six specimens of each site. The aim here is to identify which method is more convenient for the demagnetization processes (14). From the (12) pilot specimens, eight specimens were conducted in Oklahoma University (USA), four specimens for each thermal and alternating field demagnetizations.

1. Thermal Demagnetization

Thermal demagnetization analysis was applied for eight pilot specimens (Ma 7.3, Ma 8.4, Ma 9.3, Ma 11.4, Zr 21.3, Zr 24.2, Zr 25.1 and Zr 26.3) using the thermal demagnetizer model (TSD-1) available in Geology Department, Baghdad University. These specimens were heated and cooled in a laboratory-built, shielded furnace. The demagnetization was carried out by heating to (50)°C and then in (12) steps up to (600)°C. Unfortunately, the noise level of the Spinner magnetometer was too high (0.02-0.05 mAm-1) during the measuring time, therefore, and after (200)°C, each step was repeated twice in order to control the considered noise effect. Four pilot specimens (Ma 9.4, Ma 10.5, Zr 25.2 and Zr 26.2) were sent to Oklahoma University.

These specimens were measured using cryogenic magnetometer with a noise level of (3×10-6) mAm-1, and demagnetized by a thermal demagnetizer model (TSD-1) existed in USA.

Temperature steps of (100, 50 and 25)°C up to a peak temperature of (600)°C were used. For these pilot specimens measured in Baghdad University, the changes in the magnetic directions of Maukaba and Zardabe rocks, along with the appropriate normalized intensity curves are shown in the example of figure 2. Specimens (Ma 7.3, Ma 8.4) show negative shallow inclinations at (450, 300)°C respectively . While the declination values of all pilot specimens show good grouping around or near the earth's south magnetic pole (especially Zr 21.3 and Zr 25.1), which could suggest reversed polarity components.

A systematic behavior of Zijerveld diagrams and Lambert equal-area projections of all pilot specimens is noticed above (250-300)°C (except Ma 7.3) with the temperature increase up to (600)°C. Gradual drop was occurred in the magnetic intensity values of all pilot specimens with the increasing temperature up to (600)°C. Also, there is a distinct increase in the magnetic intensities at (250)°C for all pilot specimens.

Figure 3 illustrates the Zijerveld diagrams of Maukaba and Zardabe pilot specimens (Ma 9.4, Ma 10.5, Zr 25.2, and Zr 26.2), which were thermally demagnetized in Oklahoma University. It is appeared that the magnetic direction of the pilot specimen (Ma 9.4) has largely moved further from its initial NRM direction at (100)°C. Moderately to high upward inclinations with good clustering of the declinations values around the Earth's south magnetic pole was observed in all Maukaba and Zardabe pilot specimens (except specimen Zr 25.2 which has shallow inclinations). A systematic behavior was noticed in Zijerveld diagrams from (250)°C up to (600)°C for these specimens too.

In other word, the thermal demagnetization analysis for Maukaba and Zardabe pilot specimens that was conducted in both Baghdad and Oklahoma Universities reveal same magnetic results. Up to three main magnetic components can be detected in the thermal demagnetization analysis: ❶ a present-day field (low-temperature component-LT) or laboratory overprint (VRM) ranging from (20-200)°C; ❷ a medium-temperature-MT component ranging from (200-300)°C; and ❸ a high-temperature-HT from (300-600)°C.

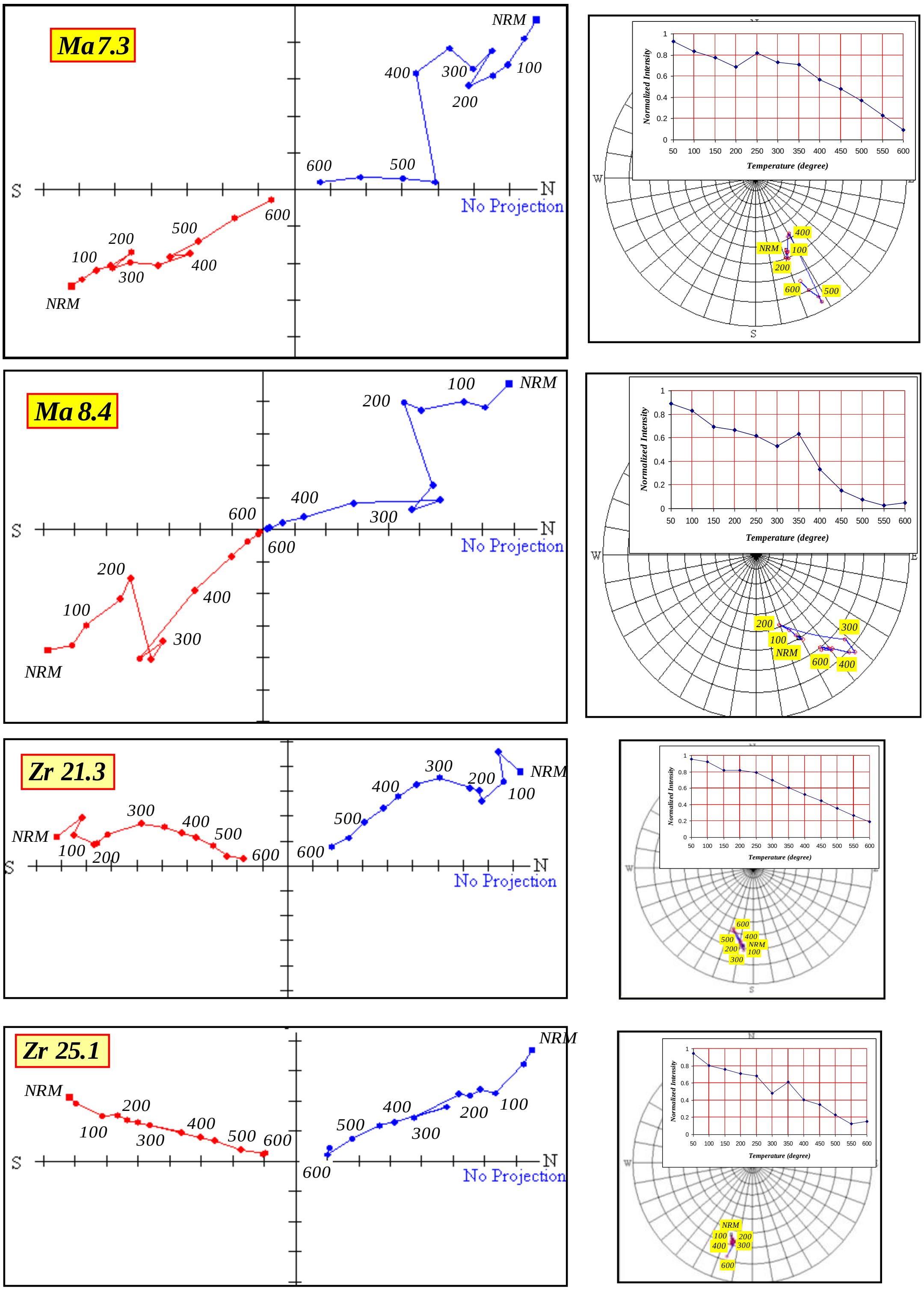

Figure 2: Thermal - demagnetization for Maukaba and Zardabe pilot specimens which conducted in Iraq showing Zijerveld diagrams and Lambert equal-area projections and their appropriate normalized intensity curves

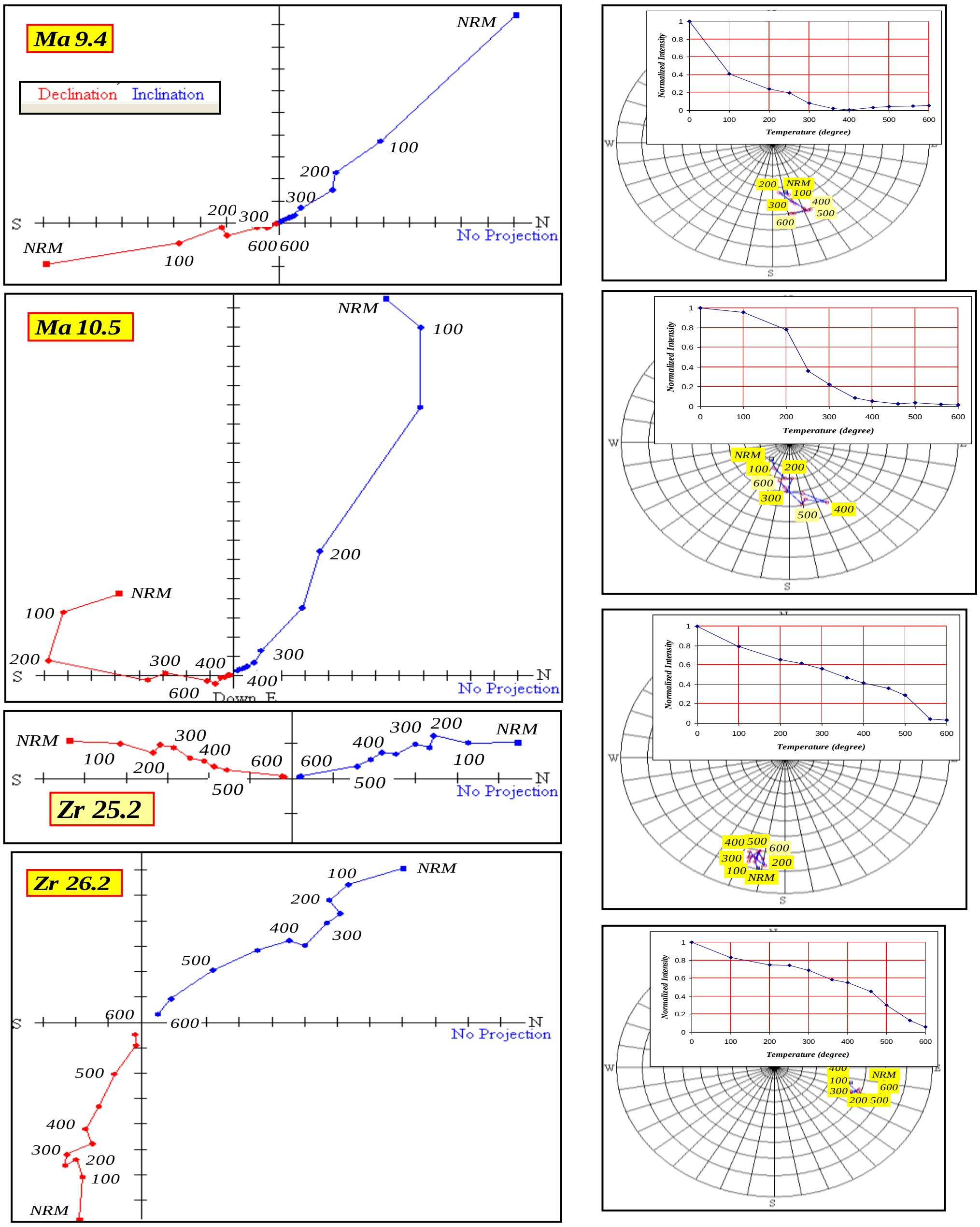

Figure 3: Thermal - demagnetization for Maukaba and Zardabe pilot specimens which conducted in USA showing Zijerveld diagrams and Lambert equal-area projections and their appropriate normalized intensity curves

2. Alternating Field Demagnetization

Four pilot specimens (Ma 7.4, Ma 8.1, Zr 21.2 and Zr 24.5) were progressively demagnetized in an alternating field (AF) with (10) mT increments up to (100) mT. NRM of these pilot specimens were measured by a cryogenic magnetometer existed in USA. Figure 4 showed that the magnetic intensity values of the above pilot specimens were reduced to about (70-80) % from their initial NRM at (70, 70, 90 and 80) mT respectively. This indicates that high coercivity field with reversed polarity. The reversal polarity in specimens (could indicate stable paleomagnetic components. An increase of the magnetic intensities were noticed when these specimens were subjected to AF-demagnetization at the low coercivity steps which could mean removal of the normal overprinting components.

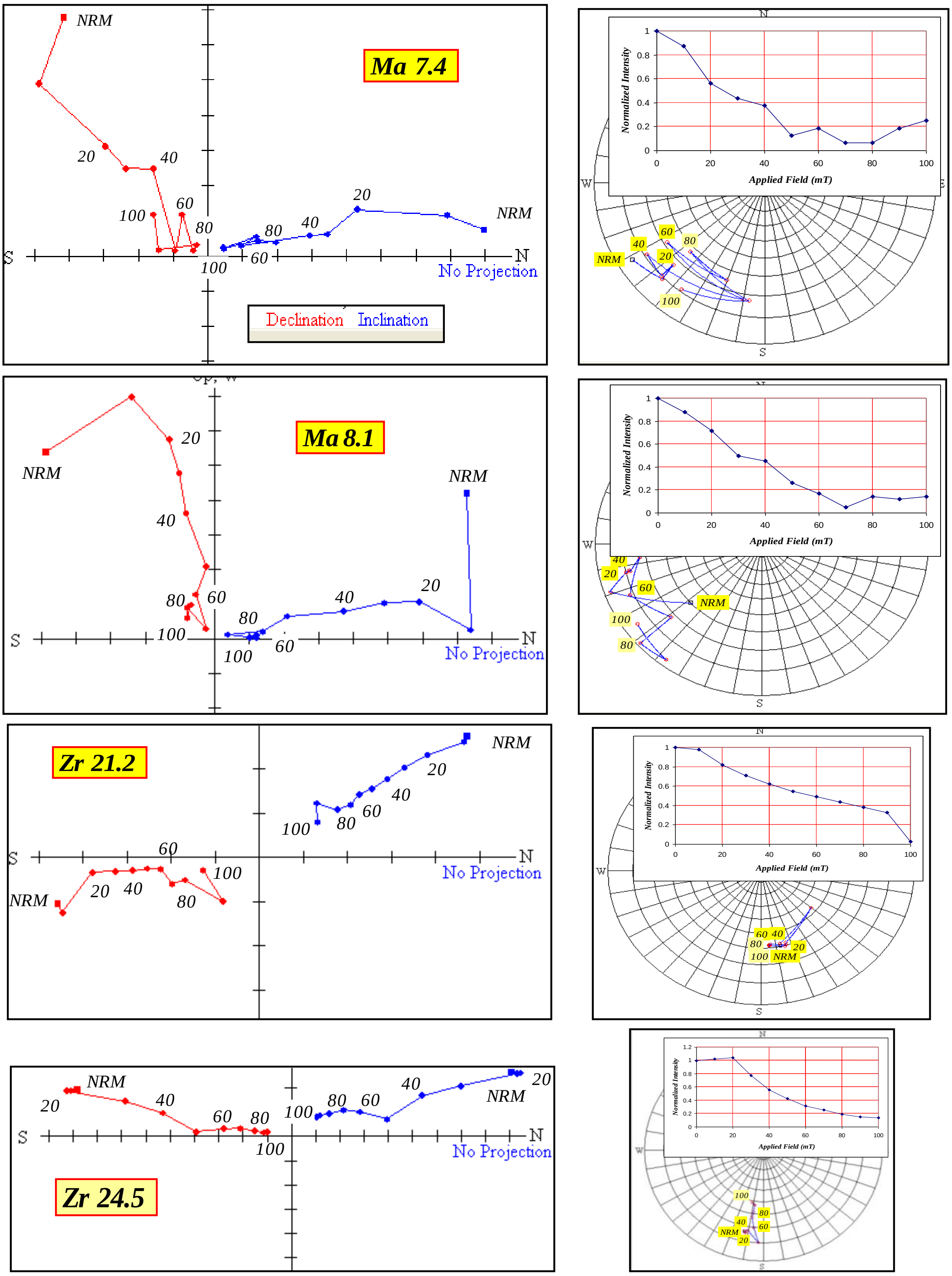

Figure 4: AF - demagnetization for Maukaba and Zardabe pilot specimens which conducted in USA showing Zijerveld diagrams and Lambert equal-area projections and their appropriate normalized intensity curves

Initial NRM and Bulk Demagnetization

Thermal demagnetization is chosen in this study for bulk demagnetization of the remaining (68) samples instead of the AF-demagnetization, because the AF-demagnetizer instruments are not available in Iraq and also because the thermal demagnetizing analysis show good result that is better than the AF-demagnetization. The bulk demagnetization is chosen to be (250)°C according to the results of the pilot specimens analysis where most specimens show a removal of one magnetic component at (250-300)°C. After initial measurements of natural remnant magnetization, all samples were thermally demagnetized at (250)°C (Table-3). Site mean directions, resultant (R), precision factor (K), circle of confidence (α95), co-latitude, Virtual Geomagnetic Pole (VGP) and the overall mean directions in two cases, the initial NRM and thermally cleaning at (250)°C were also calculated with the assistance of the modern paleomagnetic programs named (Georient version 9.2, 2005) and (Super IAPD, 2000).

The initial NRM directions for six sites (Ma1-Ma6) extracted from Maukaba locality are plotted in (Figure.8a). The NRMs directions have a distribution highly scattered around the present Earth's magnetic field. The overall mean direction obtained for these sites before and after bedding correction are Dec=198.6°, Inc=57.6° (α95=64°, N=34) and Dec=112.5°, Inc=45.7° (α95=70.7°) respectively. These directions have downward inclinations and declinations mostly moved far away from the present Earth's magnetic field, and the within-site scatter is more than between-sites scatter. Generally, all Maukaba specimens have low intensities with values varying from (0.0325-0.0625) mAm-1, while those specimens that conducted in USA (Ma 7.4 and Ma 9.4) have intensities between (0.016-0.655) mAm-1 respectively.

At (250)°C thermal demagnetization however, the mean magnetic directions of Dec=175.4°, Inc=-14.5° (α95=23.4°) and Dec=140.9°, Inc=-18.9° (α95=34.1°) are obtained before and after bedding correction respectively (Figure.8b). Here, the paleomagnetic direction reveals reversal polarity. All the Maukaba specimens show low magnetic intensities even after thermally demagnetization at (250)°C, with values ranging from (0.0198-0.0463) mAm-1.

The initial NRM directions of eight sites for Zardabe specimens (Zr7-Zr14) before and after bedding corrections are shown in (Figure.9a). The overall mean direction of the initial magnetic directions before bedding corrections is Dec=140.1°, Inc=48.2° (α95=30.8°, N=46), while after the tilt-correction it is Dec=242.8°, Inc=63.4° (α95=39.3°). Both overall mean directions are far away from the present Earth's magnetic field. For the Zardabe magnetic directions, the within-site scatter is more than the between-sites scatter. In general, all specimens (including those conducted in USA) have moderately to high intensity values ranging (0.0854-1.002) mAm-1. When Zardabe specimens thermally demagnetized at (250)°C, the overall mean directions before and after bedding corrections are changed to Dec=133.9°, Inc=3.9° (α95=49.9°) and Dec=172.1°, Inc=-30.6° (α95=54.6°) respectively. Shallow negative inclinations and southerly declinations distribution is noticed (Figure.9b), which may indicate reversal polarity for the Maastrichtian Aqra limestone Formation. Again for these specimens the magnetic directions show the between-sites scatter is less than the within-site scatter. While their magnetic intensities are still relatively high (0.0331-0.781) mAm-1. It seems that Maukaba and Zardabe specimens have a similar magnetic behavior (Figure.10). Good clustered with southerly direction indicates reversal polarity may acquire prior to the event(s) of folding in these rock units.

Table 3: Initial NRMs and magnetic directions after thermally cleaned at 250°C before and after bedding tilt-corrections for all specimens

Locality / attitude	Site No.	Sample No.	Initial NRM						Intensity (mAm^{-1})	Magnetic directions at 250 ° C						Intensity (mAm^{-1})
			Before field correction		Field-corrected		Tilt-corrected			Before field correction		Field-corrected		Tilt-corrected		
			Dec°	Inc°	Dec°	Inc°	Dec°	Inc°		Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	
Maukaba / (Strike: N 23 ° W Dip: 65 ° NE)	1	Ma 7.1	168	48.2	186	48	114.2	37.4	0.0418	265	-67	157	-6	152.4	-3.4	0.0368
		Ma 7.2	162.3	23.8	202.6	73.8	81.6	36.2	0.0452	270	31	60	14	236.5	-50.6	0.0321
		Ma 7.3	118.3	-80.1	188.7	-14	157.2	-34.4	0.0409	117.8	-81.6	187.4	-13.2	157.7	-33.6	0.0328
		Ma 7.4	1503	26.6	230.4	58.5	82.3	55.2	0.016	148.4	39.3	214.8	49.5	104.4	55.5	0.007
		Ma 7.5	288.5	11.9	80.8	23.7	263.5	-39.9	0.0325	291.8	23	68.6	27.1	249.8	-38.5	0.0256
		Ma 7.6	90.7	-50.4	320.7	-4.5	334.7	-17.1	0.0396	275.8	-81.7	171.7	-10.8	153.4	-18.6	0.0278
	2	Ma 8.1	154.9	46.5	227.4	32	130.5	71.4	0.042	178.7	19.9	264.1	51.6	45.5	60.1	0.025
		Ma 8.2	248.9	-61.1	193.9	3.4	171.4	35.2	0.0456	274.1	-69	159.5	-32.6	128.7	-15.3	0.0198
		Ma 8.3	142	37.2	238.1	26.2	147.6	82.1	0.0520	269.5	5.8	81.3	34.9	260.3	-29.8	0.0325
		Ma 8.4	113.8	-87.3	182.7	-17.2	151.2	-30.2	0.0453	273.8	-63.6	154.8	-31.3	127.1	-11.6	0.0285
		Ma 8.5	269.7	-70	15.2	-7.4	183.5	30.5	0.0602	272.1	-62.3	153.1	-35.7	123.1	-11.2	0.0463
		Ma 8.6	169	-16.2	126.5	32.2	295.3	-9.7	0.0583	116.2	-84	186.3	-20	149.6	-34.7	0.0308
	3	Ma 9.1	182.3	14.4	60.4	67.2	64.1	2.5	0.0447	114.1	-65.3	204.4	-41.4	121.3	-51	0.0258
		Ma 9.2	261.2	-71	159.9	-17.8	142.3	-10.6	0.0468	313.1	-28	321	30.3	0	25.4	0.0223
		Ma 9.3	274.3	-84.2	174.3	-19.6	145.2	-23.6	0.0415	280.8	-74.5	166.1	-13.7	148.1	-14.4	0.0261
		Ma 9.4	60.5	-66.8	203.3	-11	168.1	-46.1	0.655	40.8	-76.8	191.6	-9.2	163.6	-35.8	0.127
		Ma 9.5	292.7	-10	300.6	48.5	21.4	42.6	0.0371	114.1	-71	191.8	-27.4	141.5	-41.5	0.0219
	4	Ma 10.1	343	-11	0	50	31.2	6.3	0.0624	286	-77	168	-21	142.8	-18.7	0.0315
		Ma 10.2	77.4	-43.2	312.8	-9	335.6	-26.4	0.0584	273	-80.4	170.7	-16.1	148.6	-19.6	0.0329
		Ma 10.3	223.8	-47	38.6	-5.5	201.9	49.6	0.0536	126	-50.5	160.1	6.5	152.5	6.9	0.0307
		Ma 10.4	14	72	347	36	14.7	7.7	0.0579	94	10	270	29	353.1	69.8	0.0384
		Ma 10.5	64.3	-31.7	238.6	-7.3	221.3	-71.7	0.410	60.8	-52.4	218.1	-12.6	176.5	-60.5	0.148
		Ma 10.6	198.2	-30	205.6	37.9	127.5	53.1	0.0638	132.3	-79	188.2	-24.9	144.4	-37.4	0.0487
	5	Ma 11.1	248.1	4.2	93.1	18.1	280.7	-40.5	0.0459	276	11	80	11	268.3	-52.5	0.0365
		Ma 11.2	259	-64	29	-24	207.6	29.7	0.0423	273.8	-70	158.5	-23.5	136.4	-11.2	0.0297
		Ma 11.3	173	-6	190	54	107.3	39.5	0.0418	285	-80	170	-25	138.5	-21.6	0.0352
		Ma 11.4	116.4	-77.1	194.6	-42.4	121.2	-44.5	0.0476	117.9	-57.5	221.2	-48.6	101.2	-59.4	0.0273
		Ma 11.5	258.1	-19	106.4	-9.5	300.4	38.6	0.0387	125.2	-55.8	217.5	-51.2	100.5	-55.9	0.0246
	6	Ma 12.1	129	-55	324	-18	349.4	-19.6	0.0569	284	-64	149	-32	125	-7.6	0.0453
		Ma 12.2	204	-47	182	13	155	28.4	0.0548	288	-55	140	-26	306.3	3.4	0.0394
		Ma 12.3	202	25	349	81	57.6	23.2	0.0574	123	2.5	272.9	8.8	308.4	60.1	0.0384
		Ma 12.4	162.3	42	249.2	57.3	65.5	58.5	0.0453	299.8	-64	149.1	-31.6	125.6	-7.8	0.0257
		Ma 12.5	88	19	273	36	9.4	65.1	0.0506	101	34	295	30	355.5	47.6	0.0423
		Ma 12.6	52	-47	21	23	200.5	-24.8	0.0425	313.7	-88	178	-14.2	152.4	-25.3	0.0286

(Table-3) Continued

Locality / attitude	Site No.	Sample No.	Initial NRM						Intensity (mAm^{-1})	Magnetic directions at 250 °C						Intensity (mAm^{-1})
			Before field correction		Field-corrected		Tilt-corrected			Before field correction		Field-corrected		Tilt-corrected		
			Dec°	Inc°	Dec°	Inc°	Dec°	Inc°		Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	
Zardabe / (Strike: N 17 ° E Dip: 30 ° NW)	7	Zr 20.1	134	33	110	62	109.3	32.2	0. 861	194	56	37	23	22.5	30.6	0.643
		Zr 20.2	332	-10	75	2	252	-23.6	0.765	189	-73.9	162.9	-31.6	185.4	-44.9	0.538
		Zr 20.3	9	-38	314	-7	320.1	-33.4	0.936	302	-66.1	198.7	-20.4	209.6	-17.8	0.511
		Zr 20.4	74.6	45.3	186	80.6	124.5	57.4	0.748	173.1	-56.7	142.7	-25.8	159.3	-48.9	0.367
		Zr 20.5	97.7	-18.2	202.1	31.7	184.6	30.1	0.651	188.2	-60.5	149.9	-22.8	165.4	-42.3	0.318
		Zr 20.6	121.9	-65.4	16.7	-15.5	25.9	-14.5	0.701	237.4	-84.1	177.3	-29.5	196.7	-35.6	0.370
	8	Zr 21.1	190	-6	289	19	290.4	49.7	0.934	237.8	-75	175.7	-14.5	186.2	-23.4	0.694
		Zr 21.2	205.1	-63.3	157.6	-12.2	337.2	7.3	0.545	204.1	-69.6	162.2	-16.7	174.6	-31.8	0.387
		Zr 21.3	251.4	-76.6	177	-14	173.3	-2.2	1.002	252.5	-79.9	178	-17.8	190.3	-25.6	0.781
		Zr 21.4	125	2	64	42	75.6	18.8	0.8664	114	11	65	56	9.2	68.5	0.6365
		Zr 21.5	252	-32	333	24	349.1	42.6	0.9482	163	-51	34	-6	29.2	-14.7	0.6154
		Zr 21.6	173	-41	129	-15	309.1	13.3	0.7916	231	-62	166	0	170.2	15.4	0.5393
	9	Zr 22.1	182	-4	265	2	262.5	30.1	0.6395	269	-57	356	8	175.7	-3.6	0.4296
		Zr 22.2	267	-66	166	-5	347.3	10.5	0.7619	262	-61	161	-2	166.2	-19.7	0.3845
		Zr 22.3	199.2	-26	117.5	-4.2	299.7	25.4	0.8958	235	-60	160	-6	167.3	-23.6	0.6351
		Zr 22.4	170	9	85	25	267.8	-3.3	0.6473	265	55	24	62	337.9	52.4	0.3343
		Zr 22.5	116	-25	209	28	192.5	30.8	0.5327	174	-59	34	-24	19.5	-29.5	0.3896
	10	Zr 23.1	175	-16	246	4	240.4	26.9	0.3315	177	-49	41	-17	29.4	-27.8	0.2182
		Zr 23.2	78	-10	190	38	170.6	29.1	0.4753	90	-8	205	38	224.1	29.5	0.2694
		Zr 23.3	108	-35	207	11	200.3	15.7	0.4865	143	-49	39	-16	28.6	-25.1	0.2222
		Zr 23.4	119	-11	119	19	299.2	-10.6	0.3571	256	-26	63	-7	56.4	-28.7	0.3578
		Zr 23.5	253	-72	182	-12	178.4	-3.8	0.3972	227	-85	178	-25	194.7	-31.6	0.2441
		Zr 23.6	151	4	73	31	78.5	5.2	0.4697	142	4	67	39	39.4	57.3	0.3693
	11	Zr 24.1	130	20	74	12	254	-13.2	0.0962	217	-85	180	-31	200.5	-35.3	0.0769
		Zr 24.2	153.3	-80.3	171	-27	162.4	-11.4	0.1259	139.4	-81.1	170.3	-29.6	190.5	-39.5	0.0853
		Zr 24.3	223	-38	8	19	19.5	21.5	0.0854	159	-79	170	-25	187.3	-35.4	0.0551
		Zr 24.4	191	-12	295	14	298.6	44.3	0.1187	184	-34	128	-40	150.1	-66.5	0.0762
		Zr 24.5	230.1	-70.3	184.8	-11.8	181.3	-4.7	0.189	228.5	-69.8	184.3	-11.2	192	-16.6	0.146
	12	Zr 25.1	221.5	-79.2	182	-22	173.5	-12.3	0.8359	217.5	-75.2	182.2	-18.3	194.4	-23.4	0.5639
		Zr 25.2	241.3	-61.9	196.9	-11.4	191.3	-10.6	0.278	252.8	-59.7	202.9	-12.8	209.8	-8.9	0.172
		Zr 25.3	157	-50	152	0	336.4	-21.2	0.8037	166	-75	170	-18	182.5	-29.6	0.6021
		Zr 25.4	31	-5	180	49	156.9	34.1	0.7693	142	-39.5	133.2	-8.6	139.6	-35	0.5918
		Zr 25.5	185	33	87	68	98.4	39.5	0.6998	214	-85	180	-30	199.7	-34.6	0.4212
		Zr 25.6	284	36	294	31	299.1	61.1	0.7589	276	42	298	39	296.5	9.6	0.5384

(Table-3) Continued

Locality / attitude	Site No.	Sample No.	Initial NRM						Intensity (mAm^{-1})	Magnetic directions at 250 °C						Intensity (mAm^{-1})
			Before field correction		Field-corrected		Tilt-corrected			Before field correction		Field-corrected		Tilt-corrected		
			Dec°	Inc°	Dec°	Inc°	Dec°	Inc°		Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	
Zardabe	13	Zr 26.1	256	-22	315	35	336.2	59	0.1369	165	-44	214	13	218.4	3.2	0.0852
		Zr 26.2	207.4	-15.2	103.4	-7.5	283.6	22.1	0.201	212.7	-21.5	111.1	-4.8	112.5	-35.1	0.149
		Zr 26.3	239.2	-68.8	162	-12	341.3	6.8	0.1624	237.8	-64.7	159.1	-10.2	168.3	-27.7	0.1116
		Zr 26.4	127	3	37	61	69.5	42.1	0.0984	117	6	19	68	327.1	54.7	0.0774
		Zr 26.5	142	13	71	50	83.6	24.5	0.1248	243	-66	164	-13	174.5	-27	0.1098
	14	Zr 27.1	261	32	241	81	123.4	65.5	0.0697	270	70	0	48	337	33.3	0.0445
		Zr 27.2	66	41	222	68	153.9	62.3	0.0756	328	67	335	34	326.9	12.5	0.0592
		Zr 27.3	176	6	85	3	263.1	-25.1	0.0886	231	70	17	47	349.4	39.4	0.0476
		Zr 27.4	321	33	291	42	297.5	72.8	0.0833	301	47	314	56	304.2	28.4	0.0699
		Zr 27.5	154	-7.8	65	16.2	247.8	-7.6	0.0776	261	-65	178	0	180.3	-9.3	0.0462
		Zr 27.6	208	47	47	39	61.2	21.5	0.0694	168	-57	34	-15	24.1	-21.2	0.0331

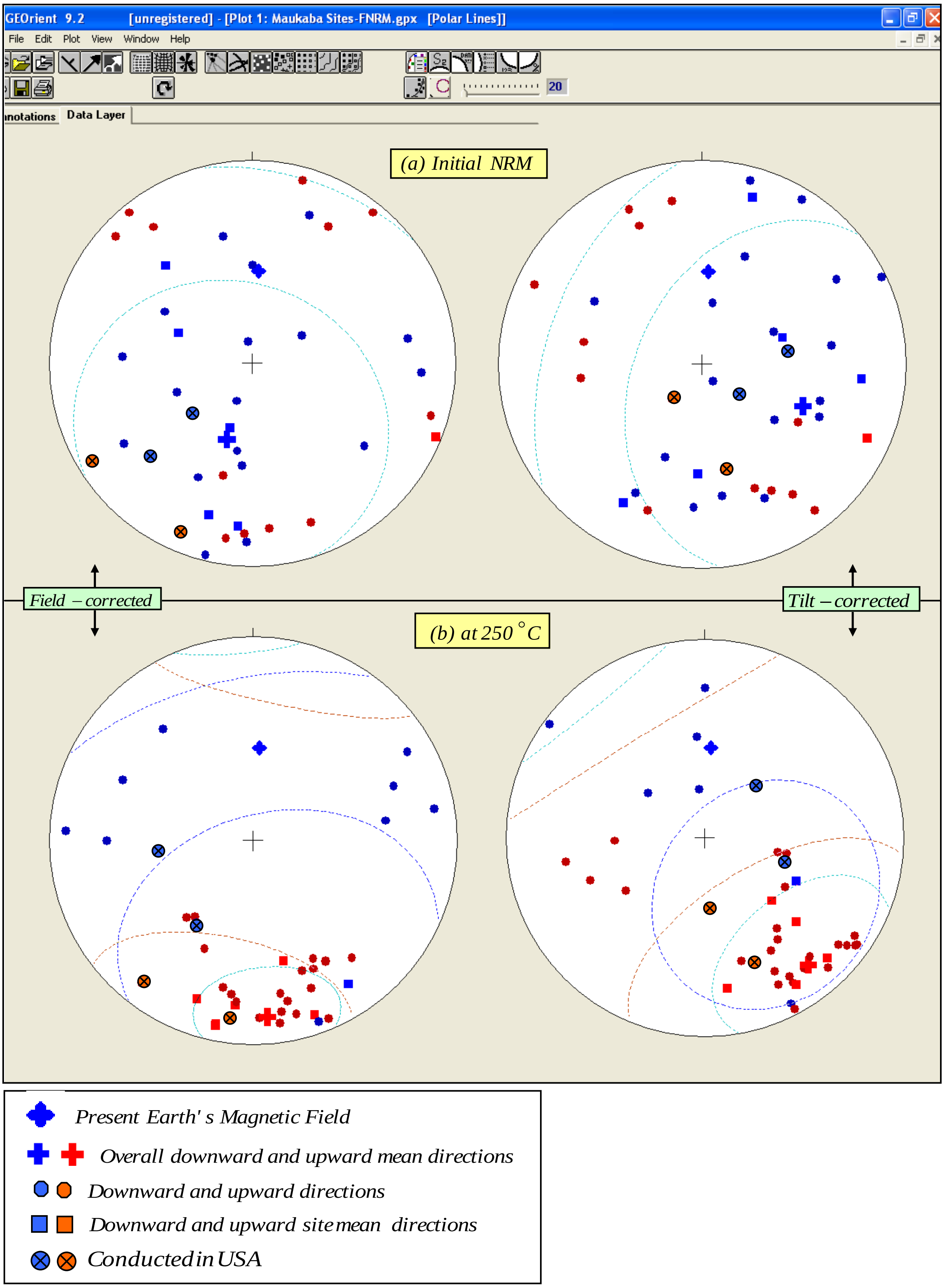

Figure 5: Lambert equal- area projections show specimens, site mean and overall mean directions of Maukaba sites before and after bedding correction at (a) initial NRM and(b) thermally cleaned at(250)°C.

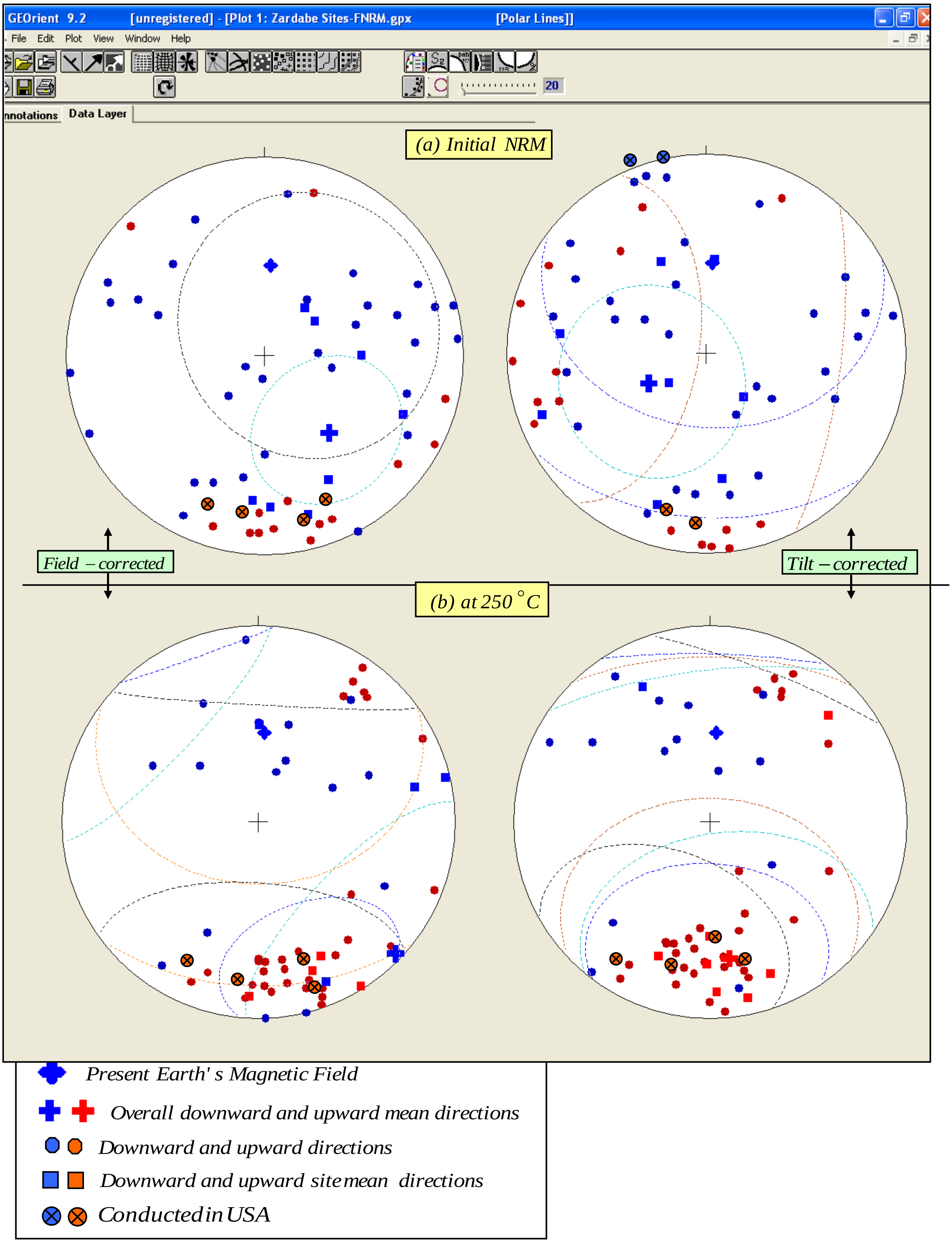

Figure 6: Lambert equal- area projections show specimens site mean and overall mean directions of Zardabe sites before and after bedding correction at(a) initial NRM and(b)thermally cleaned at(250)°C.

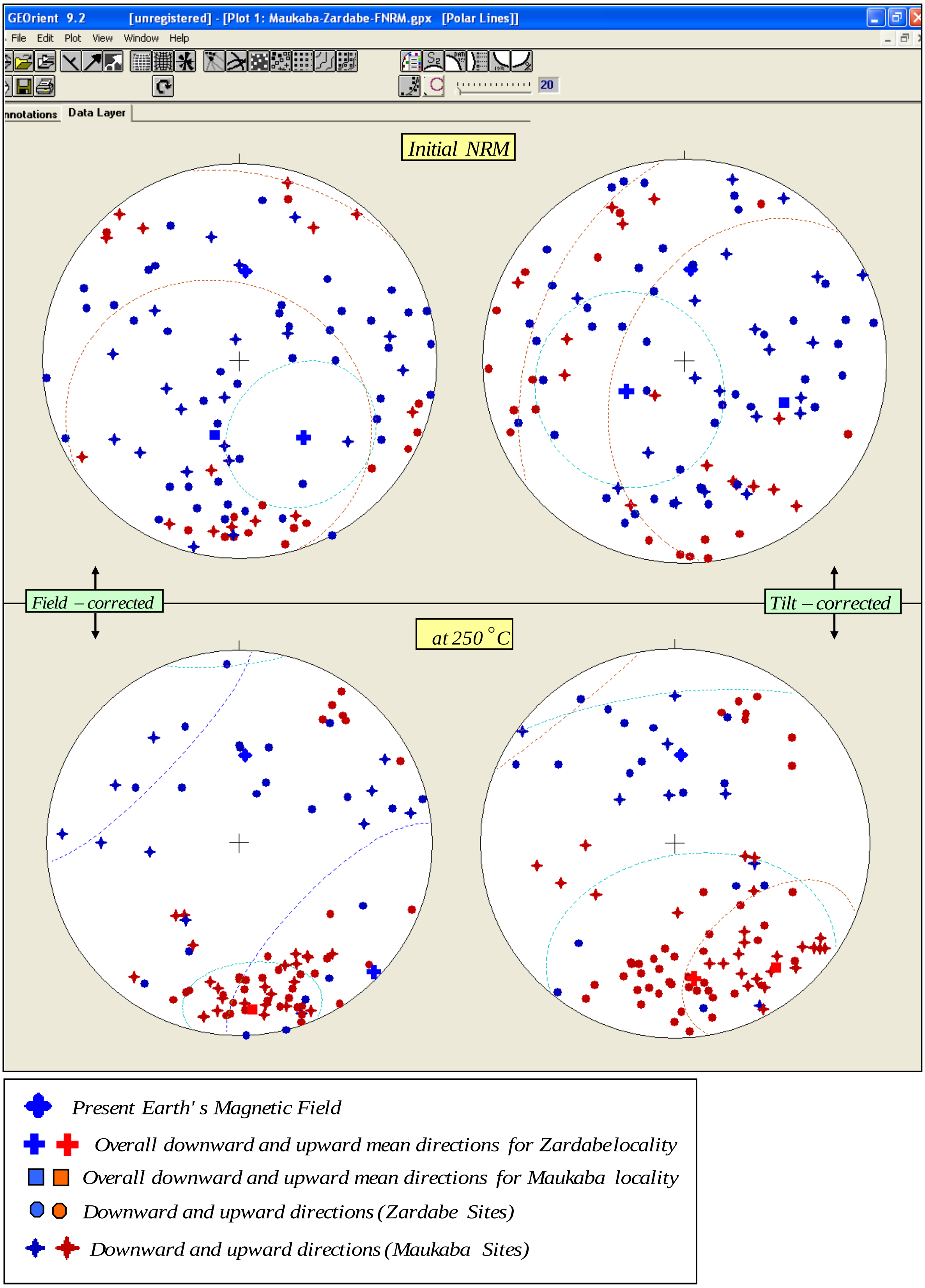

Figure 7: Lambert equal- area projections show specimens, site mean and overall mean directions of Maukaba and Zardabe sites before and after bedding correction at (a) initial NRM and(b) thermally cleaned at(250)°C.

Magnetic Carriers

A variety of Isothermal Remanent Magnetization-IRM acquisition curves were obtained with the help of a laboratory-built pulse ASC model IM-10-30 demagnetizer existed in USA. In total, two oriented samples (Ma 7.4 and Zr 21.2) were subjected to magnetic fields along their vertical axis. The fields were steadily increased with (11-12) steps up to (2500) mT, and their remanence being measured after each step using a 2G cryogenic magnetometer. By plotting a curve for IRM against the applied field, the nature of the magnetic mineral can be identified. The magnetite can be saturated at (900) mT to (1000) mT, while the haematite show a gradual increase and no saturation for more than (2000) mT. Maghemite however, shows the behavior in between these two minerals. Though, the IRM method can clearly identify the magnetic minerals but sometimes it is rather good to do other mineral identification and compare the results. The IRM test result is listed down here as thin sections and curve (Figure.11). For the specimen (Ma 7.4), the optical test shows fossiliferous dolomitic limestone with detrital fine sand grains of quartz; chlorite and iron oxides (may be magnetite and haematite). Iron oxides also present as pressure-solution seams along fossil and grain boundaries. Sometimes, the optical test cannot really identify the type of iron oxides, however, the magnetic behavior can do that easily, and i.e., the IRM curve probably corresponds to magnetite, which could be formed in the strong reducing conditions of the depositional environment. This magnetite could be of detrital origin; however, the IRM shows magnetite as a magnetic mineral carrier. The rocks here show clear and stable magnetic vector, which is more likely related to the time of the formation.

The IRM curve of the specimen (Zr 21.2) is identical, almost has highly saturation intensity and probably corresponds to magnetite which formed in reducing depositional environment. However, magnetite could be of detrital origin and considered as the main magnetic carrier of this rock unit. The optical test illustrates a compacted moderately recrystallized and dolomitized fossiliferous carbonate, with serpentine and chlorite rock fragments of coarse sand to sand sized. Iron oxides mostly present as stains along the boundaries of fossils and to a lesser extent as scattered grains.

Paleomagnetic Interpretation and its relation with tectonics

In paleomagnetic study it usually depends on statistic criteria to distinguish the meaningful results from those which are not. The cone of confidence at 95 levels usually used as the main statistic criteria. However there is no real range or value on which one can decide. In some studies, values up to $\alpha95=25o$ is acceptable, while in others a value of less than 13 degree can be considered as significant. It depends on the interpreter, number of sites, area stability, sampling locations distribution and the scatter of the data. However, in this study a value of 25o will be considered as the optimum value for accepting the magnetic mean directions of any locality. The pilot specimen analysis is one of important criteria for distinguishing between the magnetic components within a rock. This gives the magnetic components directions and their stability. There is also the nature of the magnetic carrier that shows the type and the conditions of the magnetic grains within the rocks. The reverse magnetic directions that were found in the Maukaba and Zardabe rocks have a natural remanent magnetization in a south-easterly direction far from the present Earth's magnetic field. It is likely that these are stable components. The reasons for considering these reverse magnetic directions as stable magnetic component are:

1. The directions of magnetization become less scattered after the bedding tilt-correction. This suggests that the magnetization was acquired before tilting and that the direction of polarization has since been preserved.
2. Several specimens were re-measured after a period of six months. They were stored in random directions in the present Earth's magnetic field. No significant changes in the directions of NRM were observed.
3. The thin sections examination showed magnetite grains which probably are the main magnetic carrier for these rocks.
4. The IRM test that conducted in Oklahoma University also showed magnetite as the main magnetic carrier.

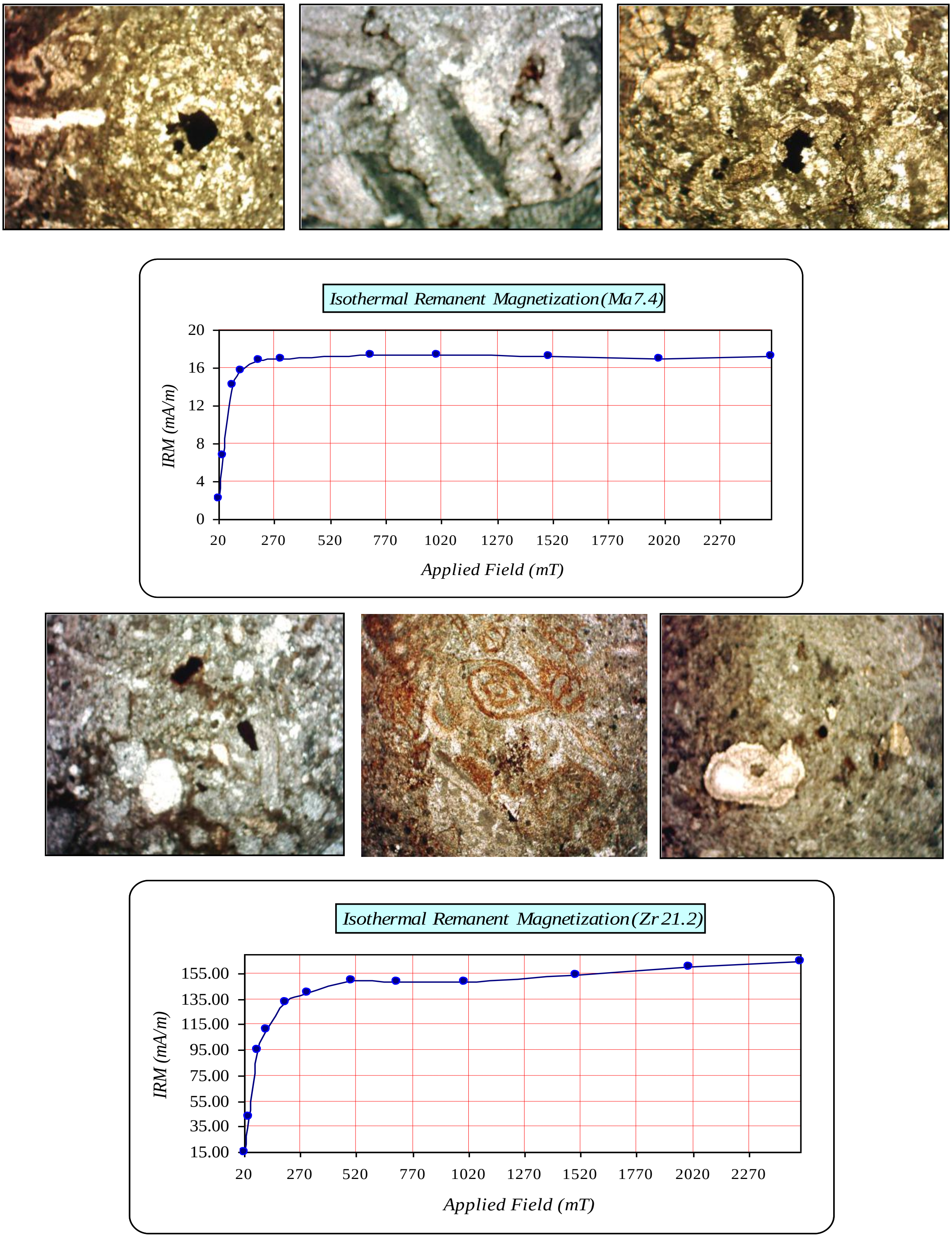

Figure 8: Thin sections and IRM curves of the specimens (Ma 7.4 and Zr 21.2)

During the thermal demagnetization at (250)ºC, the individual magnetic directions of Maukaba and Zardabe specimens move toward the reverse Earth's pole field, with shallow inclinations. As mentioned above, there were present-day magnetic components within these rocks. The thermal cleaning however removed most of these overprinting components. Yet few specimens have showed high coercivity for these overprinting components. Apparently, the 250ºC was not enough for removing these high coercivity components. Therefore, these components were removed from the calculation of the overall mean direction. After removing the rejected abnormal directions from Maukaba and Zardabe localities, the scatter mostly reduce, and the reversed polarity is clearly established (Figure.13).

The overall mean directions after bedding tilt-correction are Dec=140.7º, Inc=-26.5º, K=31.9, N=20, α95=4.5º and Dec=169.3º, Inc=-26.3º, K=28.5, N=25, α95=6.4º for Maukaba and Zardabe localities respectively.

The bedding tilt corrections have clearly showed the reduction in the magnetic directions scatter, which indicates that these magnetic components acquired prior to the tilting (Table-4).

Paleo-Pole positions have been computed for the magnetic directions of these two locations. The VGPs correspond to a reverse polarity, in other words, to the southern hemisphere. The overall mean of the VGPs positions of the Maukaba locality is Plat=44.4º S and Plong=279º, while for the Zardabe rocks is Plat=57.1º S and Plong=235º. These are the paleo-poles positions correspond to the time and place of Aqra Limestone depositional basin. However, there is a clear difference between the two paleo-poles positions. But the co-latitude that was calculated for the two localities show latitude positions which are (-14º) for Maukaba locality and (-13.9º) for Zardabe locality. They are both located on almost the same paleo- latitude Earth's magnetic pole. They are in the northern hemisphere since the reverse polarity means that the northern Earth's magnetic pole is located in the southern hemisphere. So the actual paleo-latitudes are 14º N and 13.9º N. The paleo-latitude positions of the Aqra limestone basin simply mean that on Maastrichtian times the north part of Iraq is still at low latitude.

Table 4: The overall mean directions and VGPs of the Maukaba and Zardabe rocks after rejected abnormal magnetic directions at (250)ºC

Locality	*Correction*	*N*	*Overall mean*		*K*	α_{95}	*Co-Latitude*	*VGPs*	
			Dec	*Inc*				P_{Long}	P_{lat}
Maukaba	*Field-corrected*	20	184.1	-32.7	13.25	19.1	-17.8	207.4	62.1 (S)
	Tilt-corrected	20	140.7	-26.5	31.9	4.5	-14	279	44.4 (S)
Zardabe	*Field-corrected*	25	124.3	-50.2	22.2	10.8	-31	306.9	44.9 (S)
	Tilt-corrected	25	169.3	-26.3	28.5	6.4	-13.9	235	57.1 (S)

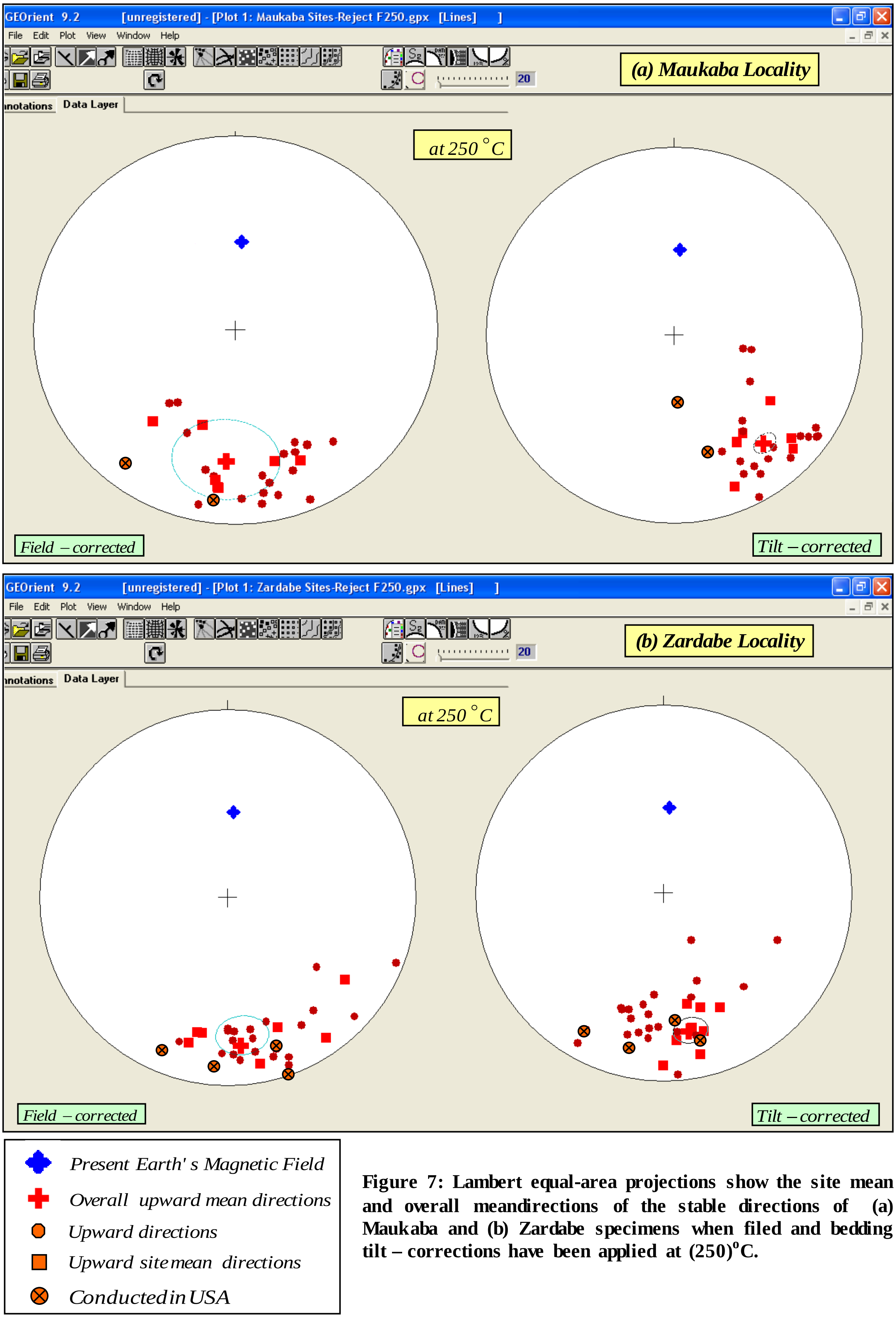

Figure 7: Lambert equal-area projections show the site mean and overall meandirections of the stable directions of (a) Maukaba and (b) Zardabe specimens when filed and bedding tilt – corrections have been applied at (250)°C.

movement of Upper Cretaceous times which caused the closure of the Neo-Tethys Ocean has not commenced yet.

3 and 11 have pointed out that on Upper Cretaceous-Lower Tertiary times there was a rotational movement for Afro-Arabian plate that caused the closure of the Neotethys Ocean, which was followed by the collision of the Arabian plate with the Iranian and Turkish micro plates. This movement caused the Arabian plate to move toward the northeast by 20 degrees in latitude. Taking this latitude movement into consideration, the Aqra Limestone basin position at the present time should be at latitude of 34ºN and 33.9ºN for Maukaba and Zardabe localities respectively. However, nowadays the actual geographic positions of these localities are around 35º40′ N and 35º50′ N respectively, which are different by nearly two degrees. This difference could be related to the geomagnetic axial dipole model and the related paleo-pole position (latitude) calculations, or it could indicate that there were other movements for Arabian plate in Miocene times. This is probably related to the two stages of the opening of the Red Sea. Being north part of Iraq at latitude of 14º N during the Maastrichtian age means that Iraq was still near the equator. This also means that warm equator or near equator environment was still prevailed on that time. Again this indicates that the oil accumulation environment can be found in rocks of ages Maastrichtian or older than Maastrichtian for the north part of Iraq.

It can be easily noticed that there are clear difference in paleo-longitudes values between Maukaba and Zardabe localities. Though, they both recorded almost the same paleo-latitude of the depositional basin. This difference in longitude could be related to the local tectonic movement between the two localities. The well known transverse faults are passing through this area. Some of these faults are clearly identified in the geologic map of Iraq, while others are not. However, their effect can be indicated by the change in the fold axis direction. This can be noticed for many fold axes in the north part of Iraq. In the study area this feature can be noticed for Azmar fold axis (Figure.14) too. This divergence in the fold axis caused the difference in the recorded magnetic declinations between the Maukaba and Zardabe limestone rocks. On first look, if one try to reconstruct the lineation of fold axis and make it as a straight line then the two magnetic directions of the two localities will be coincide, i.e. they recorded the same magnetic directions before the tectonic movements. Accordingly, the difference in the calculated paleo-longitude values is related to this tectonic movement, since they are calculated from the magnetic declinations of the two localities. This difference however can be considered as another evidence for the magnetic directions which are recorded by Aqra Limestones at Maukaba and Zardabe localities. They are genuine primary magnetic components. They were acquired before the tectonic divergence in the axis of Azmar fold.

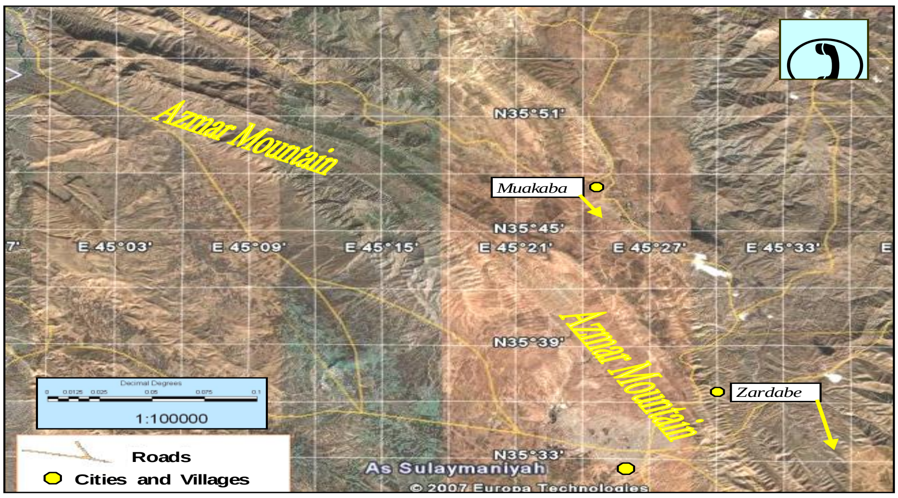

Figure 14: The divergence in the fold axis of Azmar Mountain and its relation with the magnetic declinations of Maukaba and Zardabe localities

Conclusions and Recommendations

1. The thermal demagnetization of the NRM of the Maukaba and Zardabe pilot specimens showed two main magnetic components; ❶ low-temperature magnetic component at (20-200)℃ which is carried by low coercivity magnetic grains. Their magnetic directions are mostly near to the present Earth's field. This component is regarded as overprint of secondary origin; and ❷ medium- high temperature magnetic component at (250-600)℃ which is carried by high coercivity stable magnetic grains. This magnetic component showed reversed magnetic directions. It is interpreted as a primary genuine magnetic component. These two locations showed stable magnetic components that are probably related to the time of rock formation.
2. Microscopic thin sections showed magnetite grains are the main magnetic carrier. Apparently the magnetic grains of Aqra Formation rocks have been kept intact through the geological time, which make these rocks as a good recorder of the paleomagnetic direction.
3. All computed VGPs correspond to a reverse polarity, and the overall mean VGPs position of the Maukaba locality is P_{lat}=44.4º S and P_{long}=279º, which is differ from that of the Zardabe locality (P_{lat}=57.1º S and P_{long}=235º) with co-latitude (-14º) and (-13.9º) respectively. Accordingly the paleo-latitude for Maukaba and Zardabe localities are 14º N and 13.9º N.
4. Apparently, the closure of the Neotethys Ocean happened sometime between the Maastrichtian and Lower Tertiary. The rotational movement of Afro-Arabian plate towards the NE causing the closing and then the collisions with Iranian and Turkish micro plates. This movement caused the Arabian plate to move about 20 degrees in latitude. Taking into consideration of this movement of the Arabian plate then this will lead to the latitude positions of 34º N and 33.9º N for Maukaba and Zardabe locations. However the present locations of these two localities are 35º 40′ N and 35º 50′ N. There are about 2 degrees difference between the present locations and the calculated locations. This difference could be related to the model of the geocentric axial dipole and its related calculations or it could related to other plate movements in Miocene times, i.e. the opening of the Red Sea in Miocene times.
5. The paleo-position of the Aqra Limestone basin clearly suggests that the north part of Iraq was still in the warm environmental conditions during Maastrichtian times. This means that the oil accumulation can be found in rocks of ages for Maastrichtian and older than Maastrichtian.
6. The paleo-pole positions of Maukaba and Zardabe localities showed clear difference in their longitude values, which reflect the difference in the declinations of the magnetic directions of these rocks. The difference in the declinations probably due to the local tectonic movements. Since the north part of Iraq have subjected to many transverse faults movements. These movements usually indicated by the divergence (change in the direction) of fold axes. In this study, however such case is clear for Azmar fold axis. A reconstruction of this fold axis to its previous lineation resulted in a coincidence of the Maukaba and Zardabe magnetic declinations. This clearly indicates that the folding and the divergence in the fold axis happened after Aqra Limestones rocks acquired their magnetic directions.
7. In this study Aqra Limestones rocks are considered as very good rocks for paleomagnetic studies, because they recorded the paleomagnetic directions and kept them through the geologic times. Therefore, this formation can be considered as a key formation for paleomagnetic and tectonic studies. Regional and local tectonics can be identified through these studies. This will help in reconstruction models for the tectonics and the structure of the north part of Iraq.
8. For future paleomagnetic studies, it is recommended to select Aqra Formation (Maastrichtian age) that distributed in the northeastern parts of Iraq, as a key horizon to study the local and regional tectonics. However, it is rather important to take into consideration the genuine magnetic direction of this formation and the reversal polarity which is carried by magnetite grains.
9. Detailed paleomagnetic study should be carried out in the northern parts of Iraq in order to identify the rocks that are carrying the stable primary magnetic components of Mesozoic and Paleozoic times. The paleomagnetic results then can solve many

questions concerning the tectonics and structures of Iraq. They can identify the Paleo-positions and the Arabian plate movements over the geologic times.

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