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ISSN-0974-5904
International Journal of Earth Sciences and Engineering
(**Indexed in Chemical Abstracts –CAS-USA-Ref .No:172238**)
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Dear Author(s)

I have pleasure to inform you the acceptance of your

Paper entitled" Seismo-Volcanic Investigation of 2009 Earthquake Swarms at Harrat Lunayyir (Ash Shaqah), Western Saudi Arabia"

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Accepted for publication in the Inter. J. Earth Sciences & Eng., Oct. 2009

Seismo-Volcanic Investigation of 2009 Swarms at Harrat Lunayyir (Ash Shaqah), Western Saudi Arabia

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ABSTRACT

On 18th of April 2009 A.D., a swarm of earthquakes began in the eastern side of the Cenozoic lava field of Harrat Lunayyir and in the vicinity of the town of Al-Ays. Satellite imageries and aeromagnetic features of Harrat Lunayyir lava field were verified by comparison and integration from findings obtained from seismic data and from existing geologic and geographic information. A seismic sub-network was deployed around the volcanic area and local seismicity was undergo data processing and waveform modeling.

Analysis of the seismicity data in conjunction with aeromagnetic and geologic information indicates that the seismicity is shallow and the correlation of the epicentral distribution with the major tectonic features is, in general, quite good. The recent seismic activity indicates a cyclic pattern of events consisting of seismic minima which may represent episodes of accumulation of energy, and seismic maxima which represent the release of energy that can be accumulated to cause larger events in the future.

Analysis of available broadband seismic data indicates that focal mechanism solutions are normal faulting with two major structural trends of NE-SW and NW-SE which is consistent with the opening of the Red Sea and with broad-scale tectonics of the Arabian-African rifting as well as in good agreement with linear surface cracking observed in the affected areas.

INTRODUCTION

Earthquake swarms are generated commonly by major strike-slip faulting on transform faults (*Sykes 1967;Tatham and Savino 1974; Klein et al., 1977; Hill 1977*) within volcanically active regions. They accommodate with some combination of surface deformation, local resistivity changes, summit deflation, ground cracking, increased heat flow and suggesting some transport of magma within the same region. For a given swarm, the fault plane solutions may exhibit one of two orientations: either both nodal planes are oblique to the epicentral trend, creating an en-echelon fault plane pattern (*Hill 1977*), or one of the nodal planes coincides with the epicentral trend (*Klein et al., 1977*). Surface deformation modeling studies (*Pollard and Holzhausen 1979*) have suggested that the strike of en-echelon fissures results from ascending dikes being reoriented by the stress field at the surface.

Harrat Lunayyir is located in the western part of Saudi Arabia to the northwest of Al-Madinah between Lat. $25^o.1$ - $25^o.17$ N and Long. 37.45^o - 37.75^o E, occupying approximately an area of 3500 Km^2. It was experienced with earthquake swarm during the period 10th to 20th October, 2007 and about 400 events have been recorded with magnitudes in the range of 0.89 – 2.32 trending mainly NW-SE. The earthquakes swarm has repeated again on 19 April, 2009, where more than 4200 events were recorded till 28th June, 2009. The mainshock has occurred on 19th May 2009 with magnitude of 5.4. This event was strongly felt by local residents of Al-Ays town and and to a lesser extent in the adjacent cities (Umm Laj and Yanbu). Ground failures with different directions and extensions were reported. Some of aftershocks with magnitude $M \geq 4.5$ were felt even over a very limited area.

Historical records of seismic (*Poirier and Taher 1980; Barazangi 1981*) and volcanic activity suggest that within plate volcanism has resulted in at least 21 eruptions in the Arabian Peninsula during the past 1500 years (*Camp et al., 1987*) including one on Harrat Lunayyir about 1000 years ago. The eruption in 1256 near the holy city of Madinah, Saudi Arabia is of particular historical and futuristic importance, for the lava flowed to within 8 km of the ancient city (*Camp et al., 1987*). Some volcanoes which are thought to be dormant over the years become active again, and these pose danger to the environment and to the foreseeable urbanization of nearby areas. This observation among dormant volcanoes may also happen in the northern part of the Harrat Rahat and Harrat Lunayyir lava field so that basic preparations are required to be done to mitigate the imposing danger. To minimize the future probable disastrous effects of this geologic hazard in this area, it is imperative that precautionary measures and basic preparations for the minimization of losses be undertaken as early as possible.

Harrat Lunayyir area is characterized by geothermally warm groundwater where temperatures up to 32 degrees Centigrade were measured in April, 2009 before the earthquake swarm began. Farmers in the Harrat Lunayyir area report seeing steam in many places on cold winter mornings. Harrat Lunayyir has its own characteristics than other nearby harrats where with recurrence interval of earthquake swarm is relatively short. This situation could be one of the environmental hazardous threats for the residential beings at Harrat Lunayyir. The amazing amount of microseismic activity and signs of prolific volcanism (*Kinkar et al., 1994b; Roobol et al., 1994; Roobol and Al-Rehaili 1997*) needs overall digital assessment of long-term geohazards related to volcanic, seismic and tectonic activities in the region. Therefore, the purpose of this study is to investigate the implications of this current volcano-seismic crisis and to asses the hazard implications in an area where at least one historic eruption has occurred and where there is little modern detailed study.

SEISMOTECTONIC SETTING

The western part of the Arabian Shield is made up of three major accreted tectonostratigraphic terranes (Asir, Jeddah and Hijaz) consisting mainly of variously metamorphosed layered volcano-sedimentary assemblages of older Baish, Bahah and Jeddah groups (950-800 Ma) and younger Halaban (Hulayfah) and Al Ays groups (800-650 Ma old: e.g.,) with arc-related plutonic rocks of diorite to tonalite compositions, which generally have

intrusive relationship with the volcano-sedimentary sequences (*Stoeser and Camp 1985; Johnson 2000*). The Cenozoic to Recent basaltic lava fields (harrats) of Saudi Arabia are resting directly on the so-called stable Precambrian Arabian Shield (Fig.1). Harrat Lunayyir is characterized by Cenozoic flood basaltic flows which can be differentiated into different cycles of metamorphism and tectonism with variable intensities during Tertiary-Quaternary age (Fig. 2). It was suffered from series of volcanic eruptions that took place along related fissures and cinder cones forming a zone of N-S and NW-SE trends. Magmatic lavas reached the ground surface through the prevailing deep crakes and fissures. These basaltic flows have exposed throughout western Saudi Arabia since Miocene time and extend to about 150-200
km inland from the Red Sea coast.

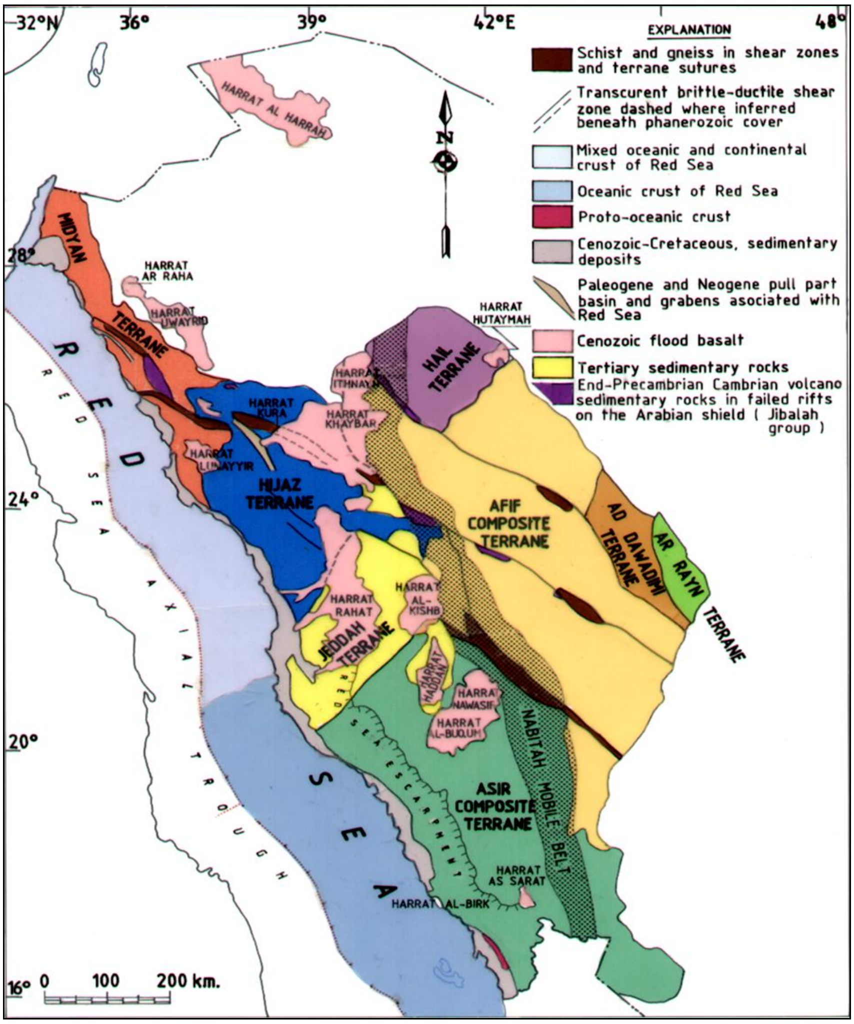


Fig. 1: Tectonic map of the Arabian Shield showing the Cenozoic lava fields (Harrats) of Saudi Arabia (modified from Johnson 1998). All lava fields occur in the oceanic-affinity arc terranes east of Nabitah Mobile Belt except Harrat Hutaymah. The MMN volcanic line harrats (Rahat, Khaybar and Ithnayn) are located in the Jeddah and Hijaz terranes.

The tectonic setting of the area is strongly related to the geodynamic processes acting in the Red Sea region. The relative movements between African and Arabian plates represented by system of normal and transform faults that run parallel and crossing the Red Sea respectively. Some of these faults extend inland over tens or hundreds of kilometers (*Al Shanti 1966; Pallister 1984*). There are three major tectonic trends are recognized through the Arabian Shield. The oldest one was formed during Precambrian with N-S direction. It includes transcurrent, normal and high angle reverse faults and major fold axes. Second one is well developed in the west -central part of the Shield and attains NE-SW direction. NE trending faults are controlled mainly by older Pre-existing Precambrian faults and reactivated during the Tertiary age due to the opening of the Red Sea and ocean floor spreading. NE faults are clustered within the central Red Sea and west-central Saudi Arabia including Harrat Lunayyir area. Whereas, the third major tectonic trend has NW-SE direction (Najd faulting system) that is responsible for rifting and opening of the Red Sea.

The Arabian Peninsula contains extensive Cenozoic lava fields of about 180,000 km^2, forming one of the largest alkali basalt provinces in the world. The presence of lava fields in western Saudi Arabia, from Yemen in the south up to Syria in the north (*Camp and Roobol 1991*), and with the historical records of volcanic eruptions (*Ambraseys 1988*) can be considered as an indication of the future possibility of recurring volcanic hazards in the western region of the Kingdom. The uplift and volcanism in the Arabian Shield are generally assumed to be the result of hot, buoyant material in the upper mantle that may have eroded the base of the lithosphere (*Camp and Roobol 1992*). However details about the nature of the upper mantle, such as its thermal and compositional state, are not known.

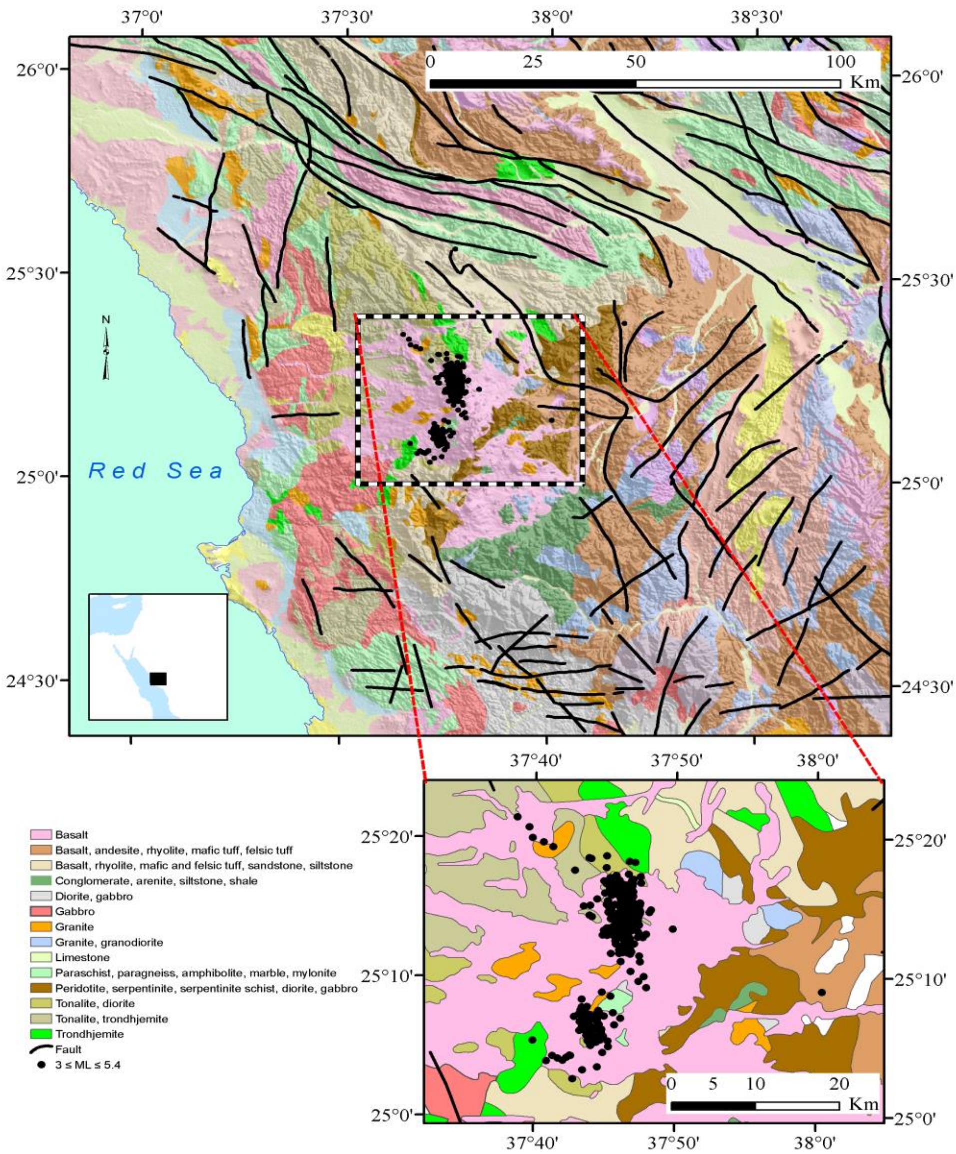


Fig. 2. Seismotectonic map of the Arabian Peninsula and Adjacent regions. The map shows Arabian plate boundaries and locations of earthquake epicenters and volcanic centers (Harrats).

The origin of the seismic waves from volcano activities can be attributed to two fundamentally different sources (*Zobin 1979*). These are the pressure variations associated with the unsteady fluid flow of magma and volatiles generating volcanic tremors, and the stress changes by sudden dislocations of shear/tensile cracks within the rigid parts of the volcanoes causing volcanic earthquakes. Earthquakes and volcanic actions have always been linked. Frequently, volcanic eruptions are reported to have been preceded by strong earthquakes or earthquake swarms occurring in a focal zone which is assumed to be common for the driving mechanism of earthquakes and eruption, but seldom in the reverse order. In a gross scale, many volcanoes are clearly connected to rift or Benioff zones, and volcanic belts follow seismifocal zones. However, tectonic earthquakes in these zones are not related to the immediate behaviour of volcanic activities. No physical processes can be specified which might be common in the crust and mantle for the occurrence of earthquakes and volcanic eruptions. But the pattern of the seismic activity close to a volcano are in space and in time among the strongest concomitants of present and future eruptive activity .

The existence of mantle plume beneath the western part of the Arabian plate including Al-Madinah Al-Munawarah region including Harrat Lunayyir has been recognized (*e.g., Moufti and Hashad 2005; Al-Damegh et al. 2005; Julia et al. 2003; Benoit et al. 2003; Daradich et al.,2003*). About 600 km long Makkah-Madinah-Nafud (MMN) active volcanic line, consisting of Harrats Rahat, Khaybar, and Ithnayn, is the surface expression of the plume-related ocean-island basalt (OIB) volcanism (*Moufti and Hashad 2005*) and northward propagating nascent rift system (*Camp et al.,1992*). The last two historic volcanic eruptions, close to the city of Al-Madinah Al-Munawwarah occurred at about 641 A.D. and then again at 1256 A.D. Since 1985, instruments have recorded frequent seismic activity within and around the City of Al-Madinah Al-Mounwwarah, especially the recent 1999 earthquake swarms (SGS 2005) and the ground deformation (*Kinkar et al., 1994b*). The signs of geothermal anomalies such as fumarolic emission and elevated well-water temperature within the City limits and also on Harrat Lunayyir also indicate the dynamic role of mantle plume occurring beneath the Harrat Al-Madinah (*Roobol et al. 1994)* and Harrat Lunayyir.

Results of *Hansen et al.* (2007) indicate that the observed splitting parameters in western Arabia are the result of a complex interaction of mantle flow in the asthenosphere. Shear caused by the absolute plate motion, which is directed approximately 40˚ east of north at about 22 mm/yr may affect the alignment of mantle minerals. However, it has also been suggested that flow radiating from the mantle plume beneath Afar is channelized towards the Red Sea Rift, which is oriented approximately 30˚ west of north. Assuming that the strain caused by the plume flow is comparable to that of the plate motion, they we combined these two flow orientations. This gives an overall resultant that is oriented with a north-south alignment. Additionally, *Hansen et al.(2007)* indicate that the motion is slightly more westerly, and Red Sea Rift parallel, fast directions, is the alignment of magma filled cracks that form perpendicular to the least compressive stress direction resulting in rift parallel fast polarization directions. This mechanism has been suggested as the dominant cause of anisotropy beneath other rift zones.

Al-Amri et al. (2008) suggest that low velocity beneath the Gulf of Aqabah and southern Arabian Shield and Red Sea at depths below 200 km are related to mantle upwelling and seafloor spreading. Low velocities beneath the northern Arabian Shield below 200 km may be related to volcanism.

Results and Interpretation

About 4147 events were recorded by Saudi Geological Survey (SGS) network in Al Ays area during the period from 19th April- 28th June 2009 with magnitude in the range from 0.43 – 5.39, 2212 events have magnitudes < 2.0 (53.3% of events); 1537 (37.06%) events with magnitudes from 2 to <3; 383 (8.51%) events have magnitudes from 3 - 4; while only 14 (0.34%) events with magnitudes > 4.0 (Fig. 3). Figure 4 shows the recorded number of events per day for the all magnitudes range. It shows three cycles of clustering; the first one was started on 19th April and increased till 23rd April where the maximum number of events was reached (107 event) then decayed rapidly till 26th April with recording 4 events; the second one initiated on 28th April and reached the maximum on 29th April and decayed slowly till 2nd June where 16 events were monitored; the third cycle recorded on 4th June and continued till 13th June as 86 events were recorded and the activity decayed till 19 June with 47 events then the activity increased again till 22nd June (141 events) and decayed till 28th June. It is cleared that more than 90% of the total energy has been released with small events which represents an important observation for releasing the energy continually and there is no chance for occurrence big event. This temporal variation in numbers of events with magnitude ranges could reflect the changing of stress level associated with upward magmic intrusions.

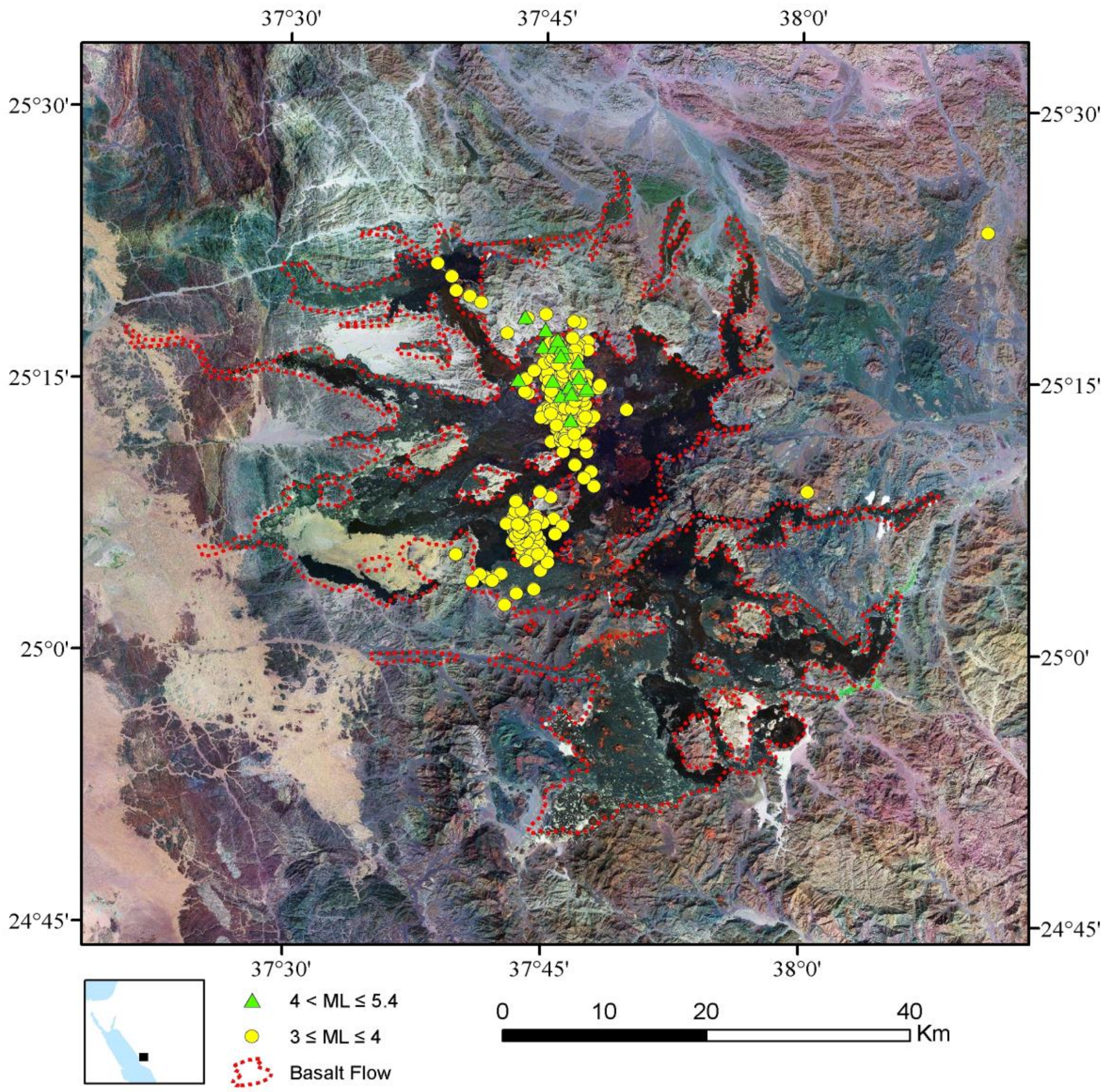


Fig. 3. Landsat- color composite image of Harrat Lunayyir showing recent seismicity which were located by the Saudi Geological Survey. There is no erosion suggesting it may be the site of the historic eruption of 1000 years ago.

Fault plane solutions indicate that there are two major structural trends of NE-SW and NW-SE are prevailing at Lunayyir area. Sometimes these directions are slightly deviated into NNE-SSW or NNW-SSE, N-S. The predominant mechanism is normal faulting but it could be contaminated with strike-slip components. Events no.1,2,3,7,8,9,10,11,12,13 and 14 have normal faulting mechanism with minor strike–slip components; While events no. 4,5 and 6 have normal faulting mechanism with large strike-slip component. The main trend of extensional stress pattern (*T*-axis) is in NE-SW direction while main trend of compressional stress (*P*-axis) is in NW-SE direction.

This is correlated well with the field measurements for the ground cracks and fissures accompanied with the mainshock.

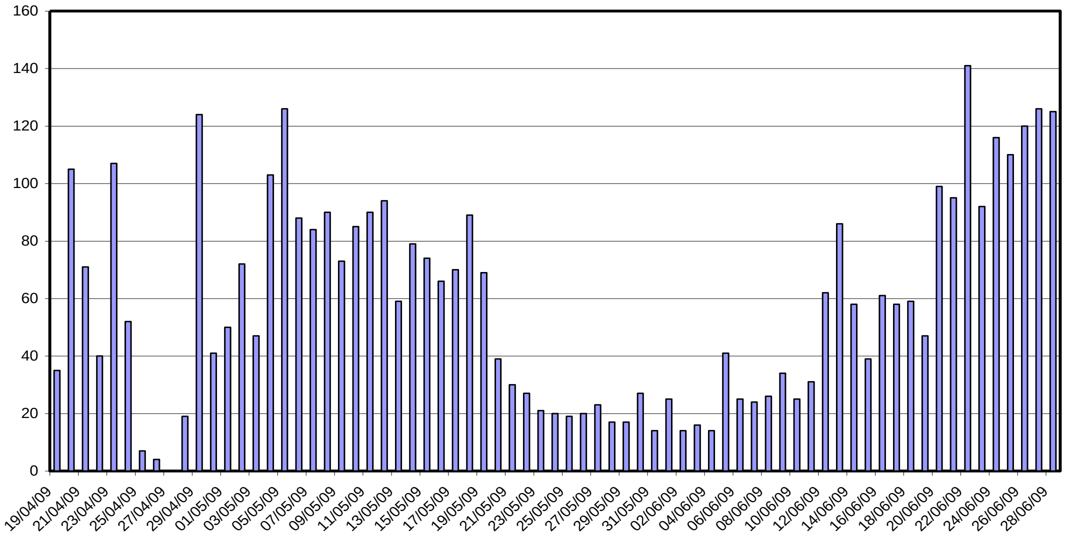
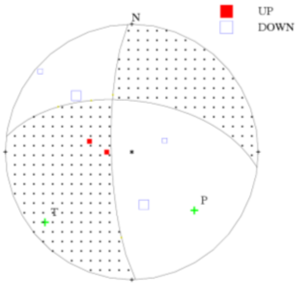


Fig. ٤. A histogram showing three cycles of clustering for the recorded events for the period from 19th April - 28th June 2009 with magnitude in the range from 0.43 – 5.39.

In general, these directions correspond to the direction of transform faults crossing the Red Sea and offsetting the median trench and spreading axis of the Red Sea. The main cluster of epicenters corresponds to a cluster of hills composed of ancient Precambrian rocks. The hills were the site of two prehistoric basaltic eruptions as there are two chains of scoria cones sitting on top of them. One chain has five cones and the other three and both are aligned East–West.

A moderate (M~5.4) earthquake struck Al-Ays on May 19, 2009. The event was large enough to be detected and located by global networks at teleseismic distances. The region is generally believed to be aseismic and large earthquakes are rare in this part of the world. Broadband complete regional waveforms were used to estimate a focal mechanism and depth of the event. We combined waveform data from RAYN-GSN and EIL stations. Figure 6 shows the event location and stations used in the focal mechanism study of this event. We followed the grid search procedure described in *Walter* (1993) to find the best-fitting seismic moment, focal mechanism and depth for all stations using the appropriate velocity model of the Arabian Shield area (*Al-Amri et al., 2008*). Love and Rayleigh wave group velocities were modeled to estimate average one-dimensional seismic velocity model of the Arabian Shield.



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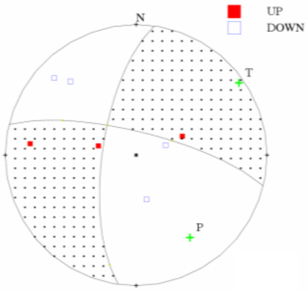

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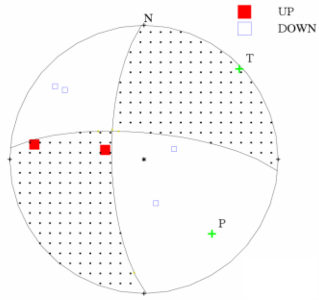

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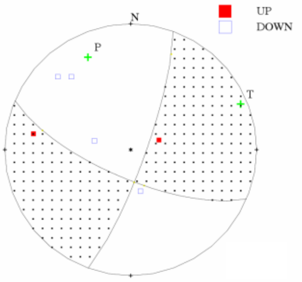

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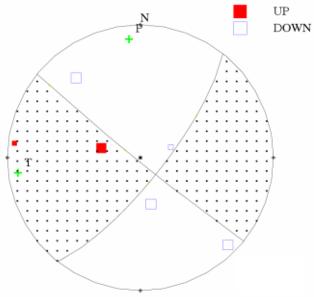

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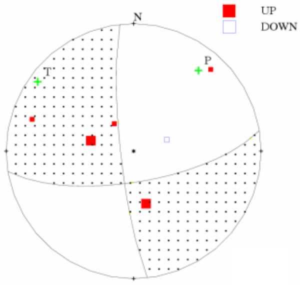

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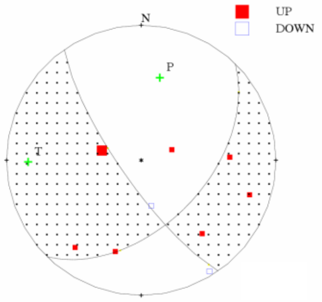

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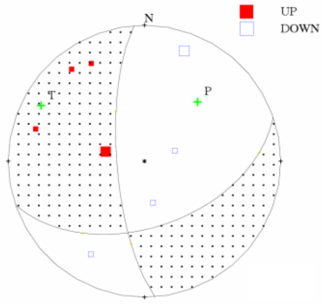

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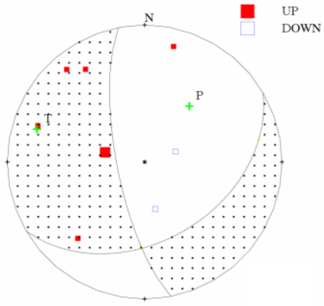

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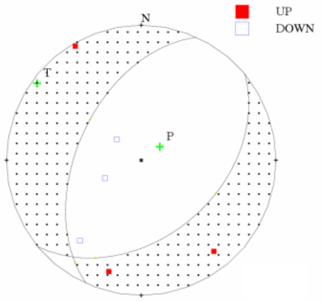

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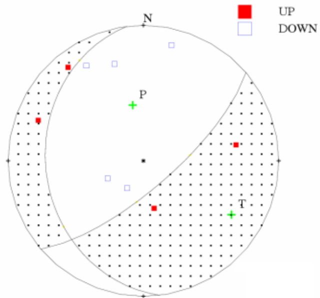

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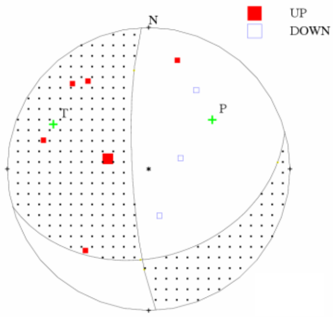

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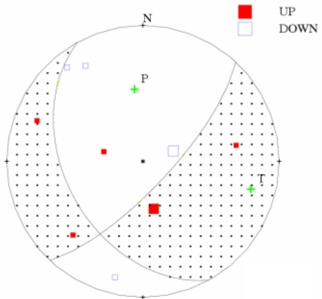

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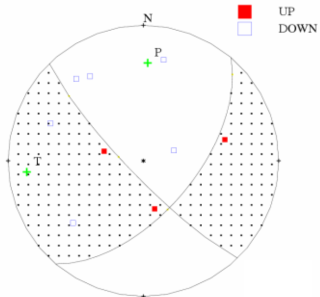

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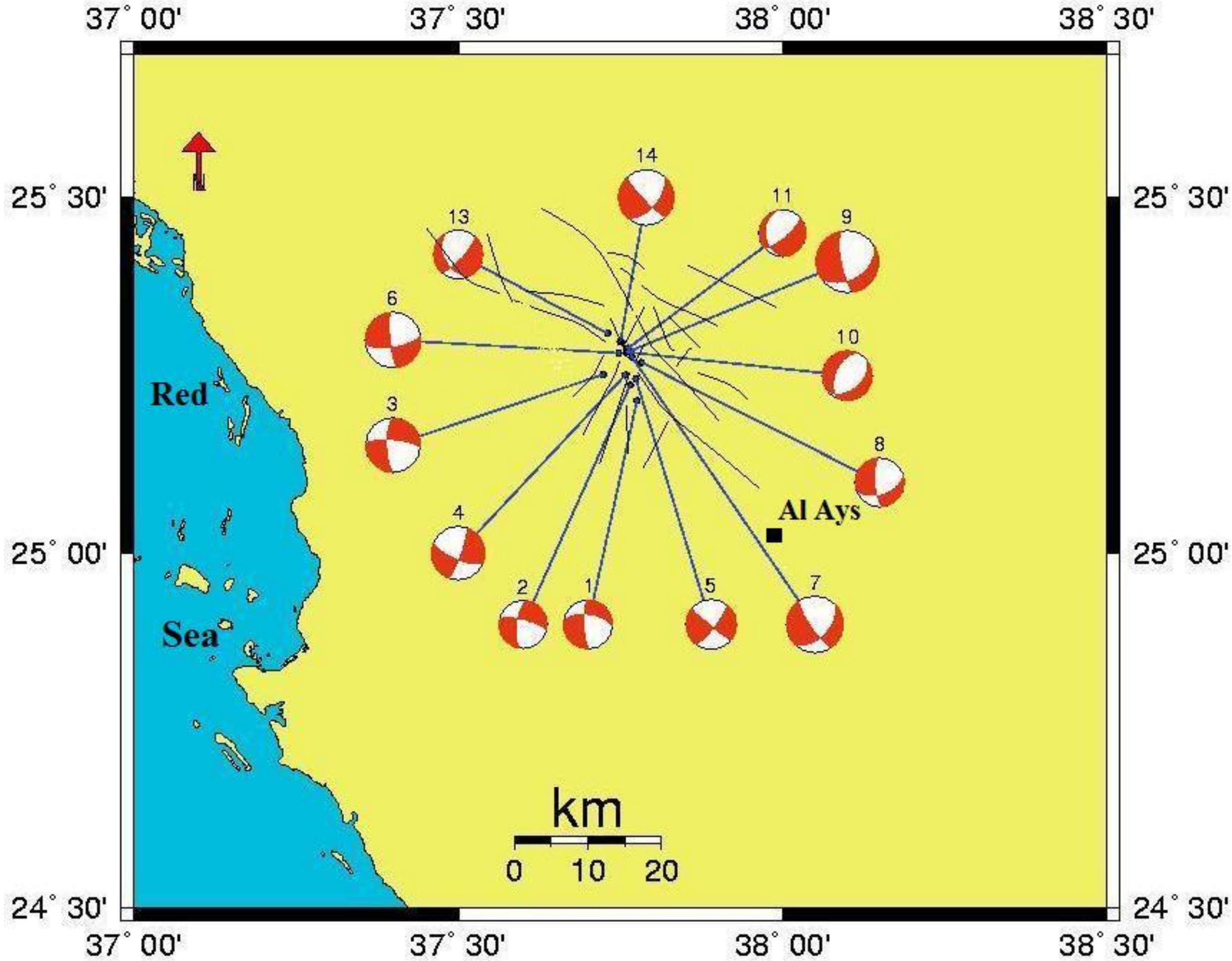

Fig. 5. Analysis of fault plane solutions for the largest fourteen events using the PMAN program (*Suetsugu, 2003*). It indicates that there are two major structural trends of NE-SW and NW-SE are prevailing at Lunayyir area.

Field investigation and focal mechanism solutions have revealed that the main shock was due to a primary coseismic rupture represented by a N137˚ (NW-SE) oriented normal faulting. The fault has a displacement of 1.1 m and dip of 48˚ SW. Secondary ruptures, trending NE-SW to ENE-WSW, have lesser displacements. During May 19th, 2009 earthquake, sympathetic activity occurred on N-S trending faults.

Depth (km)	*Thickness (km)*	V_p *(km/s)*	V_s *(km/s)*
0	1	4.0	2.31
1	15	6.2	3.58
16	20	6.8	3.93
36	∞	7.9	4.30

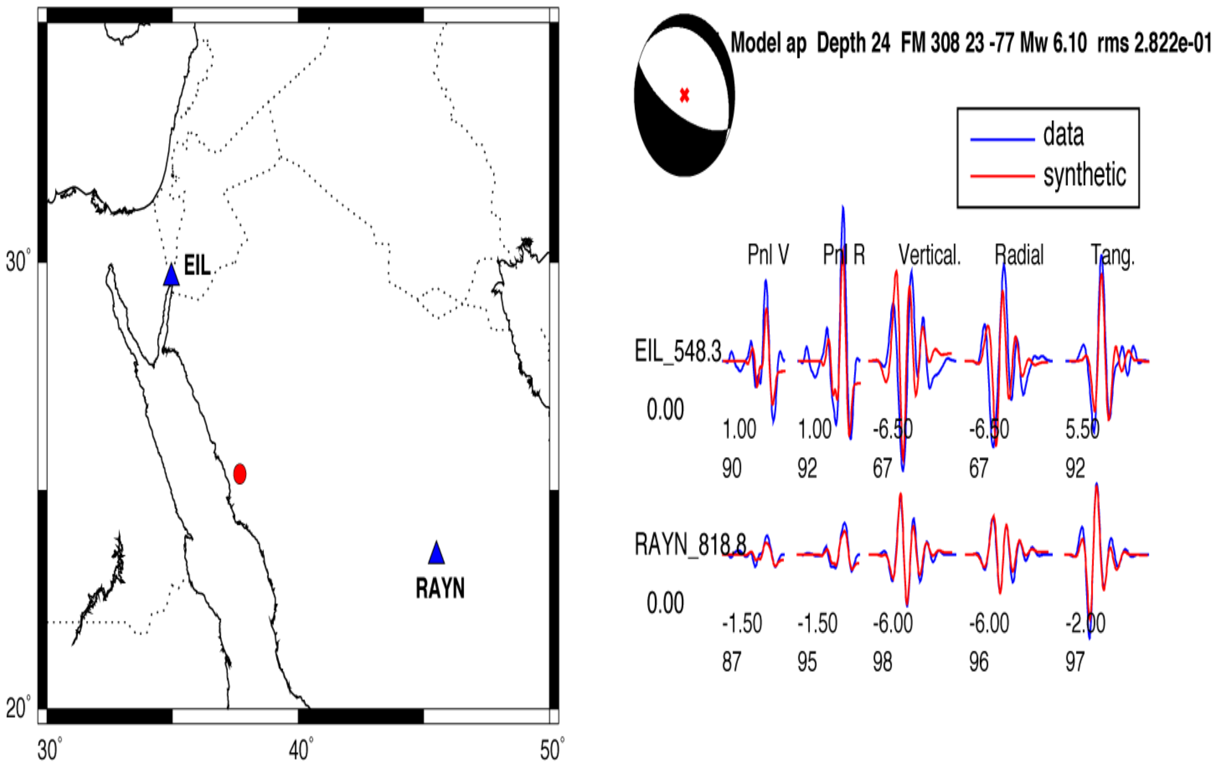

Fig.6. Observed (blue) and synthetic (Red) waveforms for the focal mechanism modeling of the May 19 earthquake. The best-fitting focal mechanism is also shown in the figure.

Intensive ruptures, rock falls and land collapses have been observed in the epicentral area of the earthquake. In Al-Ays area, the general degree of damage indicates a maximum predominant intensity of VI (Fig. 7). Ground shaking from the largest event (M 5.4) may have caused light damage. Modified Mercalli Intensities (MMI) reach values of VI. Damage to buildings is expected to be light at these levels. The affected region has low level of urban area (0%) and a low level of cultivated area (0%). In urban areas more damage can be expected than in cultivated or natural areas. Population density in the source region is very low, fortunately not many people were affected. Region of highest ground motions is very sparsely populated as shown in Fig.7 and in the table below.

City	Modified Mercalli Intensity	Remarks
Al-Ayis	VI	Strong felt
Umm Laj	From V to less than VI	Moderate felt
Yanbu and Al-Wajh	From IV to less than V	Light felt
Tabuk and Almadinah	From III to less than IV	Weak felt

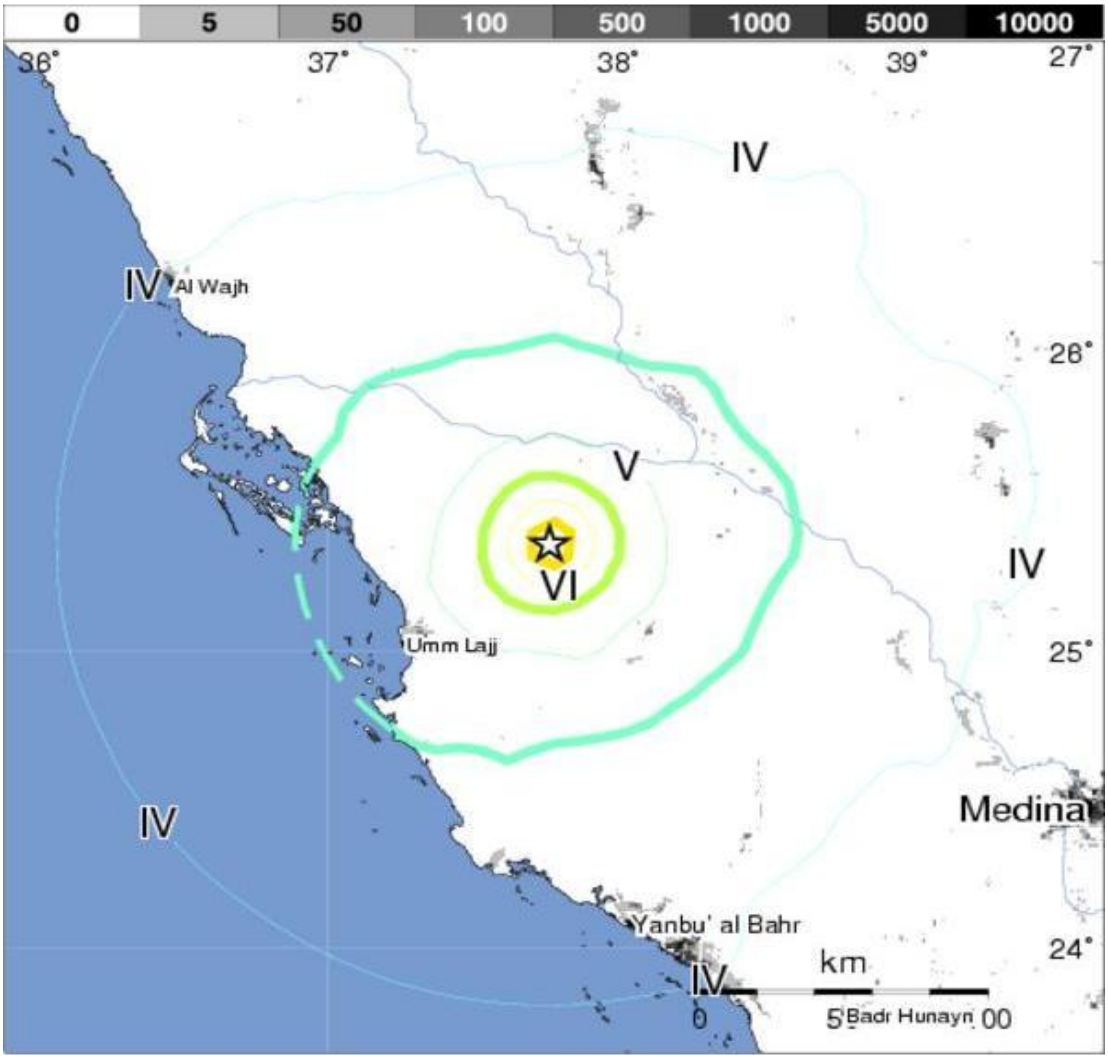

Fig. 7. Distribution of maximum intensity based on the largest earthquake affected the area. Population density in the source region is very low, and region of highest ground motions is very sparsely populated.

Examination of the total-intensity magnetic anomaly map of the Red Sea (*Hall 1979*) and remote sensing show that some magnetic anomalies are offset in a northeasterly direction and others are normal to the axial trough lineations. This could be due to the magnetic expression of transform faults which cause disturbances of the magnetic anomalies. These faults trend in a northeasterly direction, but because of the short distance across the Red Sea it is not possible to ascertain their azimuths accurately from the magnetic anomalies. *Hall (1979)* mapped large-amplitude, long-wavelength linear magnetic anomalies along the shelves of the northern Red Sea and interpreted them as the expression of oceanic crustal strips of alternating remanent polarization that were emplaced during Tertiary seafloor spreading and subsequently buried by Miocene sedimentary deposits. These anomalies extend onto the coastal plain and inland as far as the exposed margin of the shield, where they are associated with the diabase dike swarm.

In order to investigate the relation between the epicentral distribution and the tectonic features, the locations of the faults inferred from the offset of magnetic anomalies were superimposed upon the seismicity map (Fig. 8). Alignment of epicenters and the northeast trending faults near latitudes 24.5° N could indicate that this fault extends northeastward on land. The proposed extension of the northeast fault has not been field checked and traced in Umm Laj (coastal plains), because of the presence of thick deposits of unconsolidated sediments.

The scatter of some epicenters in the shield area is due to the complexity of the rift faulting and inaccuracies involved in the calculation of the epicenters because of the poor azimuthal coverage of the existing stations. The low level of seismicity in the coastal plains is caused by the fact that some deep faults existed without surface traces. Marine epicenters are considered of less risk than land earthquakes or seaquakes close to the shore because of the high attenuation of seismic waves travelling through the rather soft and hot upper mantle material beneath the sea.

CONCLUSIONS

It can be concluded from this study that recent seismic activities in Harrat Lunayyir is of swarm-type and volcanic-related and occur in the form of sequences, each are lasting up to several months, reaching peak magnitude up to 5.5 and covering a specific tectonic segment of the Harrat. The recent seismic activity indicates a cyclic pattern of events consisting of seismic minima which may represent episodes of accumulation of energy, and seismic maxima which represent the release of energy that can be accumulated to cause larger events in the future. Places of interaction of normal and strike-slip faulting in the Harrat could be the sites of swarm sources and recent stress accumulations. A clustering of swarm activity in time may suggest an episodic source of strain or a constant source with repeated slip along the fault zone.

The present activity can be termed as a volcano-seismic crisis. In an area where previously there has been little or no seismic activity, the sudden commencement of swarms of activity at shallow depths taken with the presence of fumaroles indicates a possible new cycle of activity. Such events can last for four months and then die out. Alternatively they can continue and escalate leading to felt earthquakes and result in a basaltic eruption. Basaltic eruptions are considered the safest type of volcanic activity and do not usually involve the loss of life and the lava flows can today be diverted away from settlements by building earth banks using bulldozers.

The principal mode of faulting, as determined by single focal mechanism solutions was normal faulting on planes striking NW and dipping to NE-SW. This result is what would be expected from the regional opening of the Red and from linear surface cracking observed in the affected areas.

Analysis of the seismicity data in conjunction with magnetic and geologic information indicate that the seismicity is shallow and the correlation of the offshore epicentral distribution with the major tectonic features is, in general, quite good. However, the low level of seismicity in the shield area and poor correlation with the tectonics might be due to the complexity of faulting, lack of detection of small events and poor or inaccurate azimuthal coverage of stations. Structural patterns inferred from magnetic data and earthquake locations (offshore and onland) provide evidence for continuation of the faulting regime from the northern Red Sea northeastward into the Arabian Shield and Harrat.

It should be pointed out that installation of strong ground-motion instruments in this region will lead to better estimates of the attenuation relationships and accelerations for seismic hazard assessment.

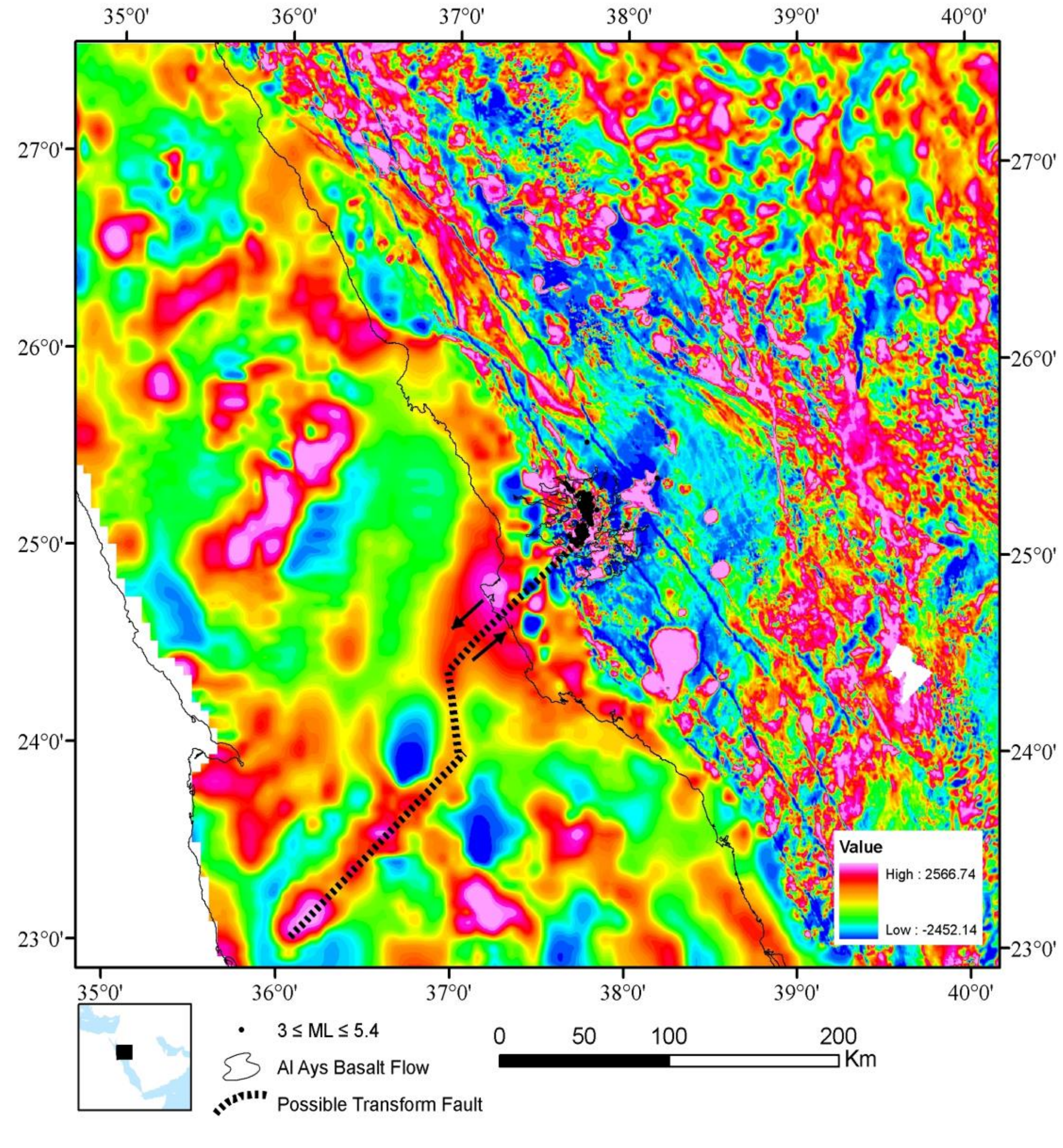

Fig. 8. Aeromagnetic map showing the relation between the epicentral distribution , tectonic features, and locations of the faults inferred from the offset of magnetic. Alignment of epicenters and the northeast trending faults near latitudes 24.5° N could indicate that this fault extends northeastward on land.

REFERENCES

AlAmri, A., Rodgers, A., and Al-khalifah, T., (2008). Improving the Level of Seismic Hazard p*arameter in Saudi Arabia Using Earthquake Location. Arabian J. of Geosciences, 1, DOI:10.1007/s12517-008-0001-5 , 1-15.*

Al-Damegh, K., Sandvol,E. and Barazangi, M. 2005. Crustal structure of the Arabian plate: New constraints from the analysis of teleseismic receiver functions. Earth Planet. Sci. Lett.(231): 177-196

Al Shanti, A. M., (1966): Oolitic iron-ore deposits in Wadi Fatima between Leddah and Mecca, Saudi Arabia. Saudi Arabian Dir. Gen. Min. Resources Bull., vol. 2, 51p.

Ambraseys, A., 1988 Seismicity of Saudi Arabia and adjacent areas, Report 88/11, ESEE, Imperial Coll. Sc. Tech. London, U.K.

Barazangi, M., 1981 Evaluation of seismic risk along the western part of the Arabian plate : discussion and recommendations, Bull. Fac. Earth Sc., King Abdulaziz Univ., Jiddah, K.S.A., 4: 77-87.

Benoti, M.H., Nyblade, A.A., VanDecar, J.C. and Gurrola, H. 2003. Upper mantle P wave velocity structure and transition zone thickness beneath the Arabian Shield. Geophys. Res. Lett. 30: 1-4

Camp, V.E. and Roobol, M.J., 1991, Geologic Map of the Cenozoic Lava Field of Harrat Rahat, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geoscience Map GM-1233, scale 1:250,000 with text 37p.

Camp, V.E., and Roobol, M.J., 1992, Upwelling asthenosphere beneath western Arabia and its regional implications: Journal Geophysical Research, v. 97, p.15,255-15,271.

Camp, V.E., Hooper,P.R., Roobol, M.J. and White, D.L., 1987, The Madinah eruption, Saudi Arabia: Magma mixing and simultaneous extrusion of three basaltic chemical types: Bulletin Volcanology, v. 49, p.489-508.

Daradich, A., Mitrovica, J.X., Pysklywec, R.N, Willett, S.D. and Forte, A.M. (2003). Mantle flow, dynamic topography, and rift-flank uplift to Arabian. Geol. Soc. Am. 31:901-904

Hansen, S., Schwartz, S., Al-Amri, A. and Rodgers, A. (2006). Combined plate motion and density driven flow in the asthenosphere beneath Saudi Arabia: evidence from shear- wave splitting and seismic anisotropy. Geology, V. 34, no. 10, p. 869 – 872.

Hall, S. (1979). A total intensity map magnetic anomaly map of the Red Sea and its interpretation. Directorate General of Mineral Resources, Jeddah, Saudi Arabia. Report 275, 260p.

HHansen,S., Rodgers, A., Schwartz, S., and Al-Amri, A. (2007). Imaging Ruptured Lithosphere Beneath the Red Sea and Arabian Peninsula. Earth and Planetary Science Letters, 259, 256 – 265.

Hill D.P., (1977): A model for earthquake swarms, *J. Geophys. Res.* **82** (1977), pp. 1347–1352

Johnson, P.R. 1998. Tectonic map of Saudi Arabia and adjacent areas. Deputy Ministry for Mineral Resources Technical Report USGS-TR-98-3 (IR 948).

Johnson, P.R**.** 2000. Proterozoic geology of Saudi Arabia: Current concepts and issues. Contribution to a workshop on the geology of the Arabian Peninsula, 6th meeting of the Saudi Society for Earth Science, King Abdulaziz City for Science and Technology, Riyadh, Saudi Arabia. 32 p.

Julia, J., Ammon, C. and Herrmann, R. 2003. Lithosphere structure of the Arabian Shield from the joint inversion of receiver functions and surface-wave group velocities. Tectonophysics 371:1-21

Kinkar, A., Shawali, A.A., Bankher, K.A., Endo, E., Roobol, M.J. and Wynn, J.C. 1994b. The Al-Madinah-Harrat Rahat volcanic monitoring project summary report. Saudi Arabian Deputy Ministry for Mineral Resources Confidential Report USGS-CR-94-1 (IR909), 47P.

Klein, B. M.; Economou, E. N. , and Papaconstantopoulos, D. A. (1977): Inverse Isotope Effect and the x Dependence of the Superconducting Transition Temperature in PdH_x and PdD_x. Phys. Rev. Lett. , Vol. 39, No. 9, pp. 574 – 577

Moufti, M.R.H. and Hashad, M.H. 2005. Volcanic hazards assessment of Saudi Arabian Harrats: geochemical and isotopic studies of selected areas of active Makkah- Madinah-Nafud (MMN) volcanic rocks. Final Project Report (LGP-5-27), King Abdlaziz City for Science and Technology, Riyadh, Saudi Arabia.

Pallister, J. S., (1984): Expanatory notes to the geologic map of the Al Lith quadrangle, sheet 20 D., Kingdom of Saudi Arabia.

Poirier, J. P., and Taher, M.A., 1980 Historical seismicity in the near and middle east, north Africa, and Spain from Arabic documents (VIIth-XVIII century), Bull. Seis. Soc. Am., 70.6, 2185-2201.

Pollard D.D. and Holzhausen G.(1979). On the mechanical interaction between a fluid-filled fracture and the earth's surface. *Tectonophysics*, 53, 27-57.

Roobol, M.J., and Al-Rehaili, M., 1997, Geohazards along the Makkah-Madinah-Nafud (MMN) volcanic line: Saudi Arabian Deputy Ministry for Mineral Resources Technical Report DMMR-TR-97-1, p.125-140.

Roobol, M.J., Bankher, K. and Bamufleh, S**.** 1994. Geothermal anomalies along the MMN volcanic line including the cities of Al-Madinah Al-Munawwarah and Makkah Al-Mukarramah. Saudi Arabian Deputy Ministry for Mineral Resources Confidential Report DGMR-MADINAH-CR-15-2, 95 p.

SGS 2005**.** Technical work program of the Saudi Geological Survey (SGS) for 2005. Jeddah, Saudi Arabia. 79 p.

Stoeser, D.B. and Camp, V.E. 1985. Pan-African microplate accretion of the Arabian Shield, Bull. Geol. Soc. Ame. 6: 817-826.

Suetsugu, D. (2003): PMAN The program for focal mechanism diagram with p-wave polarity data using the equal-area projection. IISEE Lecture Note, Tsukuba, Japan, pp. 44-58.

Sykes, L. R., (1967): Mechnism of earthquakes and nature of faulting on the mid-ocean ridge, J. Geophys. Res., vol. 72, pp. 2131-2153.

Tatham, R. H. and Savino, J. M. (1974): Faulting mechanisms for 2 oceanic earthquake swarms. J. Geophys. Res., Vol. 79, pp. 2643-2652.

Walter, W. (1993). Source parameters of the June 29, l992 Little Skull Mountain earthquake from complete regional waveforms at a single station, *Geophys. Res. Lett.*, 20, 403-406.

Zobin, V.M., 1979, Variations of volcanic earthquakes source parameters before volcanic eruptions, Journ. Volc. Geotherm. Res., 6, 279-293.