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Environmental impacts and mineralogical characteristics of dust storm in Middle-East

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Abstract：Middle Earth, including Iran, Iraq, China and Syria has been recognized as one of the most important primary sources of dust. Intensive investigations have been conducted to study the chemical composition, sources and deposition of Middle Earth particles. However, analysis of individual Middle Earth particles show that about one fifth of all the particles are mineral aggregates, and at least one fourth of the particles contain sulfur. X-ray diffraction (XRD) is used to quantify the phase and the clay mineral compositions of Middle Earth samples. Phases in the Middle Earth sample collected during the 20 March 2002 dust storm episode included clay minerals, noncrystalline materials, quartz, calcite, plagioclase, potassium feldspar, pyrite, hornblende, and gypsum in descending order. Clay minerals are mainly illite/smectite mixed layers (78%), followed by illite (9%), kaolinite (6%), and chlorite (7%). Particulate matter (PM) less than 10 mm are enriched with clay minerals and deficient with quartz by mass compared with the total suspended particulates collected during an Middle Earth episode. The PM less than 10 mm collected during the two severe dust storm episodes is characterized by the absence of dolomite, high quartz/clay ratio, and dominance of illite/smectite mixed layers in clay minerals.

Keywords：Dust storm, Mineralogy, Primary zonation, Medical geology, Middle Earth.

Ⅰ．Introduction

It is estimated that nearly 50% of troposphere atmospheric dust storms are minerals, mainly sourced from the deserts and their boundaries (Andreae, 1995). Mineral aerosols affect climate directly through scattering, transmission and absorption of solar radiation, and indirectly by acting as cloud nucleation nucleus (CNN) when coated with soluble material (Andreae, 1995; Levin *et al*., 1996; Buseck and Po´sfai, 1999; Clarke *et al*., 2001; Sokolik *et al*., 2001). Mineral aerosols also play an important role in removal, deposition and transport of atmospheric pollutants (Winchester and Wang, 1989; Dentener *et al*., 1996; Carmichael *et al*., 1996). Mineral aerosols, especially those carried by dust storms, can be transported globally, and have significant impacts on theglobal environments and climate (Buseck and Posfai, 1999; Prospero, 1999; Clarke *et al*., 2001; Bishop *et al*., 2002). In addition, the identification of mineral assemblages of aerosols may be diagnostic of their sources (Bergametti *et al*., 1989; Merrill *et al*., 1994; Davis and Guo, 2000; Ganor *et al*., 2000). Mineral dust storms are highly heterogeneous, but are commonly treated as a relatively homogeneous group, and this may lead to increasing uncertainty in atmospheric chemistry and climate models (Buseck and Posfai, 1999). Therefore improving our knowledge about the mineralogy of airborne particles is an important task for atmospheric scientists.

Middle Earth dust storm can transport mineral grains thousands of kilometers to Japan, Korea, North Pacific Ocean, Hawaii and even North America (Leinen *et al*., 1994; Merrill *et al*., 1994; Arnold *et al*., 1998; Clarke *et al*., 2001; Zhuang *et al*., 2001; Mori *et al*., 2003; Moore *et al*., 2003), thus having significant impacts on theglobal environment, climate and geochemical cycle (Fig 1). Intensive investigations have been conducted to study the chemical composition, sources and deposition of Middle Earth particles (Zhuang *et al*., 2001; Kanayama *et al*., 2002; Mori *et al*., 2003). Some studies have focused on individual particle characteristics (Zhang *et al*., 2003) and size distributions of Middle Earth particles (Chun *et al*., 2001; Mori *et al*., 2003). The mineral compositions of aerosol particles, which possibly originated from Asia, over the North Pacific Ocean, have been analyzed by Leinen *et al*. (1994), Merrill *et al*. (1994), and Arnold *et al*. (1998). The current paper seeks to analyze the deposition characteristics of dust in recent times. In addition, the study of the mineralogical characteristics and source of aerosols and deposited sediments from Middle Earth and Iran will provide background information for further research.

Fig 1. Middle Earth dust storm can transport mineral grains thousands of kilometers.

Ⅱ. Mineralogy

Little information is available on the mineralogical composition of sand and dust particles in the Middle East. Al-Ali (2000) indicated that over central and southern Iraq sand and dust particles comprised 8-45% carbonates, 18-63% quartz, 4-27% feldspar, 1-16% mica, and 1-8% gypsum in addition to 4-28% multimineral rock fragments. Texturally, most of the fallout consists of very fine sand (125-62 μm) and coarse silt (62-31μm). Alternatively, dust fallout over the Dead Sea consists of soluble salts, carbonates (6.7-47.9%), apatite (1-5%) (derived from the phosphate mining activity 45 km away), and clay minerals (Singer *et al*., 2003).

Using ESEM-EDX, Shi *et al*., (2005) have identified individual plagioclase, clay mineral, quartz and calcite particles in the 20 March 2002 dust storm sample. A typical ESEM-EDX chemical spectrum of the bar-shaped mineral particles is shown in Figure 2a. Some individual particles were mineral aggregates composed of two or more minerals, for example, aggregates of aluminosilicate and gypsum, aluminosilicate and calcite, aluminosilicate and Fe oxides, aluminosilicate and Ti oxides and quartz and calcite, rather than pure minerals. This is in agreement with observations showing that wind-blown dust particles sourced from highly arid regions tend to be aggregated (Gao and Anderson, 2001).

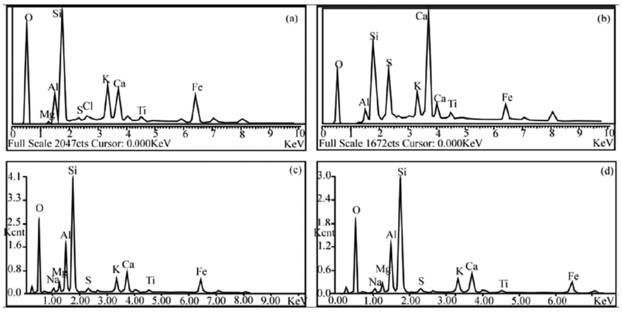

Fig. 2. ESEM-EDX spectra of mineral particles from Middle Earth collected during the 20 March 2002 severe dust storm. (a), Typical spectrum of a bar-shaped mineral particle; (b), spectrum of a mineral aggregate composed of aluminosilicate and gypsum; (c), spectrum of a microarea (bulk), showing a sulfur peak; (d), spectrum of a sulfur-containing individual particle.

Figure 2b shows the EDX spectrum of a mineral particle which was an aggregate of aluminosilicate and gypsum. Shi *et al*., (2005) have analyzed 132 individual Middle Earth dust storm particles, of which about one fifth are mineral aggregates. A randomly selected portion of the 20 March 2002 dust storm sample was analyzed with ESEM-EDX, and the chemical spectrum is shown in Figure 2c. A sulfur peak was evident in Figure 2c. By ZAF correction, the weight percentage of each element present in the spectrum could be quantified. If normalized to 100% for Si, O, Al, Ca, K, Fe, Mg, Na, S and Ti, sulfur weight percentage was 0.7%. Figure 2d shows the EDX spectrum of a sulfur-containing particle. About one fourth of the 132 individual particles analyzed contained sulfur. Although there were particles in which sulfur was the major element such as that in Figure 2a, sulfur was a minor element for most of the sulfur-containing particles.

The XRD analyses demonstrated that quartz, K-feldspar, plagioclase, calcite, pyrite, hornblende, illite/ smectite mixed layers, illite, kaolinite and chlorite were present in the 6 April 2000 dust storm sample (Shi *et al*., 2005) (Fig. 3a). The same mineral assemblage, together with hematite, was also identified in the PM10 collected during the 20 March 2002 severe dust storm episode (Fig. 3b). For comparison, Figure 3c showed a typical XRD pattern of a non-Middle Earth sample. Illitegypsum, quartz, dolomite, calcite, and hematite were identified in the non- Middle Earth sample.

The phase compositions of the PM samples collected during the two severe dust storm episodes were further quantified based on XRD patterns. By weight percentages, the TSP sample collected during 6 April 2000 dust storm episode was dominated by clay minerals (35.5%) and quartz (30.3%), followed by calcite (14.0%), noncrystalline materials (10.1%), plagioclase (7.0%), K-feldspar (1.7%), pyrite (1.0%) and hornblende (0.4%) (Shi *et al*., 2005). In particles smaller than 10 mm separated from TSP, the major phases by weight were clay minerals (39.0%), quartz (20.7%) and noncrystalline materials (20.0%), with certain amount of calcite (9.1%), plagioclase (7.8%), pyrite (1.0%), K-feldspar

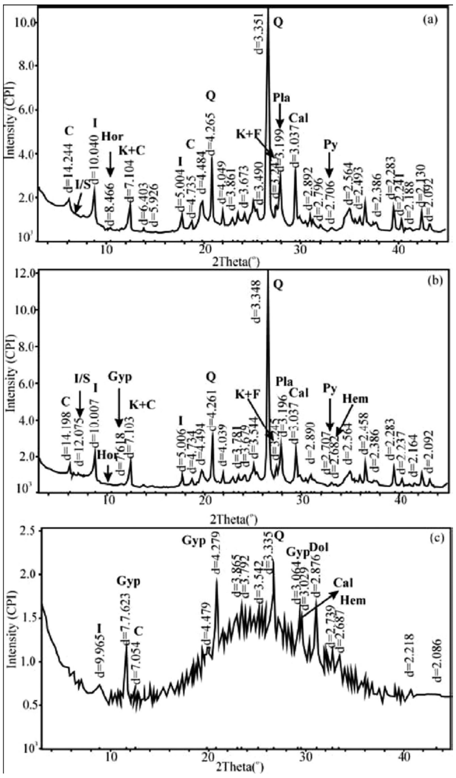

Fig.3. XRD patterns of PM10 samples from Middle Earth collected during dust storm and nondust storm episodes. (a), PM less than 10 mm (by sedimentation in water from TSP, ADS-T1) collected during the 6 April 2000 severe dust storm episode; (b), PM10 collected during the 20 March 2002 severe dust storm episode; (c), An example of nondust storm PM10 collected on glass fiber filter (28 March 2002 at 2100 LT until 29 March 2002 at 0900 LT). The dolomite peak is obvious; this pattern was used for comparison with those of MIDDLE EARTH samples only. I, illite; Hor, hornblende; Q, quartz; C, chlorite; K, kaolinite; K+C, kaolinite+chlorite; I/S: illite/smectite; Cal, calcitegyp, gypsum; Py, pyrite; K+F, potassium feldspar; Pla, plagioclase; Hem, hematite (Shi *et al*., 2005).

(2.1%) and hornblende (0.3%) (Fig. 4a). Quantification of the PM10 collected during the 20 March 2002 severe dust storm episode is shown in Figure 4b. By weight, this sample was dominated by clay minerals, accounting for 40.1%, and the other phases included noncrystalline materials (20.5%), quartz (19.5%), plagioclase (8.4%), calcite (7.5%), K-feldspar (1.5%), hematite (0.9%), pyrite (0.9%), hornblende (0.4%) and gypsum (0.3%) (Shi *et al*., 2005).

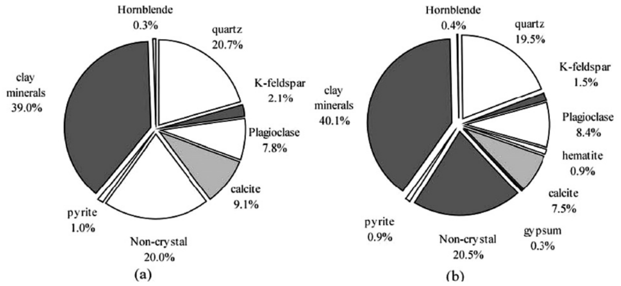

Fig. 4. Weight percentages of different phases in PM10 samples from Middle Earth collected during the severe dust storm episodes in Beijing: (a), 6 April 2000 (by sedimentation in water from TSP); (b), 20 March 2002 (Shi *et al*., 2005).

The XRD measurements of both the TSP and PM10 collected during the 6 April 2000 severe dust storm episode showed that quartz was mostly enriched in TSP and deficient in PM10, while clay minerals were mainly concentrated in PM10 and deficient in TSP. Percentages by weight of other minerals were similar in TSP and PM10. For the 20 March 2002 dust storm samples, quartz was relatively concentrated in PM10 while clay minerals were enriched in PM less than 2 mm. Because the fine Middle Earth particles could be transported a longer distance, the clay minerals may havegreater impacts on theglobal environment and climate. The results of Arnold *et al*. (1998) supported this inference.

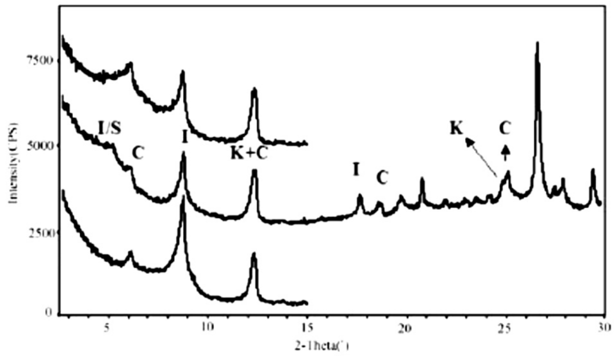

Fig. 5. XRD pattern of clay minerals collected during the 20 March 2002 severe dust storm episode (<2 mm by sedimentation in water from PM10).
I/S, illite/smectite mixed layers; C, chlorite; I, illite; K+C, kaolinite +chlorite; K; kaolinite (Shi *et al*., 2005).

Because clay minerals were the most abundant species collected during the two severe dust storm episodes, they were separated from the whole samples, and then analyzed and quantified with the XRD. Figure 5 is the XRD pattern of clay minerals in PM10 collected during the 20 March 2002 severe dust storm episode. The quantitative analysis (see Shi *et al*., 2005) showed that clay mineral assemblages of PM less than 2 mm during both severe dust storm episodes were similar. Illite/smectite mixed layers were the major clay mineral species, accounting for about 78%, followed by illite (9%), chlorite (6%) and kaolinite (7%). In addition, smectite occupied 40% in the illite/smectite mixed layers of the particles less than 2 mm for the two severe dust storms (see Shi *et al*., 2005).

Ⅲ. Morphology

Shi *et al*., (2005) have been considered three major categories of particles have been differentiated under the

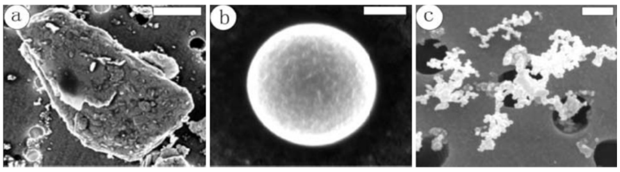

Fig. 6. FESEM of typical particle types from Middle Earth. (a), Mineral dust, represented by its irregular shape; (b), coal fly ash, characterized by spherical shape; (c), soot aggregates, developing from small groups or chains into larger chains (Shi *et al*., 2005).

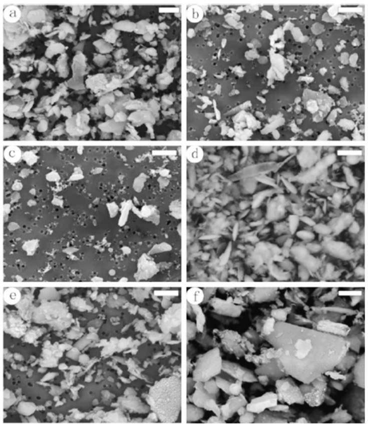

Fig. 7. FESEM of PM10 samples from Middle Earth collected during and after the dust storm episodes (scale bar 5 mm). (a), ADS98 during the 16 March 2002 dust storm episode, dominantly mineral particles with trace amounts of soot aggregates; (b), ADS99 collected after the 16 March 2002 dust storm episode, mainly mineral particles with small amounts of soot aggregates and trace amounts of coal fly ash; (c), ADS100 collected after the 16 March 2002 dust storm episode, mainly soot aggregates and coarse mineral particles with trace amounts of coal fly ash; (d), ADS1 collected during the 20 March 2002 severe dust storm episode, predominantly mineral particles in which about 30% are bar shaped; (e), ADS2 collected after the 20 March 2002 severe dust storm episode, mainly mineral particles; (f) ADS4 collected after the 20 March 2002 severe dust storm episode, mainly mineral particles with a few soot particles (Shi *et al*., 2005).

FESEM: mineral particles (Fig. 6a), coal fly ash (Fig. 6b), and soot aggregates (Fig. 6c). Soot aggregates were characterized by chain-like and "fluffy" appearance, coal fly ash by a smooth spherical shape and mineral particles by irregular shape.

The PM10 (see Shi *et al*., 2005) collected during the 16 March 2002 dust storm episode was dominated by irregularly shaped mineral grains with trace amounts of soot aggregates adhering onto the surfaces of these minerals (Fig. 7a). The PM10 collected after the dust storm was also mainly composed of minerals with small amounts of fine soot aggregates and trace amounts of coal fly ash (Fig. 7b). However, in the PM10 collected the following day, many more soot aggregates and ultrafine particles (<100 nm) were observed (Fig. 7c). This indicated an increasing influence from anthropogenic emissions.

The sample designated ADS1 (see Shi *et al*., 2005) collected during the 20 March 2002 severe dust storm episode was almost completely composed of minerals (Fig. 7d). A distinct characteristic of this sample was that many bar shaped particles were observed which were not commonly seen in the 16 March 2002 dust storm sample (Fig. 7a). ADS2 (see Shi *et al*., 2005) was also dominated by minerals (Fig. 7e). Sample ADS4 collected on 20-21 March 2002 was still dominated by mineral particles (Fig. 7f) due to the strong wind during our sampling period (see Shi *et al*., 2005), which inhibited anthropogenic particle accumulation

Ⅳ. Size distributions characterization

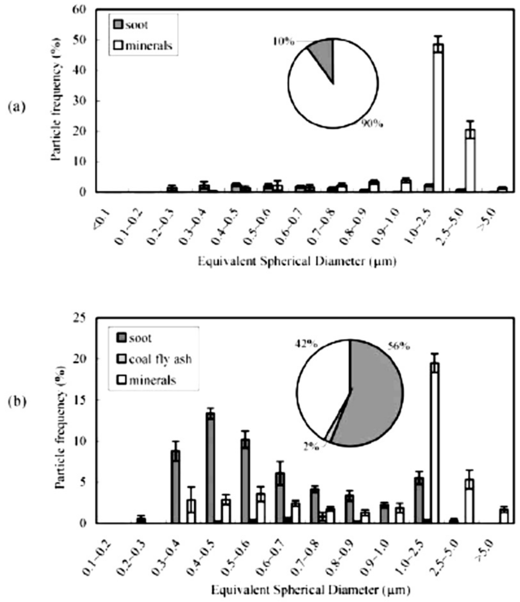

Fig. 8. Number-size distribution (bar graph) and percentage (pie chart) of PM10 from Middle Earth collected during and after the 16 March 2002 dust storm episode.
(a), PM10 collected during the dust storm episode (sample ADS98); (b), PM10 collected after the dust storm episode (sample ADS100). The legends for the bar graph and pie chart are the same (Shi *et al*., 2005).

Number percentages and number-size distributions of different types of particles in the PM samples (See Shi *et al*., 2005) were obtained based on image analysis results. Mineral particles occupied 90% by number (the pie chart in Fig. 8a) of the total PM10 collected during the 16 March 2002 dust storm episode (Shi *et al*., 2005). Soot aggregates accounted for only 10% by number (the pie chart in Fig. 8a). No coal fly ash was observed. In the PM10 (See Shi *et al*., 2005) collected one day after the 16 March 2002 dust storm episode, the percentages of soot aggregates and coal fly ash increased to 56% and 2% by number (the pie chart in Fig 8b), respectively, while the percentage of the mineral particles decreased to 42% by number (the pie chart in Fig. 8b). Thus contributions from anthropogenic emissions after the peak dust storm episode increased significantly (Shi *et al*., 2005).

The number-size distributions of PM10s (ADS98 and ADS100; See Shi *et al*., 2005) collected during and after the 16 March 2002 dust storm episode are shown in the bar graphs in Figures 8a and 8b. The particle morphologies of these two samples are shown in Figure 7a. In ADS98, particles larger than 1 mm account for 73% by number (Fig. 8a). This is very different from the number-size distribution patterns of PM10s collected during nondust storm episodes, with the latter being dominated by soot aggregates smaller than 1 mm (Shi *et al*., 2002). In ADS100, however, particles larger than 1 mm only accounted for 33% by number (Fig. 8b). Soot aggregates of ADS100 had an obvious peak in the 0.4-0.5 mm size range (Fig. 8b), indicating an increasing influence from anthropogenic emissions (Shi *et al*., 2005).

Ⅴ. MODIS and MISR Imagery from the Terra and Aqua Satellites

Gillette (1999) pointed out that many of the world's most important dust sources are not always large regions with uniform emissions of dust across them. He coined the phrase "hot spot" to identify relatively small areas that have a particularly favorable set of characteristics for dust emission. This concept was developed further by Okin *et al*. (2006) and with the subbasin geomorphology approach of Bullard *et al*. (2011). The past couple of decades have added greatly to our identification of contemporary "hot spot" dust sources. Here present examples of identification of dust sources using satellite imagery from Saudi Arabia, Afghanistan and Iran (Fig. 9), set within the context of the "hot spot" concept of Gillette (1999) and the preferential-dust-emission geomorphic scheme of Bullard *et al*. (2011).

Alluvial sources in desert regions have been identified in MODIS imagery, such as dust seen on the western Saudi Arabian coast, moving southwestward over the Red Sea and toward Sudan (Fig. 9a). The outermost part of the Saudi Arabian coast is an emergent coral reef terrace, with silt-rich sabkhah deposits, just landward of the terrace. However, it appears that the main dust sources are alluvial deposits that are landward of the coast. Drainage development in the mountains that parallel the Red Sea coast of Saudi Arabia has generated not only wadis that are filled with alluvium but also older alluvial terraces and pediment surfaces (Brown *et al*. 1989), all of which are potential dust sources. Dry lakebeds with abundant finegrained sediments that also are unconsolidated constitute one of the most important dust emission sources in Iran and Afghanistan (Gill 1996) (*eg*., Fig 9b).

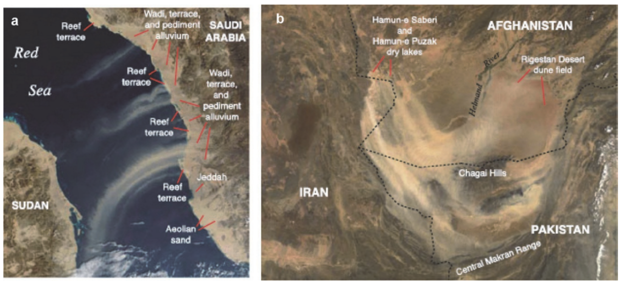

Fig. 9. Satellite photos of dust sorm.
(a), MODIS image fromthe Terra satellite acquired on 15 January 2009 showing dust plumes from Saudi Arabia moving over the Red Sea in the direction of Sudan (Image courtesy of MODIS Rapid Response, NASA Goddard Space Flight Center). Geologic features from Brown *et al*. (1989).;(b) MODIS image from the Terra satellite acquired on 20 August 2003, showing dust from the Hamun dry lakes of Afghanistan and Iran (Image courtesy of Jacques Descloitres, MODIS Land Rapid Response Team, NASA Goddard Space Flight Center (MODIS image courtesy of Jesse Allen, NASA Earth Observatory and the MODIS Rapid Response Team; extent of the Blackwater Draw Formation taken from Texas Bureau of Economic Geology (1992)).

Ⅵ. Sulfur Element in the Individual Dust Storm Particles in Middle Earth

The individual particle analysis has revealed that about one fourth of the 20 March 2002 dust storm particles collected in Beijing contained sulfur element (Shi *et al*., 2005). Falkovich *et al*. (2001) reported that about 65% of the African dust storm particles collected in Israel contained sulfur, but sulfur was from soil-derived processes in the source regions and not from atmospheric processes. The ESEM-EDX analyses showed the presence of irregularly shaped gypsum in the 20 March 2002 dust storm sample. This provides evidence that at least some of the sulfur in the 20 March 2002 dust storm sample was from processes in the source region. Using S/Al ratio as an indicator, Guo *et al*. (2004) suggested that some of sulfur in the 20 March 2002 dust storm sample in Beijing was of crustal origin. Zhang and Iwasaka (1999) also found that 14.6% of the particles showed a sulfur peak in EDX spectra although few of the dust particles collected in Beijing contained water-soluble sulfate. The results of Shi *et al*., (2005) also showed that no morphological modification, as that for dust storm particles collected in Japan (Iwasaka *et al*., 1988; Zhou *et al*., 1996; Fan *et al*., 1996), could be observed in single dust storm particles collected in Beijing (Figures 7a and 7c). On the other hand, Ion Chromatography (IC, Dionex 100, US) analysis of Shi *et al*., (2005) showed that the water-soluble sulfates account for 0.55% of the mass of PM10 collected during the 20 March 2002 dust storm episode. The sources of the water-soluble sulfates are still unknown. Therefore further work on individual particle analysis, as well as bulk chemical analysis of more Middle Earth dust storm samples during different dust storm episodes, needs to be conducted to elucidate whether and how much the atmospheric processes contribute to the sulfur content in dust storm samples collected in the Middle Earth continent.

Ⅶ. Primary zonation of dust source base on geological maps and mean annual rain in the Middle East

Different parameters, mentioned by researchers, that affect occurrence of dust storms, can be summarized as: land surface features including snow cover duration, vegetation cover, and soil texture (Nickling and Brazel, 1984; Sun *et al*., 2003a,b), local climate conditions, such as rainfall and temperature, and wind velocity: when wind velocity exceeds a threshold value (which is a function of land surface), suspension, saltation, or creep may transport sand particles over long distances (Li *et al*., 2002), depending on the strength of the weather system and the size, shape, and density of the sand particles (Zhou *et al*., 2002). Geological maps and information's can help us to assessment the soil texture that are very useful for small scale studies that is usually purpose of dust storm researches.

In recent years we havegained a much clearer picture of the main source regions for dust emissions at a global scale. This has demonstrated the primacy of the Sahara and has highlighted the importance of some other dry lands, including the Middle East, Taklamakan, southwest Middle Earth, central Australia, the Etosha and Mkgadikgadi pans of southern Africa, the Salar de Uyuni of Bolivia and thegreat Basin in the USA. Most of the major source regions at the present day are large basins of internal drainage (Bode le, Taoudenni, Tarim, Seistan, Eyre, Etosha, Mkgadikgadi, Uyuni and thegreat Salt Lake). Lake sediments, dry river beds, deltaic sediments, sandy lands and alluvial fans mentioned as dust source that all mainly composed of fine and medium grain size sediments (Gerivani *et al*., 2011).

Geological map of our study area, prepared by Haghipour (2009), include rocks (older than Quaternary) and Quaternary sediments (Q1 and Q2). Quaternary sediments are separated into 5 unites including: fluvial, alluvial, sand dune, loess and playa. Fluvial is defined as a kind of sediments consisting of materials transported by a stream as suspended or laid down. Alluvial is defined as kinds of soils consisted of clay, silt, sand and gravel or similar unconsolidated detrital materials deposited during comparatively recent geologic times by a stream or other body of running water as a sorted or semisorted sediment in the bed of the stream or on its flood plain or delta, or as a cone of fan at the base of the mountain slope. Sand dune is defined as an accommodation of loose sand heaped up by wind, commonly found along low-lying seashores above high-tide level, more rarely on the border of large lakes or river valleys, as well as in various desert regions, where there is abundant dry surface sand during some part of the year. Loess is a term for a widespread, homogenous, commonly, nonstratified, porous, friable, slightly coherent, usually highly calcareous, finegrained blanket deposit (generally less than 30 meter thick), consisting predominantly of silt with subordinategrain sizes ranging from clay to fine sand. Playa is a term that is used for dry, vegetation-free, flat area at lowest part of an untrained desert basin, underlain by stratified clay, silt or sand, and commonly by soluble salts (Bates and Jackson, 1980).

The soil grain size of thegeological unites is one of the most important parameters to estimate the susceptibility of geological unites to emission dust materials. Suspended dust particles have a bimodal size distribution (Hoock, 1984). Smaller particles are only a few microns in diameter, but most range from 20 to 40 microns. Particles capable of traveling long distances usually have diameters of less than 20 microns (Gillette, 1979) that are including salt, gypsum, clay (less than 2 microns) and silt (2 to 74 microns).

Accordingly, rocks have no susceptibility, fluvial, alluvial and sand dune may have low susceptibility and playa and loess probably have high susceptibility of dust emission. Other groups of sediments, shown in geological map, are old and new dry lakebeds which, in this area, consisted of finegrain size sediments, gypsum and salt. Old dry lakebeds usually are some compacted then have low susceptibility, but new lakebeds are loose and have high susceptibility. To check this grading of susceptibility, dust sources determined by Walter and Wilkerson (1991) and Jalali and Davoudi (2008), for 2005 and 2008 dust storms of Iran, plotted on thegeological map (Fig. 10).

All the areas were determined by Walter and Wilkerson (1991) as dust source areas are located on Quaternary sediments, 6 areas on alluvial and 7 areas on playa and loess; expect point 14 (shown in Fig. 11) that is located on old dry lakebeds and streambeds. This is in accordance with susceptibility grading of geological unites, but it must be noted that sometimes older than Quaternary sediments, as area 14, may have susceptibility of dust emission because it is erodible. Assessing of erodibility of old sediments and

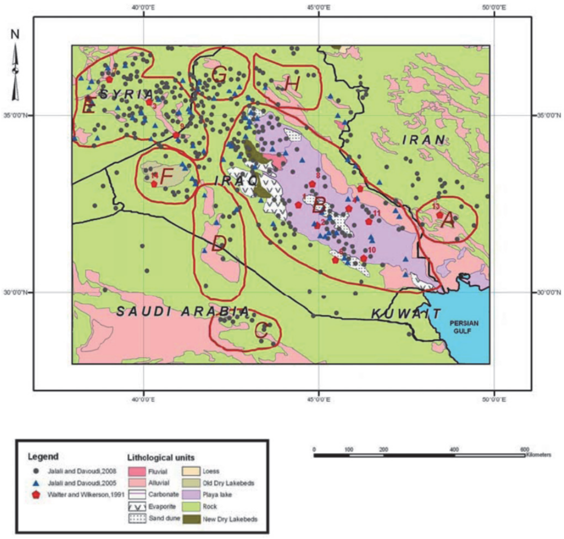

Fig. 10. Zonation map of dust emission base on geological map and points of dust sources determined by Walter and Wilkerson (1991) and Jalai and Davoudi (2008).

rocks is possible in bigger scale and more detailed geological maps. The maximum occurrence of visibility reduction, as a sign of dust producing ability, for Middle East, studied by Kutiel and Furman (2003) are higher in around group B that shows the sediments of this area, which are Playa and Loess sediments, are more susceptible. Dust sources with high effect on dust storms, studied by Jalali and Davoudi (2008), for 2005 and 2008 dust storms, are also located around group B.

Most of the pointes, determined as dust sources by Jalali and Davoudi (2008), for 2005 and 2008 dust storms, including groups A to H in figure 11, can be related to Quaternary sediments. Groups of Dust source points A, C, D, EG and H are related to alluvial sediments, group B is related to New dry lakebeds and Playa sediments and group F is related to Old dry lakebeds. Other points sound not related to geological units because they are located on rocks. For example dust source points in the west of Iran are located on Rock units that are formed western side mountains of Zagros mountain belt. This may has reasons as following (Gerivani *et al*., 2011):

These dust source points have been detected by visual interpretation of MODIS satellite images. To form a visible clued of dust in atmosphere as it can be detected in MODIS satellite images, dust materials are forced to release from lands along the wind direction and gather in far distance along this direction. Then this distance depends on meteorological properties of winds. For example wind with high velocity can suspend more dust materials and bigger size of them and can transport them to more far distance. Dust storms may be traced as far as 4000 km from their origin (Kutiel and Furman, 2003). In this area, depended on winds' metrological properties, dust particles may started to release from groups A to H and gathered in far distance on the Rock units in the east of Iran, north-west of Iraq, between groups B and F, and etc. Scale of the basic geologic map of this study is 1:5,000,000 and in this scale, rather small units of sediments which can be source of dusts are not shown. Scattered points of dust sources might be released by these small sedimentary units. Accordingly, base on thegeological units' susceptibility for producing dust particles, Gerivani *et al*., (2011) prepared zonation map of dust producing susceptibility.

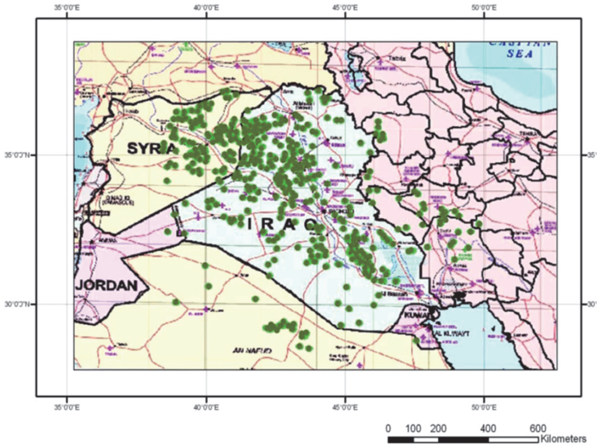

Fig. 11. Spatial distribution of sources and origins of dust storms of 2008 (Jalali and Davoudi, 2008)

Another parameter affected dust producing susceptibility is mean annual rain fall. Total Ozone Mapping Spectrometer (TOMS) data have indicated that many of the world's major dust source regions are areas of hyper-aridity, with mean annual rainfalls of less than 100 mm (Goudie and Middleton, 2001). Some other researchers reported that dust sources, regardless of size or strength, can usually be happened in arid regions with annual rainfall under 200-250 mm. Mean annual rain fall of the Middle East (Fig. 12) shows that north-east of Syria, north of Iraq and west of Iran have more than 250 mm (10 inches) mean annual rain fall, so Gerivani *et al*., (2011) omitted dust sources located in these areas and presented zonation map of dust producing susceptibility.

Ⅷ. Dust Storms Impacts on Air Pollution and Public Health under Hot and Dry Climate

Dust storms are a kind of severe natural disaster that frequently occurs in the arid and semiarid regions. Are the airborne coarse crust-originated particles harmful to human health? Kwon *et al*. (2002) explored the effect of Middle Earth dust events on daily mortality in Seoul, South Korea, during the period of 1995-1998, and showed that the

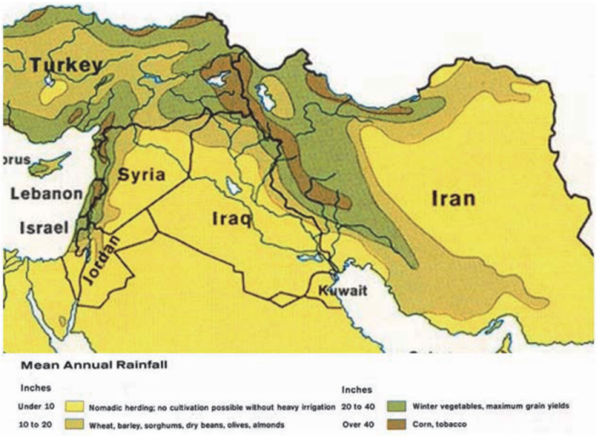

Fig. 12. Mean annual rain fall (inches) in the Middle East (Central Intelligence Agency of U.S., 1973).

association between the dust events and deaths from cardiovascular and respiratory causes was strong enough to indicate that people with advanced cardiovascular and respiratory disease might be susceptible to Middle Earth dust events. Lei *et al*. (2004) used pulmonary hypertensive rat models to examine inflammation markers in the lung and in the peripheral blood after an exposure to Middle Earth dust storm particles. Their results revealed that an exposure to particulate matters during a dust event could increase lung inflammation and injury in pulmonary hypertensive rats. Clearly, besides the dramatic effects of dust particles on visibility (Chung *et al*., 2003), their potential influence on the health risk of the younger generation and allergies of elderly people cannot be ignored.

Miri *et al*., (2007) show that about half of residents have been subject to respiratory diseases due to dust storms during the period of interest. The research indicates that the number of people affected in rural areas is more than in urban areas. Some patients had to call on a doctor during stormy days and approximately 55 percent of them visited a physician more than 20 times per year. About 40 percent called on a doctor a couple of days after a dust storm and 32 percent mentioned that they cannot call on a doctor due to financial and economic issues. Also, the results derived from hospital studies show that in stormy days most of the patients were respiratory patients, including those who were affected by Chronic Obstructive Pulmonary Disease (COPD) and asthma. The percentage of these diseases in summer (July and August) is more than other months due to more severe dust storms. The amount of financial losses due to these respiratory diseases has been estimated at over 73.5 million dollars during 1999-2004. Finally, Miri *et al*., (2007) conclude that dust storms have an important role in spreading respiratory disease in the Sistan region.

Ⅸ. Medical geology in the Middle East

Health effects of wind-blown sand and dust as well as minerogenic aerosols on human pulmonary and cardiovascular functions vary with a number of factors. These include particle size, composition, levels and duration of exposure, and the health status of the exposed population. Particles of a diameter of less than 10 μm may reach the upper part of the airways and lung while fine particles can penetrate more deeply and may reach the alveolar region. Health effects are also a function of timescale, which range from long-term exposure (months to years) influencing the incidence of chronic disease and susceptibility and short-term exposure (days) causing acute health events. On both scales, health effects may range in severity from subclinical to deadly.

The amount of dust and the kinds of particles involved influence how serious the lung injury will be Dust is organic and inorganic (Sullivan and Krieger, 2001). Organic dusts consist of particles of biological, animal, and microbial origin and contain bacteria and fungi. Allergic alveolitis is caused by organic dust (Sullivan and Krieger, 2001). Dusts can also occur from organic chemicals (*eg*., dyes, pesticides). Inorganic dusts can occur from grinding metals or minerals such as rock or soil. Examples of inorganic dusts are silica, asbestos, and coal. The influence of inorganic particles when inhaled varies with the size and nature of the particles (Collis and Greenwood, 1977). The changes which occur in the lungs vary with the different types of dust. For example, the injury caused by exposure to silica is marked by islands of scar tissue surrounded by normal lung tissue. Some particles dissolve in the bloodstream. The blood then carries the substance around the body where it may affect the brain, kidneys, and other organs. The table 1 summarizes some of the most common lung diseases caused by dust.

X. Comparison of mineral compositions of dusts from different regions

For comparison, 10 Middle Earth samples were also analyzed with XRD. Dolomite was present in all of the samples, as seen in Figure 3c. Davis and Guo (2000) and Shi *et al*. (2002) also reported the presence of dolomite in Beijing Middle Earth samples. However, dolomite was not identified by the XRD in the two Middle Earth samples. Dolomite was also an important mineral species in dust storm samples originated from other regions; for example, Western Sahara, Moroccan Atlas and Central Algeria (Avila *et al*., 1997), African, southern Algeria and northern Chad (Falkovich *et al*., 2001). Thus the absence of dolomite was an important

Table 1 Some types of pneumoconiosis according to dust and lung reaction

Inorganic dust	Type of disease	Lung reaction
Asbestos	Asbestosis	Fibrosis
Silica (quartz)	Silicosis	Fibrosis
Coal	Coal pneumoconiosis	Fibrosis
Beryllium	Beryllium disease	Fibrosis
Tungsten carbide	Hard metal disease	Fibrosis
Iron	Siderosis	No fibrosis
Tin	Stenosis	No fibrosis
Barium	Baritosis	No fibrosis
Organic dust		
Moldy hay, straw, and grain	Farmer's lung	Fibrosis
Droppings and feathers	Bird Fancier's lung	Fibrosis
Moldy sugarcane	Bagassosis	Fibrosis
Compose dust	Mushroom worker's lung	No fibrosis
Dust or mist	Humidifier fever	No fibrosis
Dust of heat-treated sludge	Sewage sludge disease	No fibrosis
Mold dust	Cheese washers' lung	No fibrosis
Dust of dander, hair particles, and dried urine of rats	Animal handlers' lung	No fibrosis

Source: Data from CCOHS, 2005

characteristic of the two severe dust storm samples (Shi *et al*., 2005).

It has been previously suggested that the mineralogy of dust storm particles may be more diagnostic of their sources (Ganor *et al*., 2000). Gomes and Gillette (1993) also showed that calcite/clay and quartz/clay ratios could be used as tracers to identify the origins of the dusts. The ranges of calcite/clay and quartz/clay ratios of silt size mineral aerosol sampled in northern Sahara, Soviet Central Asia and southwestern United States were also provided by Gomes and Gillette (1993). Calcite/clay and quartz/clay ratios of the PM10 collected during the 20 March 2002 Middle Earth episode were 0.19 and 0.49, respectively, while those of the PM less than 2 mm separated from the PM10 collected during the 20 March 2002 MIDDLE EARTH episode were 0.19 and 0.24, respectively. Calcite/clay and quartz/clay ratios of the TSP collected during the 6 April 2000 Middle Earth episode were 0.2 and 0.85, respectively, while those the PM less than 10 mm separated from TSP collected during the 6 April 2000 Middle Earth episode were 0.14 and 0.40, respectively. Therefore proportions of different mineral species in PM samples vary significantly with the sizes of the particles. Unfortunately, mineral dusts weregenerally sampled as silt and clay sizes (*eg*., Arnold *et al*., 1998). This made it difficult to compare the calcite/clay and quartz/clay ratios of Middle Earth samples in this study with those of dust samples collected in other regions. However, even with clay minerals being enriched in the finer dust sizes, the quartz/clay ratios in PM less than 10 mm collected during the two severe dust storm episodes in this study were still higher than those of silt size mineral aerosols from northern Sahara, Soviet Central Asia and southwestern United States. The quartz/clay ratios of PM in these regions are equal to or less than 0.36 (Gomes and Gillette, 1993).

XI. Conclusions

Middle Earth particles collected in Beijing are mainly composed of irregularly shaped minerals. More than 50% of Middle Earth particles are larger than 1 μm in equivalent spherical diameter. About 20% of individual particles collected during the 20 March 2002 dust storm are mineral aggregates and at least 25% of the individual particles contain sulfur. Sulfur in some of the Middle Earth particles is originated from processes in the source region. The XRD analyses of phase compositions of samples from two severe dust storm episodes show that clay minerals are major mineral species, accounting for more than 40%, followed by noncrystalline materials and quartz (both around 19%), with small amounts of calcite, plagioclase, K-feldspar, pyrite and other trace minerals (all less than 10%). Clay minerals in the PM samples collected during the two severe dust storm episodes are mainly illite/smectite mixed layers, with small amounts of illite, kaolinite and chlorite. Samples collected during the severe dust storm episodes are characterized by the absence of dolomite, high quartz/clay ratio as well as dominance of illite/smectite mixed layers in clay mineral species.

Zonation map of dust producing susceptibility are prepared base on geological map of the Middle East in scale of 1:5,000,000 and mean annual rainfall map and it was shown that the most of dust storms in Iran, during the recent decays, have generated by young geological unites in south-west of Iran, Iraq, Syria, and north of Arabia. This study was an example and showed that geological maps can be used for preparing zonation map of dust sources. Geological maps for most of the world have been created (for example in Iran, geological map in scale of 1:100,000 were prepared and engineering geology with larger scale are preparing) and can be used. Other effective factors in producing dust particles like precipitation, temperature *etc* can be added to geological zonation with GIS.

Health effects of dust storms in Middle East particularly in the southwestern Khuzestan Province in Iran and Al-Basra in Iraq include asthma and allergies especially for people with chronic respiratory and cardiovascular diseases.

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Reference

Al-Ali, J.T. (2000), Study of Textural, Mineralogical Composition and Amount of Aeolian Deposits in Al Basra. Unpublished M.Sc Thesis, Al Basra University, 95 p. (in Arabic).

Andreae, M.O. (1995), Climate effects of changing atmospheric aerosol levels, in Future Climates of the World. *In* A Modeling Perspective, edited by A. Henderson-Sellers, pp. 341-392, Elsevier, New York.

Arnold, E., Merrill, J., Leinen, M. and King, J. (1998), The effect of source area and atmospheric transport on mineral aerosol collected over the North Pacific Ocean. Global Planet. Change, 18, pp. 137-159.

Avila, A., Queralt-Mitjans, I. and Alarcon, M. (1997), Mineralogical composition of African dust delivered by red rains over northeastern Spain. Journal of Geophysical Research, 102, pp. 21977-21996.

Bates, R.L. and Jackson, J.A. (1980), Glossary of Geology, Second Edition, American Geological Falls Church, Virginia, p. 16 and 483.

Bergametti, G., Gomes, L., Coudegaussen, G., Rognon, P. and Le Costumer, M. (1989), African dust over Canary Islands: Source regions, identification and transport pattern for some summer situations. Journal of Geophysical Research, 94, pp.14855-14864.

Bishop, J. K.B., Davis, R.E. and Sherman, J.T. (2002), Robotic observations of dust storm enhancement of carbon biomass in the North Pacific. Science, 298, pp.817-821.

Brown, G.F., Schmidt, D.L., Huffman, A.C.Jr. (1989), Geology of the Arabian Peninsula: shield area of western Saudi Arabia. US Geological Survey Professional Paper, 560-A.

Bullard, J.E., Harrison, S.P., Baddock, M.C., Drake, N., Gill, T.E., McTainsh, G., and Sun, Y. (2011), Preferential dust sources: a geomorphological classification designed for use in global dust-cycle models. Journal of Geophysical Research, 116, F04034. <doi:10.1029/2011JF002061>

Buseck, P. R. and Posfai, M. (1999), Airborne minerals and related aerosol particles: Effects on climate and the environment. Proceedings of National Academy of Science, U.S.A., 96, pp.3372-3379.

Carmichael, G. R., Zhang, Y., Chen, L.L., Hong, M.S. and Ueda, H. (1996), Seasonal variation of aerosol composition at Cheju Island, Korea. Atmosphere Environment, 30, pp.2407-2416.

Chun, Y., Kim, J., Choi, J.C., Boo, K.O., Oh, S.N. and Lee, M. (2001), Characteristic number size distribution of aerosol during Asia dust period in Korea. Atmosphere Environment, 35, pp.2715-2721.

Chung, Y.S., Kima, H.S., Dulama, J., Harris, J. (2003), On heavy dustfall observed with explosive sandstorms in Chongwon-Chongju, Korea in 2002. Atmosphere Environment, 37, pp.3425-3433.

Clarke, A. D., Collins, W.G., Rasch, P.J., Kapustin, V.N., Moore, K., Howell, S. and Fuelberg, H.E. (2001), Dust and pollution transport on global scales: Aerosol measurements and model predictions. Journal of Geophysical Research, 106, pp.32555-32569.

Collis, E.L. and Greenwood, M. (1977), The Health of the Industrial Worker. Ayer Publishing, 450 p.

Davis, B.L., and Guo, J. (2000), Airborne particulate study in five cities of China. Atmosphere Environment, 34, pp.2703-2711.

Dentener, F.J., Carmichael, G.R., Zhang, Y., Lelieveld, J. and Crutzen, P.J. (1996), Role of mineral aerosol as a reactive surface in theglobal troposphere. Journal of Geophysical Research, 101, pp.22869-22889.

Falkovich, A.H., Ganor, E., Levin, Z., Formenti, P. and Rudich, Y. (2001), Chemical and mineralogical analysis of individual mineral dust particles. Journal of Geophysical Research, 106, pp.18029-18036.

Fan, X.B., Okada, K., Niimura, N., Kai, K., Arao, K., Shi, G., Qin, Y. and Mitsuta, Y. (1996), Mineral particles collected in China and Japan during the same Asian Dust-storm event. Atmosphere Environment, 30, pp.347-351.

Ganor, E., Deutsch, Y. and Foner, H.A. (2000), Mineralogical composition and sources of airborne setting particles on Lake Kinneret (the Sea of Galilee), Israel. Water, Air, Soil, Pollution, 118, pp.245-262.

Gao, Y. and Anderson, J.R. (2001), Characteristics of Chinese aerosols determined by individual-particle analysis. Journal of Geophysical Research, 106, pp.18037-18045.

Gerivani, H., Lashkaripour, G.R., Ghafoori, M. and Jalali, N. (2011), The source of dust storm in Iran: a case study based on geological information and rainfall data. Carpathian Journal of Earth and Environmental Sciences, 6, pp.297-308.

Gill, T.E. (1996), Eolian sediments generated by anthropogenic disturbance of playas: human impacts on the geomorphic system and geomorphic impacts on the human system. Geomorphology, 17, pp.207-228

Gillette, D.A. (1979), Environmental Factors Affecting Dust Emission by Wind Erosion, Saharan Dust, Mobilization, Transport, Deposition. Scientific Communication of Problems of Environment, 14, pp.72-91.

Gillette, D.A. (1999), A qualitative geophysical explanation for "hot spot" dust emitting source regions. Contribution to Atmospheric Physics, 72, pp.67-77.

Gomes, L. and Gillette, D.A. (1993), A comparison of characteristics of aerosol from dust storms in central Asia with soil-derived dust from other regions. Atmosphere Environment, Part A, 27, pp.2539-2544.

Goudie, A.S. and Middleton, N.J. (2001), Saharan dust storms: nature and consequences. Earth Science Review, 56, pp.179-204.

Guo, J. H., K. A. Rahn, and G. Zhuang (2004), A mechanism for the increase of pollution elements in dust storms in Beijing, Atmos. Environ., 38, 855-862.

Haghipour, A. (2009), International geological map of the Middle East. Geological survey of Iran and Commission for thegeological Map of the World (CGMW), Subcommission for the Middle East. Published by CGMW.

Hoock, D. (1984), A Survey of Available Data Characterizing the Battlefield Dust Environment," Battlefield Dust Environment, Symposium I, US Corps of Engineers, Washington, DC, Dec 1984.

Iwasaka, Y., Yamato, M., Imasu, M. and Ono, A. (1988), Transport of Asia dust (KOSA) particles; importance of weak KOSA events on the geochemical cycle of soil particles. Tellus, Ser. B, 40, pp.494-503.

Jalali N. and Davoudi, M.H. (2008), Inspecting the origins and causes of the dust storms in the Southwest and West parts of Iran and the regions affected. Internal reports of Soil Conservation and Watershed Management Research Institute (SCWMRI), Iran.

Kanayama, S., Yabuki, S., Yanagisawa, F. and Motoyama, R. (2002), The chemical and strontium isotope composition of atmospheric aerosols over Japan: The contribution of long-range-transported Asian dust (Kosa). Atmosphere Environment, 36, pp.5159-5175.

Kutiel, H. and Furman, H. (2003), Dust Storms in the Middle East: Sources of Origin and their Temporal Characteristics. Indoor Built Environment, 12, pp.419-426

Kwon, H.J., Cho, S.H., Chun, Y., Lagarde, F. and Pershagen, G. (2002), Effects of the Asian dust events on daily mortality in Seoul, Korea. Environmental Research, Sec A, 90, pp.1-5.

Lei, Y.C., Chan, C.C., Wang. P.Y., Lee, C.T. and Cheng, T.J. (2004), Effects of Asian dust event particles on in ammation markers in peripheral blood and bronchoalveolar lavage in pulmonary hypertensive rats. Environmental Research, 95, pp.71-6.

Leinen, M., Prospero, J.M., Arnold, E., and Blank, M. (1994), Mineralogy of aeolian dust reaching the North Pacific Ocean: 1. Sampling and analysis. Journal of Geophysical Ressearch, 99, pp.21017-21023.

Levin, Z., Ganor, E. and V. Gladstein, V. (1996), The effects of desert particles coated with sulfate on rain formation in the eastern Mediterranean. Journal of Applied Meteorology, 35, pp.1511-1523.

Li, X.Y., Wang, J.H. and Liu, L.Y. (2002), Wind tunnel simulation experiment on the erodibility of the fixed aeolian sandy soil by wind. Proceedings of ICAR5/GCTE-SEN Joint Conference, International Center for Arid and Semiarid Lands Studies. Texas Tech University, Lubbock, Texas. USA Publication, p. 40.

Merrill, J., Arnold, E., Leinen, M. and Weaver, C. (1994), Mineralogy of aeolian dust reaching the North Pacific Ocean: 2. Relationship of mineral assemblages to atmospheric transport patterns. Journal of Geophysical Research, 99, pp.21025-21032.

Miri, A., Ahmadi, H., Ghanbari, A. and Moghaddamnia, A. (2007), Dust torms impact on air pollution and public health under hot and dry climate. International Journal of Energy Environment, 2(1), pp.101-105.

Mori, I., Nishikawa, M., Tanimura, T. and Quan, H. (2003), Change in size distribution and chemical composition of kosa (Asian dust) aerosol during long-range transport. Atmospherre Environment, 37, pp.4253-4263.

Moore, K. G., Clarke, A.D., Kapustin, V.N. and Howell, S.G. (2003), Long-range transport of continental plumes over the Pacific Basin: Aerosol physiochemistry and optical properties during PEM-Tropics A and B. Journal of Geophysical Research, 108(D2), <doi:10.1029/2001JD001451>

Nickling, W.G. and Brazel, A.J. (1984), Temporal and spatial characteristics of Arizona dust storms (1965-1980). Journal of Climatology, 4, pp.645-660.

Okin, G.S., Gillette, D.A. and Herrick, J.E. (2006), Multi-scale controls on and consequences of Aeolian processes in landscape change in arid and semi-arid environments. Journal of Arid Environments, 65, pp.253-275.

Prospero, J. M. (1999), Long-range transport of mineral dust in theglobal atmosphere: Impact of African dust on the environment of the southeastern United States. Proceedings of National Academy of Science. U.S.A., 96, pp.3396-3403.

Shi, Z., Shao, L., Jones, T.P. and Lu, S. (2005), Microscopy and mineralogy of airborne particles collected during severe dust storm episodes in Beijing, China. Journal of Geophysical Research, <doi:10.1029/2004JD005073>

Shi, Z., Shao, L., Li, H., Whittaker, A.G., Jones, T.P., Be´rube´, K.A. and Richards, R.J. (2002), Physicochemical characterization of PM10 in ambient air of northwestern urban area in Beijing (in Chinese with English abstract). Environmental Science, 23(1), pp.30-36.

Singer, A., Ganor, E., Dultz, S. and Fischer, W. (2003), Dust deposition over the dead sea. Journal of Arid Environments, 53(1), pp.41-59 (Abstract).

Sokolik, I. N., Winker, D.M., Bergametti, G., Gillette, D.A., Carmichael, G., Y. J. Kaufman, Y.J., Gomes, L., Schuetz, L. and Penner, L.E. (2001), Introduction to special section: Outstanding problems in quantifying the radiative impacts of mineral dust. Journal of Geophysical Research, 106, pp.18015-18027.

Sullivan, J.B. and Krieger, G.R. (2001), Clinical Environmental Health and Toxic Exposures. Lippincott Williams and Wilkins, 1323p.

Sun, J.H., Zhao, L.N. and Zhao, S.X. (2003a), An integrated modeling system of dust storm suitable to north China and applications. Climate and Environment Research, 8, pp.125-142.

Sun, L., Zhou, X.K., Lu, J.T., Kim, Y.P. and Chung, Y.S. (2003b), Climatology trend analysis and prediction of sandstorms and their associated dustfall in China. Water Air Soil Pollutions, Focus 3, pp.41-50.

Walter, M. and Wilkerson, D. (1991), Dust and Sand Forecasting in Iraq and Adjoining Countries. Technical Report, Air Weather Service, Scott AFB (AWS/XTX), IL 62225-5008.

Winchester, J.W. and Wang, M.X. (1989), Acid-base balance in aerosol components of the Asia-Pacific region. Tellus, Ser. B, 41, pp.323-327.

Zhang, D., Iwasaka, Y., Shi, G., Zang, J., Matsuki, A. and Trochkine, D. (2003), Mixture state and size of Asian dust particles collected at southwestern Japan in spring 2000. Journal of Geophysical Research, 108(D24), <doi:10.1029/2003JD003869>.

Zhuang, G., Guo, J., Yuan, H. and Zhao, C. (2001), The compositions, sources, and size distribution of the dust storm from China in spring of 2000 and its impact on the global environment. Chinese Science Bulletin, 46, pp.895-901.

Zhang, D. and Iwasaka, Y. (1999), Nitrate and sulfate in individual Asian dust-storm particles in Beijing, China in spring of 1995 and 1996. Atmosphere Environment, 33, pp.3213-3223.

Zhou, X.J., Xu, X.D., Yan, P., Weng, Y.H. and Wang, J.L. (2002), Dynamic characteristics of spring sandstorms in 2000. Science of China, Ser. D, 45, pp.921-930.

Zhou, M., Okada, K., Qian, F., Wu, P.M., Su, L., Casareto, B.E. and T. Shimohara, T. (1996), Characteristics of dust-storm particles and their long-range transport from China to Japan — Case studies in April 1993. Atmosphere Research., 40, pp.19-31.