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ORIGINAL ARTICLE

Geophysical-geochemical investigation of fire-prone landfills

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Abstract This paper deals with the integration of electrical resistivity tomography and geochemical methods for studying four different fire-prone landfills. Landfill gas composition (CH_4, H_2S, O_2, CO, CO_2) and subsurface temperature were measured with the constant net 50 × 50 m from the depth 10–60 cm. 28 electrical resistivity tomography lines were surveyed, while Wenner and Sclumberger electrode arrays were employed for all measurements. At the studied sites the landfill gas and temperature measurements mapped gas and temperature anomalies over underground fire sources. 2D electrical resistivity tomography lines, performed over these anomalies, showed these fire sources as high-resistivity zones. The joint employment of the electrical imaging and geochemical survey seems to be a useful tool in carrying out diagnostic investigations at fire-prone landfills.

Keywords Electrical resistivity tomography · Landfill · Fire gas mapping · Gas composition

Introduction

Investigation of landfill disposals usually deals with the composition and history of waste, leachate presence, biogas content, monitoring of water contamination and definition of landfill influence on environment, including, as a rule, leachate, biogas and water sampling from the specific network (landfill surface and drilled wells) and chemical analysis of samples taken from and around the landfill disposal under investigation (Martinho and Almeida 2006; Abu-Zeid et al. 2004).

Although landfill fires threaten the environment through toxic pollutants emitted into the air, water, and soil (USFA 2002), such a phenomenon was granted less attention than, e.g., studies of history of waste, presence of leachate or biogas content. It is known that hundreds of landfill annually fire in Sweden (Hogland and Marques 2003) and in Finland (Ettala et al. 1996). According to international experts, landfill fires are common in Iceland, UK (Oygard et al. 2005) and Jordan (El-Fadel et al. 1977). One-fifth of the landfill disposals had more than one fire, while one quarter of fires were deep fires at a depth of more than 2 m (Ettala et al. 1996). The reported causes of fires are sparks from machinery working on the landfill, flammable matter accidentally or illegally deposited on the landfill, or spontaneous combustion, which could be due to the heat generation from aerobic processes after the intrusion of oxygen into a landfill (Stearns and Peyotan 1984; Oygard et al. 2005).

Landfill fires are classified as follows: surface and underground. The surface fires generally burn at relatively low temperatures and are characterized by the emission of dense white smoke and the products of incomplete combustion (USFA 2002). The underground fires in landfills occur deeper below the landfill surface and involve materials that are months or years old. There can be great difficulty in their detection because these fires often smolder for weeks under the surface (USFA 2002; Oygard et al. 2005). In addition, an underground fire may cause cavities in the landfill that can later cave in and cause hazardous situations (USFA 2002; Oygard et al. 2005). The underground fires are often visually detected by smoke emanating from the landfill site or by the presence of carbon monoxide, carbon dioxide or methane in landfill gas

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(USFA 2002; Oygard et al. 2005; Hogland and Marques 2003). Such a method provides a discontinuous subsurface picture and can be a very labor intensive and expensive.

Application of electrical resistivity tomography (ERT) is very popular for landfill sites characterization since electrical resistivity of waste in landfill disposal varies considerably with time during waste decomposition and leachate generation, and since it allows continuous site study (e.g., Bernstone et al. 2000; Aristodemou and Thomas-Betts 2000; Depountis et al. 2005; Zume et al. 2006; Mondelli et al. 2007; Soupios et al. 2006, 2007; Frid et al. 2008, Georgaki et al. 2008). For example Soupios et al. 2006, 2007 employed ERT as a part of integrated geophysical method for landfill characterization, while Georgaki et al. 2008 used ERT together with methane and carbon dioxide emission measurements in order to improve the estimation of landfill gas emission.

Moreover, ERT is highly employed techniques for caves exploration (e.g., Zhou et al. 2002).

As it was noted above, formation of fire-induced caves is a frequent phenomenon. Investigations of the ERT ability to characterize fire-induced subsurface caves are surprisingly lacking in scientific literature.

Our investigations consisted of two stage approach are as follows:

- A geochemical survey comprising gas and temperature mapping and gas analysis.
- A geophysical study (ERT) and statistical analysis.

The geochemical survey was employed to evaluate potentially smoldering (firing zones), while the geophysical survey was carried out aiming to investigate the depth, the structure and the dimensions of fire epicenters.

Methodology

The fire sources noted above were discovered from biogas, near surface temperature and visual observations. Landfill gas measurement was performed with the Gas Field Analyzer GA 2000. Five components of landfill gas (CH_4, H_2S, O_2, CO, CO_2) were measured with the constant net 50×50 m in landfills themselves and in their close vicinity. The depth of the gas sampling was changed from 10 to 20 cm down to 50–60 cm from the existing ground level so as to measure into the uppermost part of the waste, covered by clayey or loamy layers. In addition to landfill gas content near surface, temperature was measured with a digital thermometer at the same points of the landfill gas net.

As it was previously shown, dipole–dipole (Dahlin and Zhou 2004) and mixed arrays (Zhou et al. 2002) are the best candidates for underground openings investigation. However, dipole–dipole array is known to be more at risk of noise contamination (Dahlin and Zhou 2004) that makes its application in a landfill to be very problematic: our own experience completely confirmed this conclusion when dipole-dipole array was used on a landfill site, less than 30% of the whole data set remains for inversion after noise filtering. It was also shown that Sclumberger and Wenner arrays have less noise contamination and better signal-to-noise ratios than dipole–dipole array (Dahlin and Zhou 2004) that makes them to be a better candidate for landfill characterization. Moreover, Ezersky (2008) showed that Wenner array does allow subsurface caves describing with suitable accuracy. These were the reasons to use Wenner and Schlumberger arrays in our investigations.

A total of 28 ERT lines were surveyed: 7 ERT lines of different lengths were carried out on each landfill sites above and outside fire sources. Length of the lines depended on the landfill depth and the supposed size of underground fire openings. The electrode spacing was changed between 2 and 10 m while maximum lines length was 290 m. Two conventional (Wenner and Sclumberger) electrode arrays were employed for all measurements separately. The measurements were carried out with the multi-electrodes tool (Sting R1) with 30 electrodes (manufactured by the Advanced Geoscience, Inc., USA). Maximum investigation depth was 55 m for Schlumberger array, while depth of investigation with Wenner array was slightly less, about 50 m. The collected ERT data were inverted using commercial package Earthimager 2D/3D. The inversion routine consists of the smoothness-constrained least squares procedure employing finite element method for the forward resistivity calculations. It includes dividing of subsurface into number of layers consisting of rectangles, and minimizing the difference between the calculated and the observed apparent resistivity. The fitting accuracy is defined by means of root mean square (RMS) error, which for all the carried ERT lines was less than 15%. The percentage range of data filtered was 10–15% and 15–25% for Wenner and Schlumberger array, respectively. Taking into account highly heterogeneous build up of the sites under investigation such values of RMS and the percentage range of data filtered are satisfactory.

Landfill description

The location of four landfill sites under study is shown in Fig. 1.

The Lon landfill is situated on the outlying area of Beersheba city (at approx. 100 km to the south from Tel Aviv). The site was being used mainly for burying the construction waste during 1990–2004 and by now it is closed. The municipal solid waste of unknown volume has been buried on the site in a pirate manner. The landfill is a

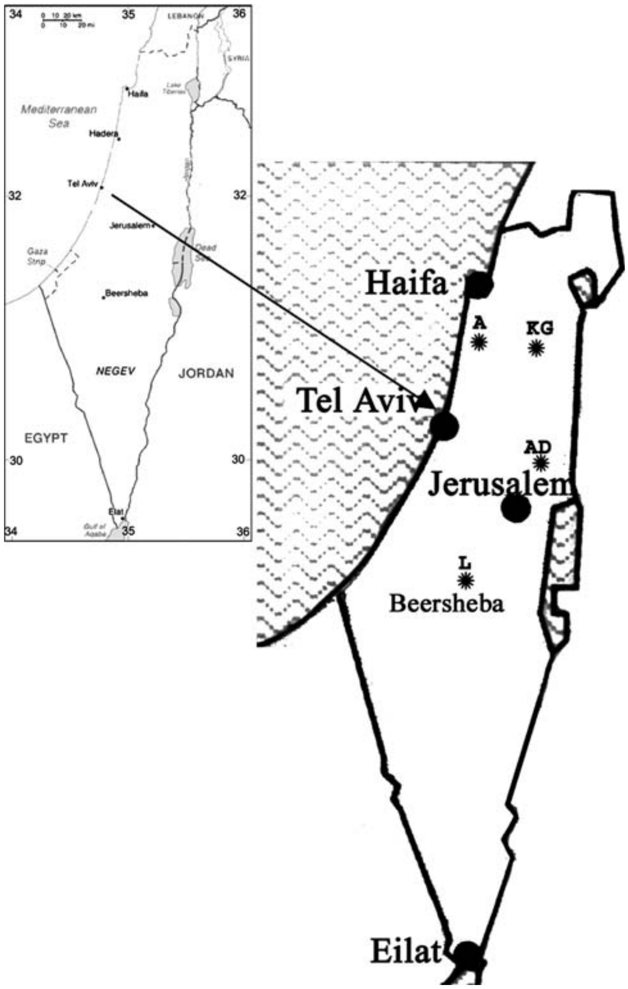


Fig. 1 Location scheme of the studied sites. *A* Alonim landfill, *KG* Kfar Gidon landfill, *AD* Abu Dis landfill, *L* Lon landfill

trapezium-shaped hill disposed on a natural surface of recent and sub-recent loess soils. The maximal height of the landfill is about 20 m above the existing ground level.

The Alonim (or Hadera) landfill is situated in the coastline part central Israel about 45 km from the Tel Aviv downtown. It is located in a series of old quarries closely pinched and extended in a meridian direction which were excavated for extracting building sandstone (Table 1). The landfill was used for municipal solid and construction waste burying from 1965 till the end of 1996. In the central landfill part, the waste thickness is up to 12 m and it gradually decreases towards the landfill peripheral parts. The site is characterized by a shallow ground water level and in some cases the quarry floor and as consequence the waste body bottom is located near the ground water surface (Levitte and Yechiely 2003).

The Kfar Gidon (or Gidon) landfill is situated in north-eastern Israel about 100 km away from the Tel Aviv downtown. Like the Alonim, the Gidon landfill had been built up on an abandoned quarry that was used for basalt building stone extraction. The landfill is located on the quarry slope (Table 1). The mixed industrial and municipal solid waste was being buried there mainly in a pirate manner during a period of 10 years. The maximal waste thickness here is estimated to be about 15 m.

The Abu Dis landfill is located near Jerusalem (about 60 km away from the Tel Aviv downtown). It was opened in the early 1980s and was being operated as a pirate landfill mainly for municipal solid waste burying. Since the first half of 1990s, the activity of this landfill has been organized for both solid municipal and construction waste disposal. The landfill was built on the area of a V-shaped erosion valley naturally formed in chalky rocks (Table 1).

More detailed characteristics of the landfills under study including geological data for the wall of rocks and soils, landfill area, waste volume, etc. are listed in Table 1.

As it is seen, the landfills under investigation are located in the different Israeli landscape zones and likely cited as typical representatives of the Israeli landfills including uncontrolled ones: they were disposed on technogenius (Alonim and Gidon) and natural sites (Lon and Abu Dis) with wall rocks (soils) of different type and composition, they are characterized by different history of waste burning, waste content and age, by different landfill areas and heights.

Results

Gas and temperature characterization

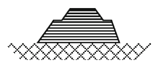
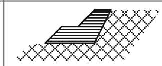
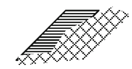
A landfill gas composition is the best indicator of the potential of fire hazard on a landfill site (El-Fadel et al. 1977; Oygard et al. 2005; Hogland and Marques 2003). As it is known, landfill gas is generated by the waste biodegradation and its content is influenced by waste composition and environmental variables. Such a biodegradation mainly results in generation of two gases: methane and carbon dioxide (USFA 2002), an increase of concentration of which is an important part in a "genesis" of a spontaneous waste combustion. As this takes place, two main processes of waste anaerobic biodegradation consequently is carry out as follows: acetogenesis (with carbon dioxide generation) and methanogenesis (with carbon dioxide and methane generation).

When oxygen penetrates into a landfill body it causes a spontaneous waste combustion. According to Lanini et al. (1997), El-Fadel et al. (1977) and Hogland and Marques (2003) oxygen diffusion controls carbon dioxide and temperature increasing in landfills as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Heat} \uparrow \qquad (1)$$

As it was shown by (Hogland and Marques 2003), a microbiological activity is of great importance for

Table 1 The characteristics of different uncontrolled Israeli burning landfills

Landfill name	Lon	Alonim	Kfar Gidon	Abu Dis
Location	Negev, Southern Israel	Costal Plain, Central Israel	Galil, Northern Israel	Judea hills, Eastern Israel
Typical cross – section: - waste; - wall of soils/rocks				
Waste type	Construction basically	Mixed municipal solid and construction	Mixed industrial and municipal solid	Mixed municipal solid and construction
Landfill structure	Hill, above grade	Old quarry, below grade	Old quarry, above grade	Erosion valley, above grade
Landfill type	Trapezium – shaped (in cross-section) embankment	Open pit	Quarry slope	Valley slope
Filling structure	Hill, above grade	Open quarry, below grade	Quarry slope, above grade	Erosion valley, above grade
Wall of soils/rock – **Soil / rock type**	Loess	Calcareous sandstones, occasionally covered by loam and clay layers	Basalts occasionally covered by clay layers	Chalk, chalky limestone
Wall of soils/rock – **Formation**	Recent	Kurkar group of Hefer formation	Cover Basalt	Mishash
Wall of soils/rock – **Age**	Holocene	Pleistocene - Holocene	Pliocene	Senonian
Landfill area (m^2)	100000	~10000	~40000	300000
Landfill volume (m^3)	900000	~80000	~300000	6000000
Maximal waste thickness, m	20	12	18	22
Landfill status	Closed	Closed	Opened	Opened

temperature range between 20 and 60°C. However, when temperature is above 70°C, chemical oxidation becomes to be the dominant heat-generation process.

This mechanism may be stopped when the refuse is covered with either other refuse or a clay layer (Bernstone et al. 2000).

H_2S and CO are also frequently presented in landfill gas. They are generated by the waste biodegradation when an oxygen quantity is not enough for oxidation reaction. Their significance from the point of view of spontaneous waste combustion forecasting is certainly less than one of carbon dioxide and methane. However, an increase of H_2S and CO concentration shows a landfill potential for spontaneous combusting if an oxygen quantity would be enough.

Analysis of landfill gas composition

Table 2 presents the generalized results of landfill gas measurement. Three main verities are shown in the table: main landfill body (the part of the landfill disposal, where no active combustion–smoldering–burning was found), the part of the landfill, where such phenomena were discovered, and the wall rocks (soils).

As it is seen, wall soils/rocks are characterized by low landfill gas concentration and different (from a main landfill body) landfill gas composition. Note slightly increased CO_2 values measured in the Alonim and Abu Dis wall rocks.

Analysis of Table 2 shows that the main landfill bodies are characterized by low landfill gas concentration (CO_2, CO, CH_4) that steeply increases in the smoldering areas.

Figure 2 presents the relationship between carbon dioxide and methane in the main landfill bodies (Fig. 2a) and in the burning areas (Fig. 2b). Figure 2a shows that when CO_2 and CH_4 content is higher than 1%, the ratio of CO_2 to CH_4 contents is very close to 1 (note that CO_2 content in the main body of Kfar Gidon and Lon landfills sites was negligible). The ratio highly decreases (Fig. 2b) in the smoldering/burning. The later process is the most pronounced on the Abu Dis Landfill site (CO_2/CH_4 >8). On the Lon Landfill site, CH_4 content was negligible.

Figure 3 shows CH_4-CO_2-O_2 triangle diagram for all the sites under study. Analysis of the figure shows that the landfill gas composition is indeed different in the main landfill body and in the smoldering zones on all sites under study, and it is individual for each site under study.

Table 2 shows that CO content in the main landfill bodies of Lon and Kfar Gidon landfills is negligible, while in the main landfill bodies of Abu Dis and Alonim landfills CO content is increased. However, the carbon monoxide

Table 2 Subsurface gas and temperature measured in waste and wall soils on four Israeli landfills (CH_4, CO_2, O_2 (%); CO, H_2S (p.p.m.)

Landfill		Lon			Alonim			Kfar Gidon			Abu Dis		
			Landfill			Landfill			Landfill			Landfill	
Component	Element	Wall soils (loess)	Main body	Smoldering/burning area	Wall soils (sand varieties)	Main body	Smoldering area	Wall soils (clay)	Main body	Burning area	Wall Soils (chalk-carbonite clay)	Main body	Smoldering/burning area
Gas	CH_4	<0.1	<0.1	<0.1	<0.1	2.8 ± 2.7	17.7 ± 4.8	<0.1	<0.1	2.1 ± 2.1	<0.1	14.5 ± 13.2	2.7 ± 2.7
	CO_2	<0.1	0.3 ± 0.3	0.8	0.3 ± 0.3	7.2 ± 4.9	18.1 ± 3.3	<0.1	0.3 ± 0.3	12.4 ± 5.3	2.9	15.6 ± 14.2	44.4 ± 30.0
	O_2	19.8 ± 0.4	19.6 ± 0.9	19.2	19.3 ± 0.6	10.9 ± 5.5	0.5 ± 0.4	21.1 ± 0.1	20.2 ± 1.0	6.4 ± 5.6	19.6 ± 2.2	10.2 ± 6.7	2.2 ± 2.2
	H_2S	<1	<1	<1	<1	<1	7 ± 5.6	<1	<1	29.5 ± 22.6	<1	4.6 ± 4.5	35.1 ± 33.8
	CO	<1	<1	146	<1	107 ± 105	>500 (2373 ± 936)	<1	<1	>500	1.5 ± 1.0	29.1 ± 28.0	>500 (2878 ± 321)
Temperature (T°C)	Air	31.4 ± 2.5	32.6 ± 3.2	35	22.3 ± 2.9	23.9 ± 3.0	22.8 ± 2.3	31.9 ± 1.0	33.0 ± 2.6	33.5 ± 3.5	21.6 ± 2.8	21.2 ± 2.5	20.8 ± 2.4
	Surface (at depth of 10–20 cm)	32.8 ± 1.8	36.4 ± 2.5	146	23.6 ± 3.6	26.1 ± 4.8	26.5 ± 5.4	31.9 ± 1.1	36.4 ± 5.1	129.7 ± 90.4	18.9 ± 2.7	21.2 ± 7.7	73.6 ± 7.3
	Subsurface (at depth of 50–60 cm)	32.7 ± 1.8	37.1 ± 2.5	162	29.8 ± 7.9	31.9 ± 6.9	53.7 ± 13.0	32.3 ± 1.1	37.5 ± 5.9	159.2 ± 113.3	ND	ND	ND
Samples (*n*)		33	43	2	6	33	7	22	21	10	10	56	6

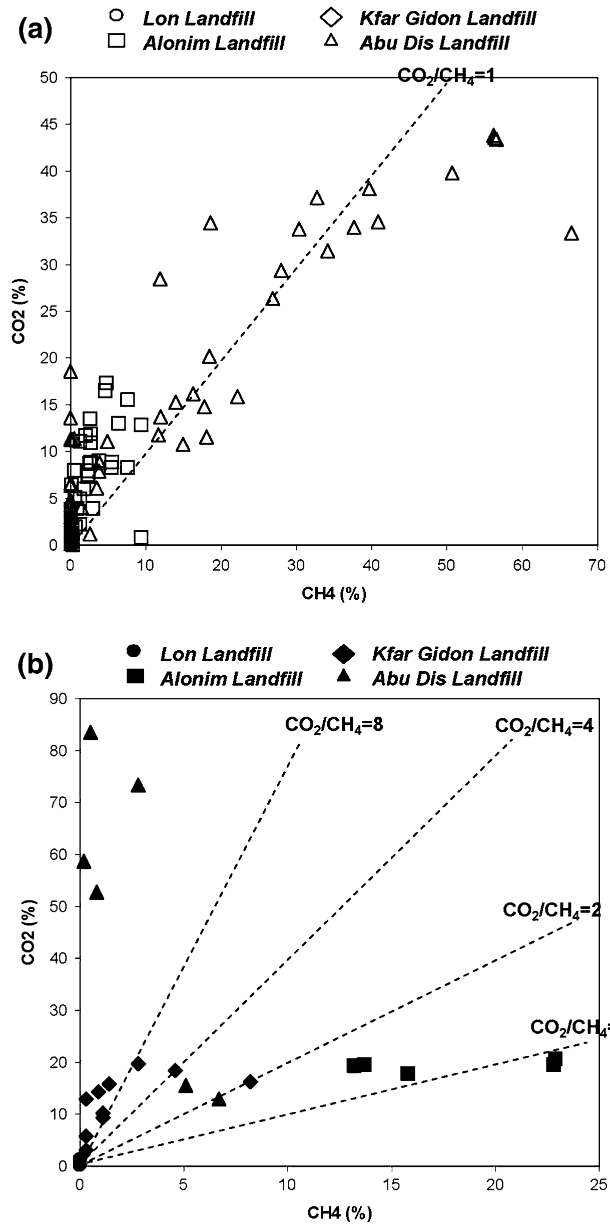


Fig. 2 The relationships between carbon dioxide and methane in the main landfill bodies (**a**) and in the burning areas (**b**)

concentration is very high in the zones of smoldering/burning waste (Table 2). Figure 4 shows the underground landfill fire hazardous zones divided into concentration levels of carbon monoxide in the waste (USFA 2002). As it is seen, carbon monoxide is a very appropriate indicator of waste potential combustion (Fig. 4a) and all the landfills under investigations are potential to the spontaneous combustion (Fig. 4b).

The temperature is an additional important indicator. Table 2 shows that waste temperature is changed between 20 and 37°C in the main landfill bodies and ranged between 53 and 160°C in the zones of smoldering/burning.

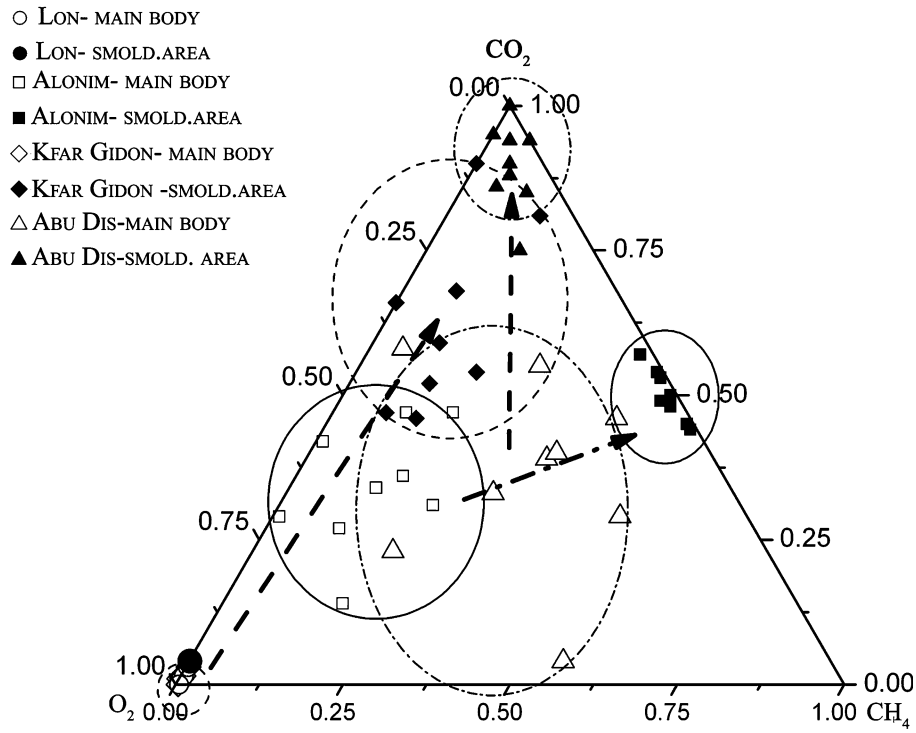


Fig. 3 CH_4–CO_2–O_2 triangle diagram for four landfill sites under study

Landfill gas mapping

Figure 5 shows typical examples of monoelement isoconcentration maps, which we used for the observation of so-called 'hot spots', (the high-emitting and high-temperature areas) where ERT lines have to be carried out. Three main "hot spots" were made evident by a measurement of all five components of landfill gas on Kfar Gidon landfill site (Fig. 5). Similar phenomena were found on Alonim and Abu Dis landfill sites. On the other hand, the appearance of landfill gas on Lon landfill site was different; the "hot spots" were only characterized by the anomalies of CO_2 and CO.

Presentation of landfill gas and temperature data as the monoelement isoconcentration maps has some specific restrictions originating from the method of measurements: it may provide information for a specific sampling point and time period (Georgaki et al. 2008) and only for near surface. However, where a fire epicenter is located or/and what its dimension/depth is, such a method does not able one to answer. That is why ERT, allowing both continuous subsurface investigation and identifying subsurface caves with appropriate accuracy, was employed.

Geophysical investigation

The ERT covered the areas under study to maximize coverage of each landfill site both in and outside the zones of gas and temperature anomalies. As we noted above, seven ERT lines utilizing the conventional Schlumberger and Wenner arrays each were employed on each landfill site. All resistivity sections were inverted to produce relatively low RMS errors to smooth the variation in the resistivity values. Four typical ERT results are presented and discussed below. For Lon site, we report an example of the 2D ERT model inverted from Schlumberger array raw data shown in Fig. 6a, profile 2 (see Fig. 9a below). The line crossed a "caldera" created in the center of gas (CO) and temperature (up to 150°C) anomaly (Fig. 6b, c). The number of electrodes was 30. The minimum electrode spacing was 4 m. The total number of measured data points was 196. The number of iterations was 4, which corresponded with the gradual decrease of the misfit error and hence with the algorithm convergence to the best solution for the true resistivity of subsurface. The model fit after the last iteration is 9.12%, which can be considered good for a study on the landfill sites. The model shows a two-layer resistivity sequence. The calculated resistivity values for the bottom layer are in the range 5–80 Ω m, compared to a resistivity of the upper layer in the range 130–560 Ω m. Our drilling campaign showed that the upper layer is landfill body, while the bottom one is underlying soil. The presence of the underground opening manifests itself in the image as a high-resistivity anomaly in the range 2,300–10,000 Ω m (between 16 and 52 m). The depth of the anomaly zone appears to be about 5.5–10 m.

The second typical example is shown in Fig. 7a. It presents the 2D ERT model inverted from Wenner array raw data measured on Kfar Gidon landfill site. The line was

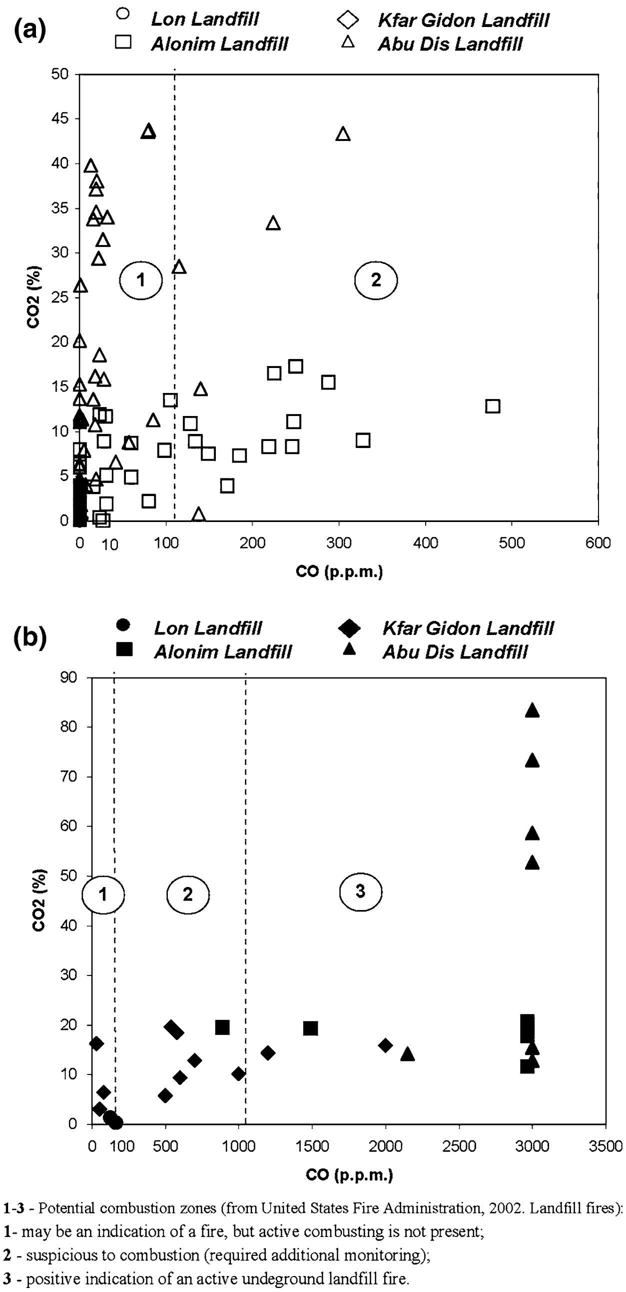


Fig. 4 The relationship between CO (p.p.m.) and CO2 (%) for subsurface waste of the different uncontrolled Israel's Landfills. **a** Main landfill body, **b** Burning/smoldering area. *1–3* Potential combustion zones (from USFA 2002). *1* may be an indication of a fire, but active combusting is not present; *2* suspicious to combustion (required additional monitoring); *3* positive indication of an active underground landfill fire

carried out via the center of gas (CH_4, CO_2, H_2S, and CO) and temperature (up to 350°C) anomaly. The number of electrodes was 30. The minimum electrode spacing was 4 m. The total number of measured data points is 135. The number of iterations is 5. The model fit after the last iteration is 9.43%. The model also shows a two-layer resistivity sequence. Relatively low resistivity layer $\rho = 1.8$–46 Ω m was at the bottom of the landfill dispose while resistivity of landfill body itself was significantly higher in the range 79–680 Ω m. The high-resistivity anomaly (3,400–10,000 Ω m) coincides with the presence of the shallow underground opening, the depth of which appears to be about 3–5 m.

Figures 6, and 7a show two typical examples of ERT under deep and shallow openings created as a results of underground firing while Figs. 7b and 8 show two typical examples of ERT in non-fired zones carried on Kfar Gidon and Alonim landfill sites, respectively. As it is seen, electrical resistivity of the landfill body mainly ranges between 70 and 700 Ω m and 10–70 Ω m for Kfar Gidon and Alonim landfill sites, respectively, with the several spots of lower resistivity.

Since deep openings created due to underground firing are 3D objects, it is preferable to investigate them using 3D techniques. However, 3D surveys have not reached up to date the same degree of reliability as 2D surveys (Loke 2000). Another way is to combine several data set produced by 2D parallel lines inverting them together to produce quasi 3D image. While quality of such "3D images" is poorer than one of complete 3D, it can assist in understanding of main transverse changes of electrical resistivity in the region (Loke 2000). Figure 9 shows such a quasi 3D resistivity contour plot produced from four parallel ERT lines measured on Lon landfill site. Four parallel lines were located near and via the "caldera" (Figs. 6b, c, 9a) with the inter line distance 16 m. The number of electrodes was 120. The minimum electrode spacing was 4 m. The total number of measured data points was 784. The number of iterations was 7. The model fit after the last iteration was 4%. Figure 9b shows four horizontal slices produced from such a quasi 3D model. This method of plotting of the collected data sets emphasizes the shape of the structures with a horizontal development. It is seen that the underground opening consists of several individual openings partly interconnected one to others, located in the frame of two internal lines and restricted by the depth 10 m.

Discussion

Gas and temperature consideration

Analysis of landfill gas concentration shows that its values in wall soils/rocks are mainly low (Table 2) while CO_2 slightly increased in the Alonim and Abu Dis wall rocks. The Abu Dis rocks mainly consist of calcite ($CaCO_3$) and hence the higher CO_2 content here could be explained by the landfill gas emanation from a specific underground atmosphere of carbonate rocks. Increased CO_2 values in porous sandstones of the Alonim landfill site probably

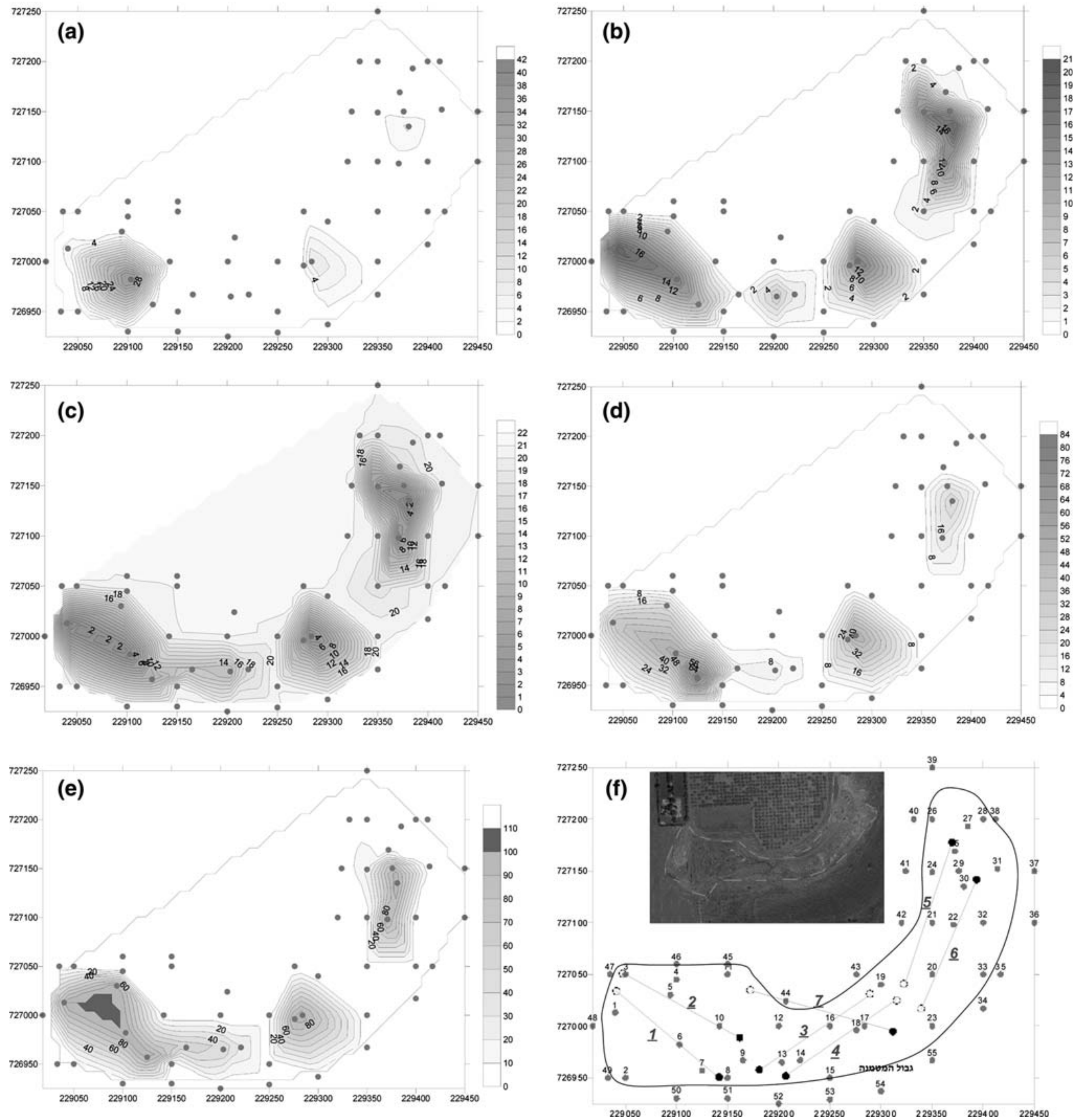


Fig. 5 Landfill gas mapping on the Kfar Gidon landfill site. **a** CH_4 (%), **b** CO_2 (%), **c** O_2 (%), **d** H_2S (ppm), **e** CO (ppm), **f** landfill scheme, *black circles* and *lines* shows the locations of landfill gas sampling points and ERT profiles, respectively. The ERT profile and sampling point numbers are denoted by the corresponding integers

imply their contamination by the products of waste disintegration. Landfill gas concentration (CO_2, CO, CH_4) in the main landfill bodies are also low but higher than in wall soils/rocks (Table 2). Such a tendency could be due to local landfill gas concentration in the main landfill body (in no smoldering areas), which peaks at the smoldering zones of landfills under study.

As was noted above not only the landfill gas concentration, but also the ratio of CO_2 to CH_4 contents could be an indicator of the existence of a smoldering/burning area on a landfill site. An increase of such a ratio perhaps implies an intensive waste anaerobic decomposition. The significant volume of organic matter in the upper part of the landfill body of Abu Dis landfill possibly is the cause of

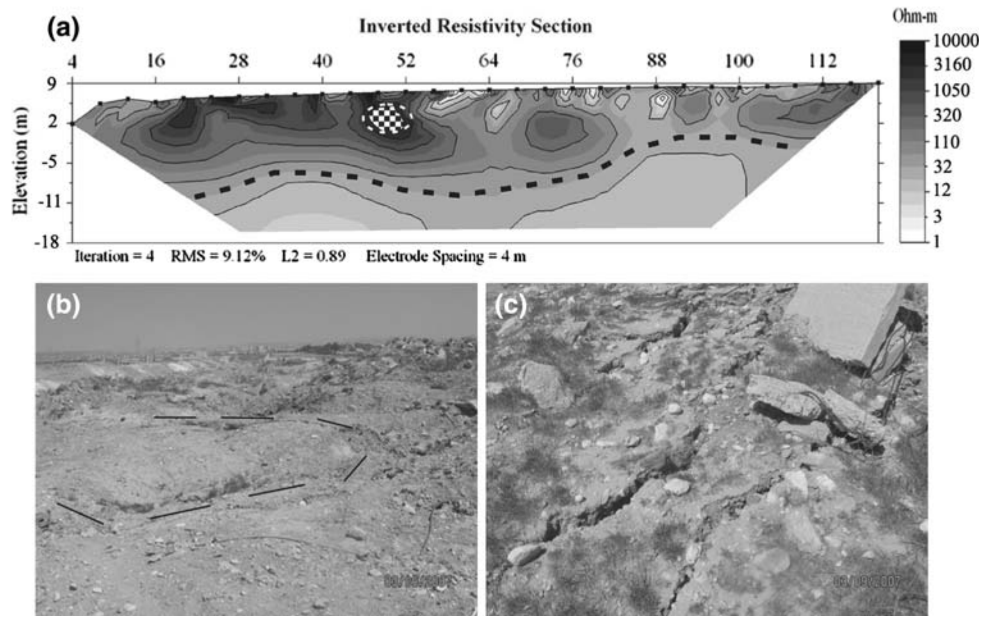


Fig. 6 **a** Typical example of the inverted resistivity section, Lon landfill site. *White dashed line* and *chess squares* show an underground fire zone while *black dashed line* separates the underground soil and the landfill body. **b** Photograph of the caldera, boundaries of which are shown by a *dashed line*. **c** Photograph of fractures on the waste surface around the caldera zone

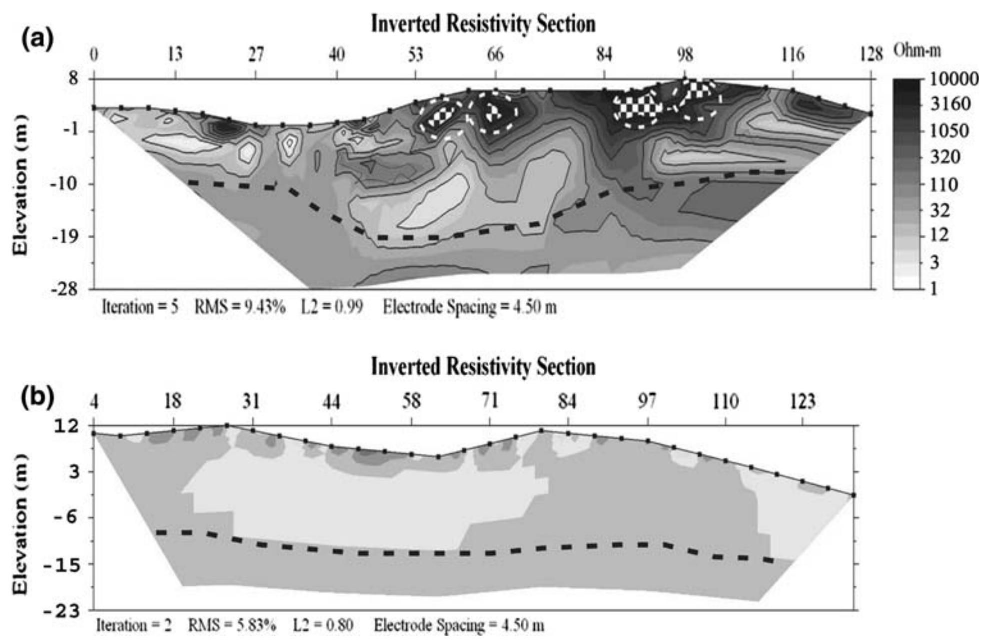


Fig. 7 **a** Typical example of the inverted resistivity section, Kfar Gidon landfill site (line 1 in Fig. 5f). *White dashed line* and *chess squares* show an underground fire zones. **b** Typical example of the inverted resistivity section in the zone where no combustion was found, Kfar Gidon landfill site (line 5 in Fig. 5f). *Black dashed line* shows the boundary between the underground soil and the landfill body

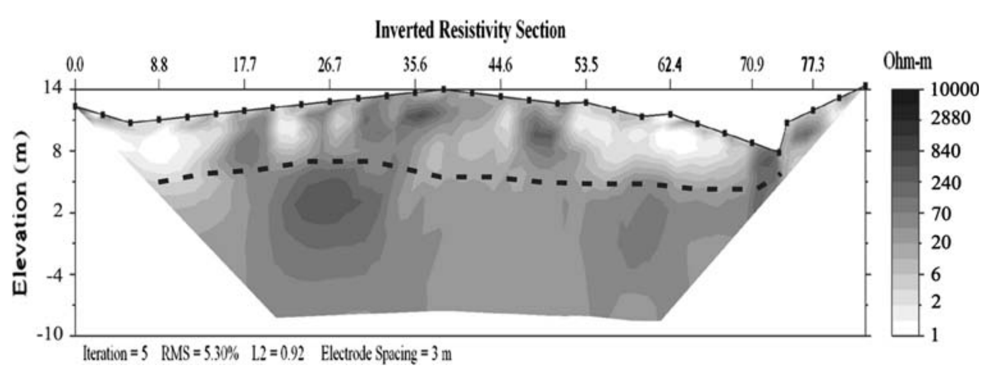


Fig. 8 Typical example of the inverted resistivity section in the zone where no combustion was found, Alonim landfill site. *Black dashed line* shows the boundary between the underground soil and the landfill body

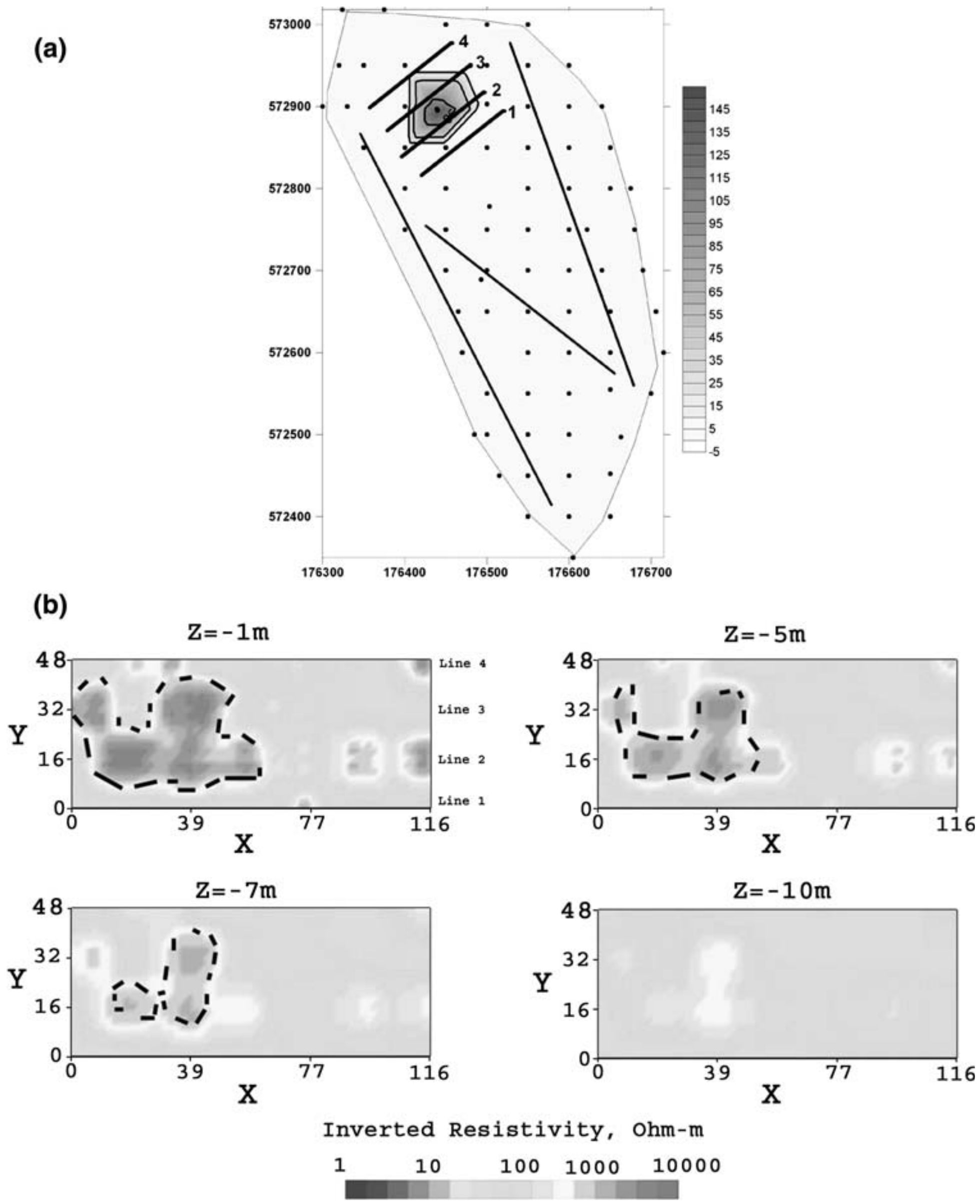


Fig. 9 **a** The scheme of Lon landfill site with the zone of CO anomaly, *black circles* and *lines* shows the locations of landfill gas sampling points and ERT profiles, respectively. Four parallel ERT profiles carried out in the caldera zone are denoted by the corresponding integers. **b** Four horizontal slices of electrical resistivity from quasi 3D ERT on Lon landfill sites with the corresponding depth (*Z*) of measurement. *Dashed line* shows an underground fire zone. Note the same numbers of four parallel ERT lines in Fig. 9a, b

such a high value of the ratio. On the other hand, Lon Landfill site CH_4 content was negligible since waste buried here is mainly constructional. A key role of waste content and a degree of its anaerobic decomposition in a landfill gas composition is well demonstrated by Fig. 3. It is seen, that the general tendency of CO_2 content increasing in the smoldering zones is common for all sites under study in accordance with Eq. 1. Moreover, carbon dioxide in these zones is the main fraction of landfill gas (more than 45–50% of the landfill gas volume) on the landfill sites consisting of a large volume of organic waste (Alonim, Kfar Gidon and Abu Dis; Table 1). This conclusion is also confirmed by the results from Lon landfill site where fraction of CO_2 content in landfill gas was less significant than on three other sites. Such a phenomenon could be again explained by the waste composition, which is mainly constructional on Lon landfill site (Table 1). As was noted above, an increase of temperature in a smoldering zone of a landfill could be either due to microbiological activity or due to chemical oxidation. Our measurements shows (Table 2) that temperature was changed between 53 and 160°C in the smoldering/burning zones of landfills under study implying a dominant role of chemical oxidation during waste decomposition.

Statistical consideration of geophysical data

Analysis of all four data sets shows that inverted electrical resistivity data for all four data sites ranges between 0.25 and 10,000 Ω m. Since such a range is significant, we, for the aim of statistical consideration, divided it in 16 logarithmic bins (as was done by the software used for inversion procedure) as follows: $\log(\rho_{max}/\rho_{min})/16 = 0.301$, where ρ_{max} and ρ_{min} are equal to 10,000 and 0.25 Ω m, respectively. Hence, values of two nearby bins are related by the following relationship: $\rho_{i+1} = \rho_i \times 10^{0.301}$, where ρ_{i+1} and ρ_i are values of electrical resistivity of two nearby electrical resistivity bins (higher and lower, respectively). Figure 10 shows two typical distributions of electrical resistivity values in fired and non-fired zones of landfill sites. As it is seen, when electrical resistivity value is larger than 38 Ω m, the general shape of histogram differs significantly. Note that this boundary value of electrical resistivity is similar to domestic waste one. Our analysis shows that percentage of the fraction of a high resistivity ($\rho > 38$ Ω m) increases by factor 1.25–3 in fire-prone zone relative to percentage of the fraction in a main waste body. The maximal value of the factor is for a landfill where only construction waste was buried (Lon), while the minimal one for the domestic landfill site. An increase of high-resistivity values probably implies changes in landfill structure and around a firing zone, e.g. waste density decrease and hence creation of ways for oxygen penetration into a landfill body following by waste firing.

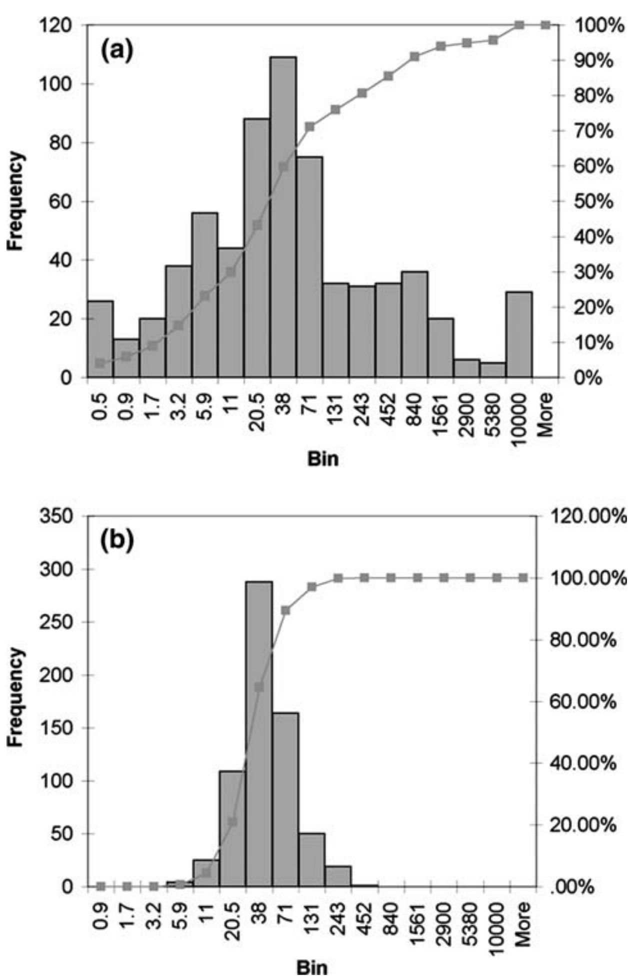


Fig. 10 Two typical electrical resistivity histograms and cumulative curves. a Smoldering area, b non-smoldering area

Analysis of these histograms shows that they are also dissimilar in the range of very low resistivity values (<11 Ω m). An increased percentage of the fraction of such a low resistivity could be probably explained by the noteworthy percentage of highly conductive industrial waste (e.g. metallic materials such as metal pipes, cables, sheets, parts of abandoned cars, etc.), free spaces between which could be good channels for oxygen penetration.

Conclusions

Four fire-prone Israeli landfills were investigated with the integrated geoelectrical and geochemical method. The main outcome of this study is the establishment that ERT is indeed a good choice for the fire zone investigation. It was shown that percentage of the fraction of a high resistivity ($\rho > 38$ Ω m) increases by factor 1.25–3 in fire-prone zones relative to percentage of the fraction in a main waste body probably implying changes in landfill structure and around a firing zone, e.g. waste density decrease and hence creation of ways for oxygen penetration into a landfill body following by waste firing.

Landfill gas composition was carefully investigated on four landfill sites. It was shown that the landfill bodies, where no combustion was found, were characterized by low landfill gas concentration that steeply increased in the smoldering areas. It was also delineated that the landfill gas composition is individual for each site under study, while the tendency of CO_2 content increasing in the smoldering zones is common for all sites under study. In addition, it was shown that carbon monoxide is a very appropriate indicator of waste potential combustion.

Combination of ERT with the subsurface landfill gas and temperature measurements enables comprehensive investigation of a landfill body and not only correct designing of ERT, but also comprehensive understanding of a degree of waste anaerobic biodegradation. Moreover, statistical analysis of the inversed electrical resistivity data and gas content could enable one to estimate a degree of the hazard of fire excitation within a landfill body and determination of the dimensions of underground fire.

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