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Mud volcanoes of Italy

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The locations and information about the sizes of 61 mud volcanoes on the Italian mainland and Sicily, plus an area of mud diapirism in the Italian Adriatic Sea, are presented. Data about the emission products are also provided. The majority of these mud volcanoes are found where thick sedimentary sequences occur within a zone of tectonic compression associated with local plate tectonic activity: the movement of the Adriatic microplate between the converging African and Eurasian plates. The principal gas emitted by these mud volcanoes is methane, which probably originates from deep within the sediments. Other mud volcanoes, associated with igneous volcanism, produce mainly carbon dioxide. The mud diapirs in the Adriatic Sea are thought to form as a result of the mobilization of shallow gassy sediments. It has been shown that radon emissions from mud volcanoes are indicators of forthcoming earthquake events.

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1. INTRODUCTION

Mud volcanoes are landforms that bear a morphological resemblance to true (igneous) volcanoes, but they are formed by the expulsion of water, gas and mud which originate from within a sedimentary sequence, often from great depth. They have been described from many parts of the world, particularly from convergent plate margins with thick sedimentary sequences, for example Taiwan (Shih 1967), Azerbaijan (Sokolov *et al*. 1969; Guliev and Feizullayev 1996) and Indonesia (Barber *et al*. 1986). Hedberg (1980), Brown (1990) and Milkov (2000) provided detailed discussions of the mechanisms of mud volcano formation.

There is a wide and rich historical literature about the mud volcanoes of Italy. They were described by Pliny in his *Naturalis Historia* (AD 77; see Conte 1982). Spallanzani (1795) and Stoppani (1908) suggested that the upwelling fluids were possibly connected to meteorological events. Mercalli (1883) excluded a link with true volcanic activity and reported testimonial evidence about a possible link between paroxysmal mud emission and earthquakes. More recently Caneva (1958) carried out a geophysical survey of a mud volcano in the Northern Apennines and demonstrated the absence of any correlation between the temporal variations in gas emissions and local meteorological conditions. Pellegrini *et al*. (1982) and Capozzi *et al*. (1994) provided evidence that mud volcanoes occur along the external compressive margin of the Apennine chain. Galli (2000) described features formed as a result of liquefaction induced by earthquakes. These included 'sand boils' (formed by the venting of a mixture of sand and water) and 'mud volcanoes'. Mud volcanoes had been described from only two of the 317 liquefaction locations he catalogued. The features are clearly associated with individual earthquake events (they all occur close to the epicentres of the earthquakes that induced them), they seem to be transient, and did not survive for long. Only two locations out of 317 host present mud volcanic structures characterized by non-episodic activity. For this reason these features are not considered suitable for inclusion in this paper.

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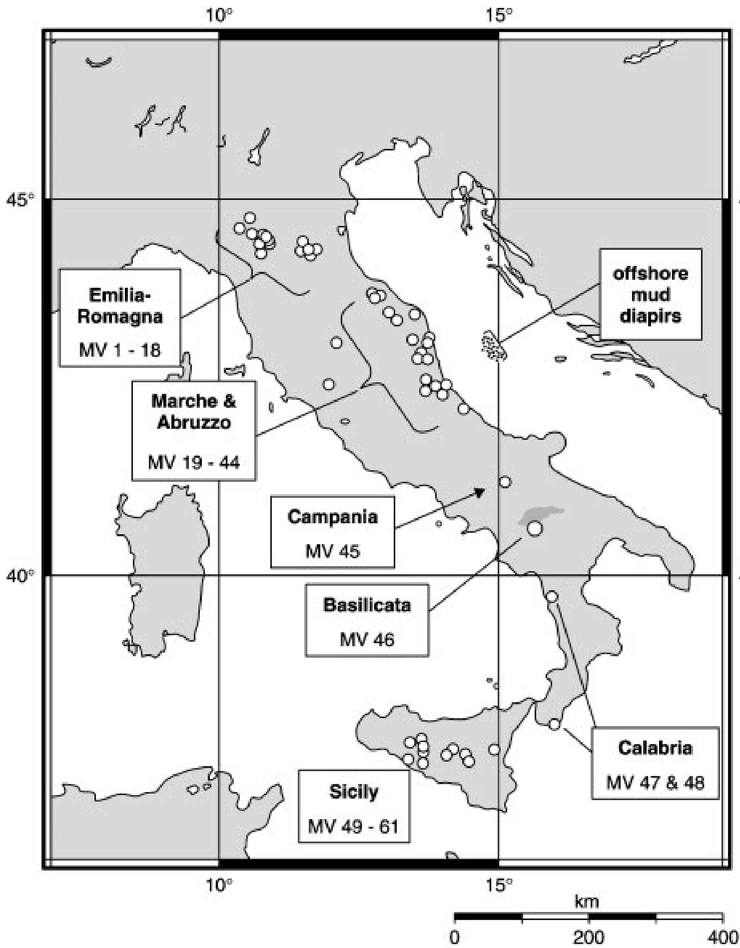

Figure 1. The geographical distribution of mud volcanoes in Italy.

This paper describes the geographical distribution and surface morphology of Italian mud volcanoes, discusses the geological contexts in which they occur, and summarizes the available data (some of which have not previously been published) concerning mud volcano activity and emissions.

2. GEOGRAPHICAL DISTRIBUTION

Mud volcanoes are clustered in three main geographical groups in northern and central Italy, and Sicily; there are also a few in southern Italy, and offshore in the Italian Adriatic Sea (see Figure 1). The details provided in Table 1 include information gleaned from the literature, and unpublished information. With the exception of those in the Adriatic Sea, accurate geographical locations have been obtained by the first author using portable GPS (Garmin 12/12XL) equipment.

3. MORPHOLOGY

The sizes and shapes of the mud volcanoes vary considerably. Only a small proportion can be described as ‘large’: 12 (20%) have a surface area of $>500\,m^2$, and only three (5%) exceed 2 m in height. Most of the larger mud volcanoes occur in northern Italy, as indicated in Table 1.

Table 1. Locations and characteristics of Italian mud volcanoes

Map number (locations shown on Figure 1)	Province*	Borough	Nearest toponym reachable by car	Latitude (deg:min:s)	Longitude (deg:min:s) East	Surface area†	Height (m)
Northern Italy							
1	RE	Viano	Casola–Querciola	44:45:44	10:31:38	D	<0.5
2	RE	Viano	Regnano	44:33:27	10:34:34	A	~2
3	PR	Lesignano di Bagni	Rivalta	44:37:45	10:19:34	A	<0.5
4	PR	Traversetolo	Torre	44:37:13	10:20:19	A	<0.5
5	MO	Sassuolo	Montegibbio	44:30:55	10:46:39	D	<0.5
6	MO	Fiorano Modenese	Nirano	44:30:48	10:49:25	A	~2
7	MO	Maranello	Puianello	44:28:36	10:52:00	B	<0.5
8	MO	Serra Mazzoni	Centora–Montardone	44:28:07	10:47:42	C	<0.5
9	MO	Marano sul Panaro	Ospitaletto	44:26:11	10:52:54	B	<0.5
10	MO	Polinago	Canalina	44:24:49	10:43:42	D	<0.5
11	BO	Ozzano Emilia	Montebugnolo	44:26:38	11:28:25	D	<0.5
12	BO	Castel San Pietro	San Martino in Pedriolo	44:21:13	11:34:22	D	<0.5
13	BO	Imola	Campo di Fondo	44:21:12	11:42:50	D	<0.5
14	BO	Monterenzio	San Clemente	44:20:09	11:27:18	A	<0.5
15	BO	Imola	Bergullo	44:18:32	10:44:14	C	<0.5
16	BO	Casalfiumanese	Casa Bubano	44:17:52	11:37:02	D	<0.5
17	BO	Casalfiumanese	Casa Campagnola	44:17:52	11:37:02	D	<0.5
18	BO	Casalfiumanese	Case Nuove di Rifiano	44:17:52	11:37:02	D	<0.5
Central Italy, Marche region							
19	PS	Petriano	Petriano	43:46:47	12:44:02	D	<0.5
20	PS	Saltara	Saltara	43:45:12	12:53:50	D	<0.5
21	PS	Isola del Piano	Isola del Piano	43:44:11	12:46:57	D	<0.5
22	AN	Ancona	Serra de' Conti	43:32:33	13:02:12	D	<0.5
23	AN		Aspio	43:32:00	13:30:04	D	<0.5
24	AN	Osimo	Santo Stefano	43:30:30	13:27:40	D	<0.5
25	AN	Maiolati Spontini	Moie	43:30:10	13:07:48	D	<0.5
26	AN	Maiolati Spontini	Contrada Calapigna	43:28:34	13:07:13	D	<0.5
27	AN	Monte Roberto	Monte Roberto	43:28:50	13:08:18	D	<0.5
28	AN	San Paolo di Jesi	Battinebbia	43:27:27	13:10:03	C	<0.5
29	AN	San Paolo di Jesi	Bagno	43:27:14	13:10:26	C	<0.5
30	MC	Macerata	Mogliano	43:11:07	13:28:45	D	<0.5
31	AP	Fermo	Capodarco	43:11:19	13:45:41	D	<0.5
32	AP	Senigallia	Vallone	43:08:18	13:43:22	D	<0.5
33	AP	Monte Rinaldo	Contrada Crocchia	43:01:39	13:34:47	D	<0.5
34	AP	Rotella	Madonna di Montemisio	42:57:14	13:33:38	D	<0.5
35	AP	Rotella	Contrada Osteria	42:56:47	13:32:33	D	<0.5
36	AP	Offida	Offida	42:56:06	13:41:26	C	<0.5
Central Italy, Abruzzo region							
37	TE	Torano Nuovo	Frola	42:39:31	13:42:14	D	<0.5
38	TE	Pineto	Pineto	42:36:29	14:04:02	D	~2
39	TE	Cellino Attanasio	Astelina	42:35:08	13:51:34	D	<0.5
40	TE	Cellino Attanasio	Pian Palazzo	42:35:08	13:51:34	D	<0.5
41	TE	Bisenti	Chiovano	42:32:07	13:40:16	D	<0.5
42	PE	Penne	Picciano	42:28:26	13:59:27	D	<0.5
43	CH	Frisa	Frisa	42:15:42	14:22:03	D	<0.5
44	CH	Poggiofiorito	Poggiofiorito	42:15:19	14:19:24	D	<0.5
Southern Italy, Campania region							
45	BV	Castelfranco in Miscano	Malvizza	41:17:49	15:05:06	A	<0.5
Southern Italy, Basilicata region							

Continues

Table 1. Continued

46	PZ	Cancellara	Contrada Bòfete	40:43:51	15:55:23	D	<0.5
Southern Italy, Calabria region							
47	CS	San Vincenzo la Costa	San Sisti	39:21:50	16:09:04	D	<0.5
48	RC	Palizzi	Rocchette	37:55:09	15:59:11	D	<0.5
Sicily							
49	CT	Paternò	Simeto‡	37:33:57	14:54:06	A	<0.5
50	CT	Paternò	Stadio‡	37:33:50	14:54:11	A	<0.5
51	CT	Paternò	Vallone Salato‡	37:33:47	14:54:15	A	<0.5
52	EN	Aidone	Aidone	37:24:54	14:26:47	D	<0.5
53	EN	Valguarnera Caropepe	Valguarnera Caropepe	37:29:42	14:23:20	D	<0.5
54	EN	Villarosa	Villarosa	37:35:08	14:10:24	D	<0.5
55	CL	Caltanissetta	Xirbi	37:29:25	14:03:24	D	<0.5
56	AG	Casteltermini	Casteltermini	37:32:24	13:38:42	D	<0.5
57	AG	Cammarata	Cammarata	37:37:57	13:38:13	D	<0.5
58	AG	Aragona	Zorba	37:23:32	13:37:26	A	<1
59	PA	Lercara Friddi	Lercara Friddi	37:44:51	13:36:12	D	<0.5
60	PA	Palazzo Adriano	Palazzo Adriano	37:40:52	13:22:44	D	<0.5
61	AG	Cattolica Eraclea	Bissana	37:26:20	13:23:42	B	<0.5

*AG, Agrigento; AN, Ancona; AP, Ascoli Piceno; BO, Bologna; BV, Benevento; CH, Chieti; CL, Caltanissetta; CS, Cosenza; CT, Catania; EN, Enna; MC, Macerata; MO, Modena; PA, Palermo; PE, Piceno; PR, Parma; PS, Pesaro; PZ, Potenza; RC, Reggio Calabria; RE, Reggio Emilia; TE, Teramo.

†A, 500 to 30 000 m^2; B, 2500 m^2; C, 5 to 100 m^2; D, $< 5\,m^2$.

‡Mud volcanoes associated with Mount Etna.

Sources: Northern Italy: Biasutti (1907), Scicli (1972), Ferrari and Vianello (1985). Central Italy, Marche region: Bonasera (1952, 1954), Damiani (1964), Nanni (1990), Nanni and Vivalda (1998); Abruzzo region: Bonasera (1954). Southern Italy: Crema (1909); Bongo (1916); Pingue and Marrone (1970); Malara (1978); Duchi *et al*. (1995). Sicily: Abruzzese (1954); Cumin (1954); Chiodini *et al.* (1996); D'Alessandro *et al.* (1995); Etiope *et al*. (2002).

For example, the Nirano mud volcano of the Emilia-Romagna region of northern Italy has a surface area of approximately 75 000 m^2 (see Figure 2). It is one of the biggest mud volcanic areas of Italy. It is situated at the bottom of an oval depression within a hilly landscape. The mud volcano lies near a small anticline in the outcrop of Plio-Pleistocene clays, and may be associated with a nearby fault (Martinelli and Rabbi 1998). The land surface on the mud volcano is generally grey in colour because the recently extruded mud has not been colonized by vegetation. As can be seen on Figure 3, there are several individual cones or 'gryphons' (i.e. individual active vents or cones; this term is in common usage in mud volcano areas such as Azerbaijan: see Yakubov *et al*. (1971) and Hovland *et al*. (1997) for example) within the area of the mud volcano. The actual number and location of these cones varies over time. These cones have the classic shape of a volcano, occupy roughly circular areas about 5 m in diameter, and stand up to 2 m above the general ground level. They intermittently emit gas bubbles and muddy water from a central crater; these vary from a few centimetres to almost a metre in diameter. Muddy water escaping from the crater runs down the sides of the cone. This mud, when dry, increases the size of the cone.

In contrast, many of the smaller mud volcanoes, especially those of the Marche region of central Italy and of Sicily, are small and difficult to find; they are often obliterated by rain or when the fields are ploughed. A recent survey carried out in Sicily (Etiope *et al*. 2002) evidences that only the main volcanic areas of the Agrigento and Catania provinces are presently active.

3.1. The mud diapirs of the Adriatic Sea

Mud diapirs, features which are morphologically similar to mud volcanoes and are also associated with the migration of gas towards the surface, have been described (Hovland and Curzi 1989) from an area in the Italian Adriatic Sea (see Figure 1). These features are about 2 or 3 m high and 50 m in diameter. There is evidence of gas within the

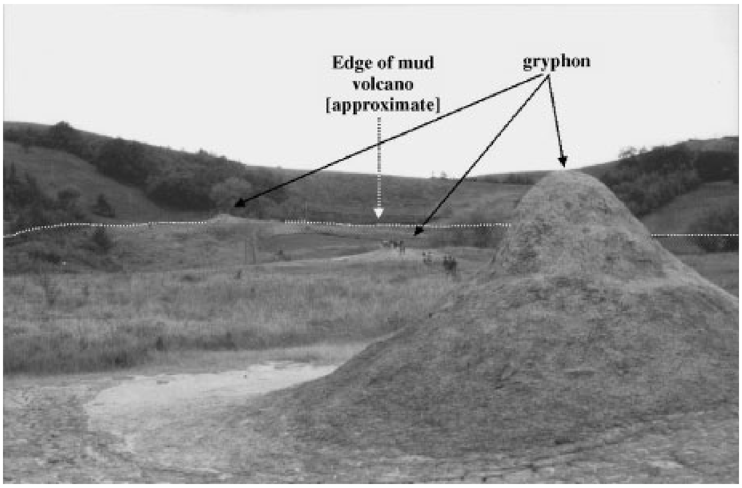

Figure 2. General view of the Nirano mud volcano. The people in the middle distance indicate the scale.

Figure 3. Gryphons of the Nirano mud volcano. The people in the middle distance indicate the scale.

sediments beneath them, and of gas seeping from some of them. However, seismic records (e.g. Figure 4) indicate that these features are confined to the surficial sediments; unlike true mud volcanoes, there is no evidence to suggest that the material of which the features are formed has migrated from depth. Hovland and Curzi (1989) considered that these features formed by the mobilization of mud by gases. Expulsive activity of these features is indicated by gas seepage, identified acoustically as plumes of bubbles on seismic reflection profiles (Hovland and Curzi 1989).

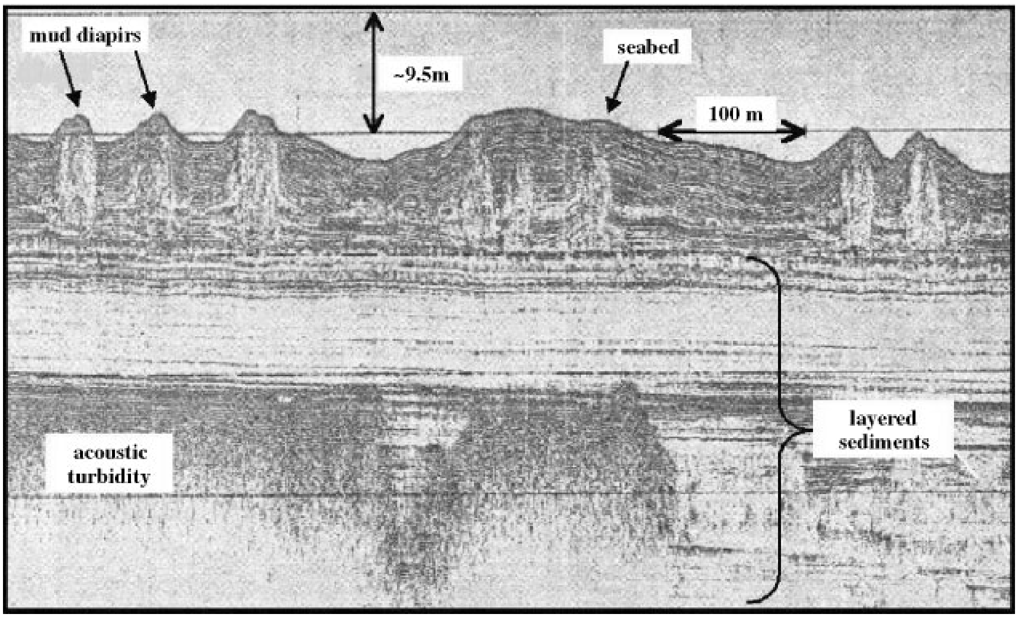

Figure 4. Seismic section of offshore mud diapirs in the Italian Adriatic Sea (adapted from Hovland and Curzi 1989).

4. EMISSION ACTIVITY AND PRODUCTS

In common with other mud volcanoes, those of Italy emit gas, water and mud. The mud volcanoes of Italy show continuous or intermittent gentle activity. For example, at the Nirano mud volcano, each of the individual gryphons produces gas and muddy water. There is a continual supply of small (approximately 1 cm diameter) bubbles, but every few minutes there may be a belch as a larger (<10 cm diameter) bubble breaks the surface. The muddy waters collect within a summit cone, and periodically overflow, running down the sides of the cone. These flows may extend a few metres from the gryphons, and they occur with sufficient frequency to prevent the growth of vegetation (as can be seen on Figures 2 and 3). Over time, the mud dries out, gradually increasing the size of the features.

Etiope *et al*. (2002) have carried out gas flux measurements in three mud volcanic areas of Sicily but to date no comprehensive survey has been undertaken of the Italian mud volcanoes to estimate the frequency and magnitude of water and gas emissions. The available data are summarized below.

4.1. Gases

According to Mattavelli and Novelli (1998), the gases emitted by Italian mud volcanoes are dominated by methane. The analyses presented in Table 2 support this, although these relate mainly to mud volcanoes of the Northern Apennines. The carbon isotope ratios (-39.1 to -69.7‰) suggested to Mattavelli and Novelli (1998) and to Minissale *et al*. (2000) that these gases are of mixed biogenic and thermogenic origin, and that they are typical of the Italian foredeep. The presence of ethane certainly suggests a thermogenic component. Minissale *et al.* (2000) noted that these gases are relatively enriched in helium, and suggested that this indicates an enrichment in crustal radiogenic ^{4}He and long underground residence times.

Analytical details from Duchi *et al.* (1995) indicate that the gases from the Malvizza mud volcano, which is also dominated by methane, were derived from an oil reservoir in organic-rich Tertiary sediments.

In contrast to these methane-dominated gases, those of Paternó (Sicily) are CO_2-rich, and are associated with igneous activity of the nearby Mount Etna volcano.

Table 2. Composition of gases from Italian mud volcanoes

Map number (locations shown on Figure 1)	Mud volcano*	Methane, CH_4(%)	Ethane, C_2H_6(%)	Nitrogen, N_2(%)	Hydrogen sulphide, H_2S(%)	Carbon dioxide, CO_2(%)	$\delta^{13}C$ in CH_4 (‰ PDB)
2	Regnano[1]	97.4	0.73	0.49	<0.0005	1.14	−44.9
3	Rivalta[1]	94.6	0.01	4.14	<0.005	1.63	—
4	Torre[1]	96.8	0.04	0.40	<0.0005	2.73	−39.1
6	Nirano[1]	98.0	0.04	1.32	<0.0005	0.66	−46.0
9	Ospitaletto[1]	97.8	<0.00001	0.63	<0.005	0.98	—
14	San Clemente[1]	90.7	4.39	1.19	<0.0005	1.72	−43.8
15	Bergullo[1]	99.4	0.05	0.42	<0.0005	0.12	−69.7
45	Malvizza[2]	92.7	0.43	3.83	1.48	0.87	—
49–50	Paternò[3]	<1 to 11	—	1 to 18	—	85 to 99	—
58	Aragona[4]	98.8	—	1.15	—	0.9	—
61	Cattolica Eraclea	96.2	—	0.83	—	2.9	—

*Data from: [1]Minissale *et al.* (2000); [2]Duchi *et al.* (1995); [3]Chiodini *et al.* (1996); [4]Etiope *et al.* (2002).

There are few details of the gas emission rates. For example, the main gryphon of the Nirano mud volcano emits an estimated 150 to 300 m^3 of gas per day (Martinelli and Rabbi 1998). This gas is dominated by methane (see Table 2), and it readily ignites when exposed to a naked flame. Total gas emission of mud volcanic areas of Sicily have been estimated at about 400 tons/year by Etiope *et al*. (2002).

4.2. *Waters*

Available data on the composition of emitted waters, summarized in Table 3, are from the mud volcanoes of the Emilia-Romagna region of northern Italy and the Campania region of southern Italy. The isotopic compositions of waters of three mud volcanoes in the Emilia-Romagna region are presented in Table 4.

The data indicate that the waters are brackish, and not dissimilar in composition to the spring and groundwaters studied by Duchi *et al.* (1995) and Conti *et al.* (2000). These are considered to be connate waters. Oxygen isotope ratios (δ^{18}O‰ SMOW) in the range +5.93 to +2.93, and deuterium:hydrogen ratios (δ^{2}H‰ SMOW) in the range −2.02 to +9.05 indicate that there has been no contamination from meteoric waters.

Radon (^{222}Rn), released from host rocks by the natural decay of radium (^{226}Ra), is easily detectable in both the muds and waters emitted by mud volcanoes; it is also present, but less easily detectable, in the gas phase (Martinelli *et al.* 1995; D'Alessandro *et al.* 1995). ^{226}Ra concentrations in the mud volcanoes of the Emilia-Romagna region were found to range between 260 and 470 pCi kg^{-1} in the clay fraction, and around 20 pCi kg^{-1} in the waters. Monitoring of ^{222}Rn activity of the Nirano, Regnano and Ospitaletto mud volcanoes (Emilia-Romagna region of northern Italy) demonstrated a direct correlation with air temperature. However, once the data had been smoothed to remove temperature effects, it was found that anomalously high ^{222}Rn values occur from time to time, and that these peaks could be correlated with low magnitude ($M < 4.5$) local earthquakes (Martinelli and Ferrari 1991; Martinelli *et al.* 1995). A correlation between radon emissions and earthquake activity was also demonstrated in the mud volcanoes around Mount Etna (D'Alessandro *et al.* 1995).

4.3. *Mud*

Pingue and Marrone (1970) carried out detailed research on the mineralogy of the Malvizza mud volcano (south Italy) using diffractometric and thermal differential analyses. They found that more than 95% of the extruded mud comprised illitic clay, and there were traces of calcite and quartz. As the macroscopic features of the clay minerals extruded from Italian mud volcanoes, and the geological contexts, are very similar, it is believed that the principal mineralogical characteristics of the other mud volcanoes do not differ significantly from those of Malvizza.

Table 3. Ion composition of waters emitted by mud volcanoes of Italy

Map number (locations shown on Figure 1)	Mud volcano	Data source*	Temp. (°C)	pH	Cl^{2+} (mg/l)	SO_4^{2-} (mg/l)	HCO_3^- (Mg/l)	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Total dissolved solids	I^- (mg/l)	Br^- (mg/l)
Emilia-Romagna region, northern Italy														
2	Regnano	1	†	†	8020	53	1880	5500	21.5	220	84	15 800	40.5	58.8
		3	28	8.76	8190	244	1769	5731	20.0	40	57	†	†	†
3	Rivalta	3	31	8.55	8545	88	1202	5490	16.0	100	226	†	†	†
4	Torre	3	29	8.70	5390	92	1238	3542	16.0	82	84	†	†	†
6	Nirano	1	†	†	7300	200	405	4350	42.0	95	265	12 700	40.3	62.6
		3	27	8.34	6335	200	641	4053	27.0	126	197	†	†	†
9	Ospitaletto (1)	1	†	†	7350	0	970	4800	11.0	105	101	13 300	24.7	37.7
	Ospitaletto (2)	1	†	†	8090	0	490	4950	18.0	190	131	13 900	—	—
		3	30	8.40	8190	164	793	5106	20.0	160	125	†	†	†
Campania region, southern Italy														
45	Malvizza	2	†	†	5183	134	2910	4600	12.0	20	16	13 255	†	†
	Sea water				18980	2649	140	10560	380	400	1272	—	—	—

*Data from: 1, Martinelli and Ferrari (1991); 2, Duchi *et al.* (1995); 3, Minissale *et al.* (2000).
†Not determined.

Table 4. Isotopic composition of waters emitted by mud volcanoes of the Emilia-Romagna region, northern Italy

Map number (locations shown on Figure 1)	Mud volcano	Data source*	δ^2H‰ SMOW	δ^{18}O‰ SMOW	^{87}Sr/^{86}Sr
2	Regnano	2		2.93	
		1			0.70899
		1	−2.24	3.58	0.70872
6	Nirano	1	−2.02	4.69	
		1	4.03	5.51	0.70894
9	Ospitaletto	1	9.05	5.93	0.70918
		1	3.27	4.62	

*Data from: 1, Conti *et al*. (2000); 2, Arione (1984); quoted in Conti *et al*. (2000).

5. GEOLOGICAL CONTEXT

The geology of Italy (reviewed by Pieri and Mattavelli 1986) is primarily a function of its location between the converging African and Eurasian plates. The geological complexity of Italy results from the collision between the Adriatic microplate, which is being thrust westwards and northwards over the Eurasian plate beneath the southern Alps, the flexure of the Adriatic lithosphere below the Apennines, and the westward subduction of the Ionian lithosphere below the Calabrian Arc (Doglioni and Flores 1997; Montone *et al.* 1999). As Montone *et al.* (1999) explained, there has been considerable controversy (as yet unresolved) about the precise processes that have been active in the recent geological past. However, it is clear that tectonic forces have created a stress environment which features areas of tension/extension and areas of compression. As can be seen in Figure 5, northern Italy (the Po valley and northwards to the Alps) is an area of compression; the majority of peninsular Italy, south of the Po valley, and Sicily are dominated by an asymmetric thrust belt which has compressional and extensional fronts, and active oceanic subduction. Within this tectonic setting the geology may be crudely considered to comprise:

(i) the crystalline basement of the Alps;
(ii) the Liguride nappes: sedimentary, metamorphic and magmatic rocks which have undergone complex folding and thrusting;
(iii) Tertiary to Recent volcanics;
(iv) Mesozoic and Cainozoic sediments.

The sediments of the Apennines (lying to the west of the main thrust belt) have been folded and faulted. In contrast, areas to the north (the Po valley), east (the Adriatic coastal plain) and south (southern Sicily) are composed of thick (in places, such as the Po valley, >7 km) sequences of Mesozoic and Cainozoic sediments (Pieri and Mattavelli 1986).

As can be seen from Figure 5, the majority of the mud volcanoes are located within compressional zones in which there are thick sequences of sediments.

6. DISCUSSION

Compared to the mud volcanoes of some parts of the world (e.g. Azerbaijan, where some individual mud volcanoes are >250 m in height and cover areas of up to 100 km^2: Guliev and Feizullayev 1996), the mud volcanoes of Italy are small and unspectacular. They do not exhibit the periodic explosive activity characteristic of some mud volcanoes, rather they are characterized by the continuous, but relatively quiescent expulsion of gas, water and mud. Some may be comparable in size to the liquefaction features reported by Galli (2000); however, those described here are not transient features induced by individual earthquake events. They bear some similarity to the ‘mud springs’ of the Wootton Bassett area of southern England (Bristow *et al.* 2000). However, these features

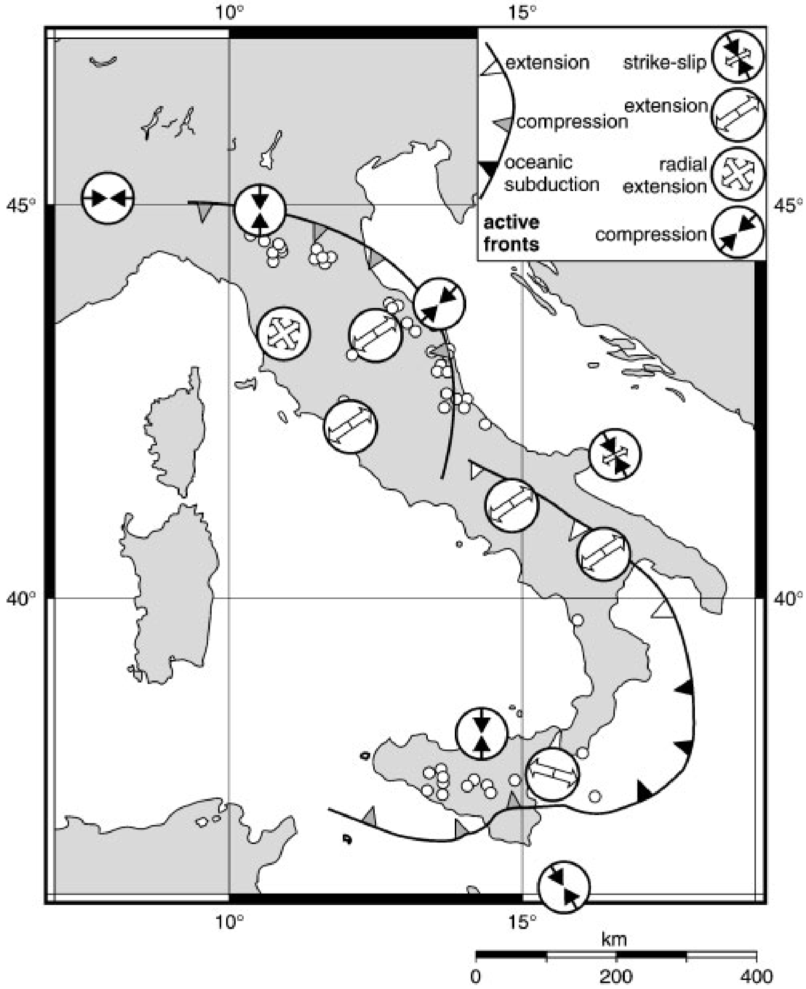

Figure 5. The stress environment of Italy (incorporating data from Montone *et al*. 1999).

seem to emit only muddy water; artesian flows of groundwater from a Jurassic limestone (the Coral Rag) liquefy the overlying mudstone (Ampthill Clay) so springs are muddy. There are no reports of gas being emitted here.

Detailed studies of radon emissions from the mud volcanoes of the Emilia-Romagna region of northern Italy have demonstrated that the radon concentration of the liquid phase provides a reliable indicator of forthcoming local earthquake events. Martinelli and Ferrari (1991) and Martinelli *et al.* (1995) attributed these peaks to sharp pressure variations at depth, caused by crustal deformation. The decay of ^{226}Ra to ^{222}Rn does not vary with time, so changes in the ^{222}Rn emission rate must result from variations in the expulsion velocity of the fluids. The fluids are confined within the source rocks, so sudden changes in the pressure environment caused by crustal movements explain the variations in fluid expulsion velocity. In contrast, D'Alessandro *et al.* (1995) demonstrated that variations in radon concentrations in the mud volcanoes around Paternò (Sicily), which were also associated with earthquake activity, resulted from changes in the gas: liquid ratio as carbon dioxide from volcanic (igneous) sources varied.

Milkov (2000) identified four closely related groups of reasons for the formation of mud volcanoes:

(a) geological (thick sedimentary sequences; the presence of plastic clays; rock density inversions; gas accumulations; and high formation pressures);

(b) tectonic (rapid sediment burial because of high accumulation rates or over-thrusting; diapirism or anticlinal folding; faulting; tectonic compression; seismic activity; isostatic processes);
(c) geochemical (petroleum generation; dehydration of clay minerals);
(d) hydrogeological (fluid flow along fracture zones).

The evidence presented in this paper, including the comparison of the geochemistry of mud volcano waters with groundwater and spring waters, suggests that the mud volcanoes of Italy fall into four categories. The majority are found in areas of tectonic compression where there are thick sedimentary sequences. It is probable that the expulsion products rise from considerable depths within these sedimentary sequences as a consequence of the tectonic pressure, possibly aided by the loss of density associated with gas generation. This is indicated by the emission of connate waters uncontaminated by meteoric waters and by the emission of methane whose $^{12}C/^{13}C$ value is in the range −39 to −70‰.

Milkov's first two categories of mud volcanoes are associated with these areas.

1. Mud volcanoes in areas with thick sedimentary sequences in which petroleum gases are generated, and migrate towards the surface.
2. Mud volcanoes in areas with thick sedimentary sequences in which connate waters flow towards the surface.

It is possible that mud volcanoes in categories 1 and 2 form only because of the gas content, and that, where there is an absence or low concentration of gas, fluid migration is restricted to normal groundwater circulation.

3. Mud volcanoes whose gaseous emissions are dominated by CO_2, and which are associated with igneous volcanism. It is likely that these mud volcanoes are located over fracture zones.
4. Despite their location close to the area affected by compressional tectonic movements, the offshore mud diapirs seem to owe their origin to processes confined to the topmost sediments where gas generation and migration mobilize the sediments (Hovland and Curzi 1989).

With the exception of category four, these categories can be correlated with the reasons for the formation of mud volcanoes identified by Milkov (2000).

The mud volcanoes of categories 1 and 2 are methane-dominated. They occur in Sicily and on the eastern side of the Italian peninsula in areas of tectonic compression associated with the Italian foredeep and thrust belts. In contrast, the western side of Italy, the extensional back-arc zone, is typified not only by igneous activity (e.g. Etna and Vesuvius), but also by geothermal springs and other types of fluid emission. Duchi *et al*. (1995) reported that thermal and cold springs of the Campania region of southern Italy were dominated by CO_2 associated with Vesuvius, Solfatara and Roccamonfina volcanic areas. Chiodini *et al.* (1996) linked the CO_2 emissions of the Paternó mud volcanoes to Mount Etna. Minissale *et al*. (2000) described thermal springs and other CO_2 emissions (fumaroles, springs and mud basins) in an area to the west of the Northern Apennines (including the Larderello–Travale geothermal field).

7. CONCLUSIONS

The mud volcanoes of Italy provide important evidence of the compressive tectonic regime, the presence of hydrocarbons at depth, and the flow of fluids towards the surface. They provide possible predictions of local seismic events, and they make direct contributions of methane and/or carbon dioxide, both important 'greenhouse' gases, to the atmosphere. They also give clues about the locations of deep methane reservoirs. They are more than mere geological curiosities.

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