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Geofluids Hosted in the Deep Crust: From Systematics to Parametrization of their Significance

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Earthquake is a sudden release of energy due to fault motions. The severity of the damages can be minimized by development of a culture of prevention which includes the Seismic Hazard Assessment, microzonation studies and appropriate building codes. Earthquake risk assessment methods require seismo tectonic information usually organized in earthquake catalogues utilized in Probabilistic Seismic Hazard Assessment (PSHA) based on initial work by Cornell (1968), where probability distributions for magnitudes and source site distances reported in earthquake catalogues were utilized for the first time. In following years the method furtherly improved reporting an upper bound on the earthquake magnitude in each region avoiding the inclusion of unrealistically big earthquakes. A different approach has been followed in Countries characterized by significant incompletenesses in available earthquake catalogues. In these places the Deterministic Seismic Hazard Assessment (DSHA) methods have been often utilized. In particular the DSHA takes into account the maximum possible earthquake to evaluate the intensity of seismic ground motion distribution at a site by taking account the seismotectonic setup of the area. A deepening in the knowledge of seismotectonics and of morphostructural features of the studied area has been carried out in pattern recognition studies (Gelfand et al., 1976 and references therein). More updated applications named Neo-Deterministic Seismic Hazard Assessment (NDSHA) proposed by Wang et al. (2021) also consider morphostructural zoning which, in turn, considers nodes (fractured areas), lineaments and topographical features like the maximal elevation and the minimal elevation of the studied area. The steepness of topographic surfaces and sharp variations in morphostructural parameters indicate high tectonic activity. Some geological features are also presently utilized in PSHA methods in some Countries and considers basic parameters like the top and the bottom of seismogenic layers deduced by faults geometry within the frame of the Earthquake Rupture Forecasting (Bird and Liu, 2007). Thus, methodological convergences characterize both methods when geological parameters are considered. The two described methodologies (PSHA and DSHA), in principle, may complement one another to provide more precise insights to the seismic hazard topics. Studies about the occurrence of geofluids in faulted areas may add valuable information about the local stress-strain fields and about the evolution of them during time. In particular the occurrence of warm spring waters, the degassing of CO_2, CH_4, noble gases and, among them, of Helium produced in the crust under different conditions consists in the release of volatiles from rocks and in their transport toward the surface. CH_4 gas leaks typically occur near the margins of petroleum fields that are mostly located in convergent basins with relatively low heat flow values. Methane emissions from sedimentary basins are mostly due to hydrocarbon production (biogenic and thermogenic methane) and, to a lesser extent, to inorganic processes in geothermal systems. Geologic CH_4 emissions take the form of diffuse fluxes across large regions, or microseepages, as well as localized flows and gas vents on both the land and offshore. Mud volcanoes are the most visible manifestation of geologic methane release. Several articles have been published on mud volcanoes during past decades, the overall number of mud volcanoes is unknown and uncertain particularly those on the deep sea environment.

The number of known seabed mud volcanoes has grown significantly during the previous two decades, and continues to grow each year as better techniques for investigating abyssal seafloors are used. Mud volcanoes are grouped irregularly in isolated regions, producing zones that almost entirely correlate with active plate boundary areas. These belts are defined by the presence of sedimentary sequences that are at least two kilometers thick. They are primarily concentrated within compressional zones, such as accretionary complexes, thrust and overthrust belts.

Outside of these belts, the mud-volcano groups are linked with regions of rapid recent sedimentation, such as contemporary fans (including underwater deltas of major rivers) or intense salt diapirism formation. More than half of all mud volcanoes are located along the Alpine Himalayas Active Belt, which has some hundreds terrestrial and offshore examples. The largest and most

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active mud volcanoes are found here, including those in Azerbaijan which have the world's highest concentration of mud volcanoes. The Alpine-Himalayan Active Belt has more than one hundred mud volcanoes, and extends to Italy, which have more than 50 mud volcanoes. The belt continues eastward, passing through Eastern Carpathians, where various examples exist, Iran, and the Great Caucasus and adjacent Azov and Black sea. To the east, the belt continues southward into Turkmenistan, which hosts some hundreds mud volcanic structures.Further east, in Pakistan several onshore and offshore mud volcanoes exist. The Alpine-Himalayas Active Belt then continues south through the southern Himalayas to the most northeastern part of the Indian Ocean, on and around numerous forearc islands located along the Indonesia-Australia accretion and collision complexes. Various mud volcanoes are present in the Sakhalin Island and in the Sea of Okhotsk. The belt then goes across Hokkaido Island and surrounds the East China Sea, passing via the Okinawa islands and the Nankai Trough up to Taiwan Mud volcanos are also present in Indonesia, Philippines and Papua New Guinea and in the Samoan Islands. Some mud volcanoes are located in Southern Alaska, offshore in the Aleutian accretionary complex , in California, Costa Rica, Panama, Ecuador and Peru. Further mud volcanoes are found in Columbia, Venezuela, and Trinidad.

The Barbados accretionary complex has several mud volcanoes. Mud volcanoes have been discovered recently offshore from Portugal and offshore from Morocco. Mud volcanic areas are also connected to submarine deltaic and fan complexes and areas of salt diapirism, such as the Dead Sea. CO_2 is emitted globally from both metamorphic and non-metamorphic rocks. CO_2 is considered to originate from three distinct sources which are biological matter, marine carbonate rock metamorphism, and the mantle. Stable-isotope measurements are useful for determining the origin of CO_2. Organic matter, such as coal, fossil wood, and petroleum, is relatively depleted in ^{13}C. Marine carbonates have a ^{13}C isotope content of around 0 per mil in comparison to the PDB standard. ^{13}C values of −5.4 and −5.8 per mil were found in discharges from the East Pacific Rise, respectively, while −4.7 per mil characterized CO_2 from the Cayman trough. The Loihi Seamount's CO_2 has a ^{13}C value of −4.8 per mil. ^{13}C for mantle-derived CO_2 is characterized by values in the range −4.7 and −8.0 per mil (Tamburello et al., 2018 and references therein) Non-mantle derived Carbon dioxide and methane are produced during thermometamorphism of rocks and during mechanochemical reactions due to tectonic activity. Another possible source of CO_2 is mantle degassing due to volcanic or tectonic activity. CO_2 emissions may originate from a mixture of these sources. Noble gases are recognized as a powerful tracers in various fields, including hydrocarbon exploration, magma degassing, mantle processes,groundwater hydrology and tectonics. Among them Helium and Argon are particularly sensitive to the release of volatiles from the rocks, to their transport toward the surface and to eventual accumulation processes. In particular ^4He produced by U and Th decay in the crust may accumulate together with CH_4 or dominated or CO_2 dominated geofluids. Theoretical calculations and experimental studies have highlighted that He produced in the crust can be effectively released under compression and the related grinding or fracturing. Fractures in fault zones are recognized as pathways of fluid flow in the crust. The transport of He through the crust to the near-surface system needs a driving force represented by a carrier geofluid. Geofluids like CO_2 and CH_4 are subjected to concentration and pressure gradients able to induce gas migrations at depth. Furthermore the isotope of Helium characterized by a lower mass (^3He) is only produced by mantle degassing, resulting a powerful tracer for the resolution of problems related to the origin of deeply-sourced fluids. $^3He/^4He$ may be utilized as an indicator of deep faults able to reach mantle gaseous sources. Relatively high $^3He/^4He$ concentration and fluxes characterize areas affected by high heat flux and by a significant strain rate. Eventual deformative processes affecting these geological formations may be detected at surface when seismicity is also shallow and able to influence shallow crustal permeability (Martinelli and Tamburello, 2020). “The observation that seismic moment scales with fault area to the power 3/2 is one of the longest standing relations in modern seismology” (Leonard, 2010 and references therein), that is to say that eventual $^3He/^4He$ anomalous values, compared to the regional background, should be related to faults able to induce significant crustal permeability variations, corresponding to a length not less than 5 km and to the related width. According to available scientific literature these faults could reach the earth’s surface when magnitudes are higher than 4 or 5 approximately. Lower magnitude values could inhibit Helium uprising toward the surface. Crustal permeability of hosting geological formations is sensitive to fluctuations in geophysical parameters, thus geofluids may contribute to define a more effective description of the studied area like PSHA and DSHA already does. Most relevant precursory fluctuations in crustal permeability where chiefly observed in extensional areas (Martinelli and Tamburello, 2020 and references therein) characterized by the occurrence of warm springs and of CO_2 emissions (Tamburello et al., 2018 and references therein). According to Lucazeau (2019) these identified extensional areas are also characterized by high heat flux (>65 mW/m^2) and by significant strain rates (Kreemer et al., 2014). Shallow seismic events characterize these highly deformable crustal segments favoring intense geofluids circulations. Highly deformable crustal segments have been object of interest in past decades due to the possible existence of geothermal resources, thus geochemical and isotopic parameters where considered in local geofluids allowing detailed geochemical characterization of identified areas. Torgersen (2010 and references therein) and Polyak et al. (2020 and references therein), among others, observed that $^3He/^4He$ sampled in geofluids could have been utilized as tectonic indicator of extensional, highly deforming areas characterized by relatively high heat flux values. Kennedy et al. (2007), Umeda et al. (2013), Sano et al. (2016 and references therein), Zhang et al. (2021a) observed relations between $^3He/^4He$ values and strain rates while Zhang et al. (2021b) observed that $^3He/^4He$ relatively high values may be found in particular conditions also in areas characterized by local compressional tectonics. Thus crustal permeability anisotropies induced by tectonic activity may influence geochemical parameters. Sharp areal geochemical variations in flux and in concentration of deep originated geofluids may indicate a significant role of tectonic activity as in the analogous parameters related to sharp variations in topographic height. It is concluded that crustal permeability anisotropies revealed by Helium isotopic parameters may be utilized in Seismic Hazard Assessment activities as indicator of significant expected seismic events.

Key words: probabilistic seismic hazard assessment, deterministic seismic hazard assessment, helium isotopes, geochemical prospection, earthquake precursors

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