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Original Research Article

The outer ring of a circular structure in the Marche Region, Central Italy: Evidence of a non-extraterrestrial origin

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ABSTRACT

Google Earth images in the Marche Region of Central Italy revealed a circular structure consisting of a ring system made up of concentric hills and valleys. Cartography, DEM, geological, and available geophysical data were used to constrain the possible origin of the structure. Located in the Messinian foredeep deposits of the Central Apennines, it has a rim diameter of 3.75 km and a central uplift connected to its southernmost part. As it was formed in the clays of the Lower Pliocene, and clays are believed to have emerged definitively after the Upper Pliocene, its age might be constrained to the Lower Pleistocene. Similar concentric structures are usually found in impact craters, sedimentary domes, and volcanic landforms. As salt domes and magmatic activity are not found in this region, this study seeks to validate the results of previous work that it was the result of an ancient impact crater of hydrological, brachyanticline, or clayey diapiric origins. Specifically, an observed second ring portion with a curvature radius about double the first in size will be investigated in this work. This second ring portion appears to be concentric to the first one and is visible along its northern and western parts. Although double concentric rings are usually due to impact craters, the absence of the ring portion in the other two directions and the probable deviation of a river, deduced by studying hydrography, support the hypothesis that it might be of clay diapir origin.

Keywords: morphology analysis; hydrographical analysis; cartography analysis; impact crater; clay diapir

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1. Introduction

Large-scale morphological landforms may be revealed in diverse ways, including through remote sensing, field geology, geophysical surveys, and geomorphological analysis. The high resolution of space imagery has greatly contributed to the identification of numerous morphologies[1]. However, verification of their origin can be obtained only by identifying specific process-produced features from stratigraphic records, geological settings, sedimentary evolution, and rock formations themselves[2].

The investigated area is part of a larger morphological environment along the Adriatic Coast of Central Italy, in the southernmost part of the Marche Region, including the provinces of Macerata and Fermo (see **Figure 1).** Specific features of the outer Appennine Mountains in the southern sector of the Marche Region have already been investigated and associated with a complex foreland-foredeep geometry[3]. The influence of thrust-system propagation on the distribution of sedimentary sequences could constitute a link between the Early Miocene Apennine fold-and-thrust belt and the outer and younger belt to the east[4]. It is believed that turbidite deposition in a complex foredeep was strongly affected by tectonic activity and Messinian–Pliocene climate changes[5].

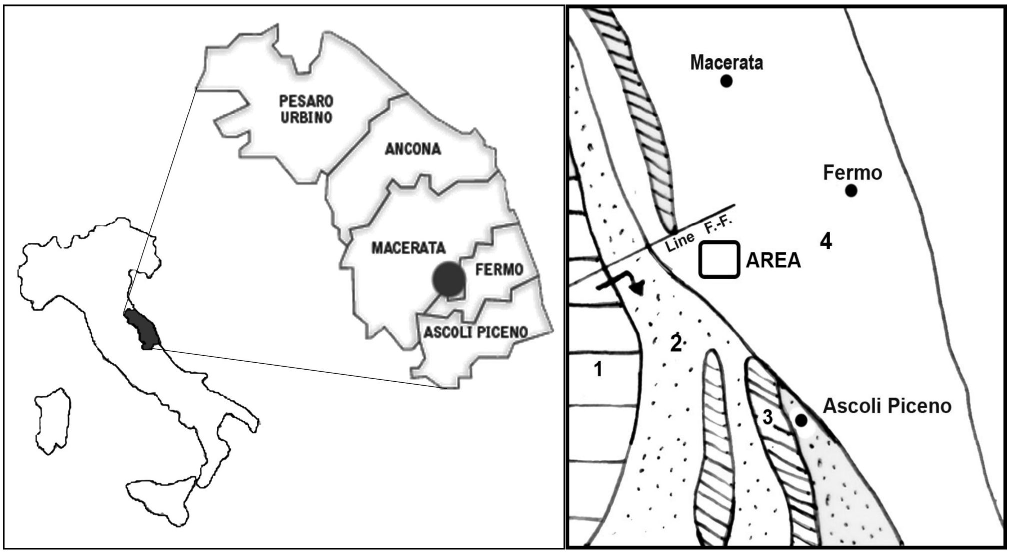

Figure 1. The geographical position of the area in Central Italy; the coordinate intervals of the landform are from 43°05’00” to 43°08’00” in latitudes and from 13°23’00” to 13°28’00” in longitudes. 1-Umbria-Marche ridge, 2-Laga basin, 3-Minor ridges, 4-External Marche basin, → Direction of supply of turbidite deposits, --Fiastrone-Fiatrella line.

This particular landform was initially detected by space images from Google Earth (**Figure 2**) and digitally analyzed by means of shape indexes[6]. It consists of a circular morphology appearing as a ring system of hills and moats, both of which are concentric with a central elevation, as evidenced by the different colors of cultivated vegetation and the terrestrial and hydrographic networks. It integrates into the landscape of this gently hilly area (the Sub-Apennines), interrupted only locally by more modest ridges extending as far as the Adriatic coast[7].

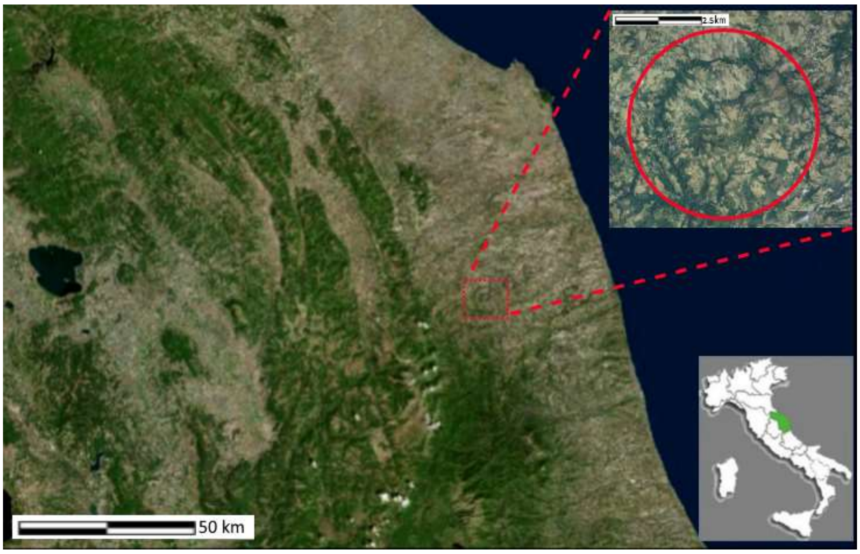

Figure 2. A Google Earth image of the landform with scales is evidenced in red, the 10X zoom of the circular shape is on the top right.

An analysis of the landform began via cartography to define the dimensions of the structure. Then, morphological and hydrographic shape indexes were calculated, which evidenced a circular, slightly elongated rim that was not compatible with a hydrographic origin[6]. Moreover, geophysical surveys provided additional constraints regarding its nature and origin; the stress orientation discouraged a brachy anticline interpretation, and magnetic data did not suggest an astrobleme. Even if we were not able to completely confirm the brachy anticline and astrobleme hypotheses, these data were in line with the aforementioned clayey rising diapir hypothesis that subsequently underwent a deep erosional process[6].

Rock microscopic morphology and geochemical surveys were not performed in this study. The discussion here is concentrated on the only part of the outer ring having a circular morphology that appears to possess an arc shape and is located in the north-west quadrant, as shown in **Figure 2 (**top right). Section 2 is devoted to the geological setting of the area, which is useful for retrieving past occurrences. Section 3 reports on past results regarding the nature of the shape, focusing on the outer ring. The discussion of the hydrographic network, based on multi-ring craters and on the hypothesis of a possible extension of the Fiastra Torrent, has suggested that the formation of the outer partial ring might have been associated with diapir, as reported in Section 4. Section 5 deals with the conclusion.

2. Geology and morphotectonics

The main formations present in the investigated area, starting from the oldest, are: the Formation of the Laga with the Evaporitic Member, the Post-Evaporitic Member of the Messinian p.p., the Colombacci Clays of the Messinian p.p., and the Blue Clays Formation of the Pliocene inf.-Pleistocene inf. Whereas, the beginning of the Apennine orogeny occurred in the Oligocene Era with the eastward migration of the chain-deep-foreland system during the tectonic compressive phase. The Umbria-Marche area constitutes the foreland, with hemipelagic sedimentation controlled by an accentuation of the ridges and depressions.

In the Lower-Middle Miocene, the morphology of the seabed, in continuous evolution, has been described as a series of longitudinal ridges and depressions interrupted by transverse faults. Among these, the best known is the Fiastrone-Fiastrella line (see **Figure 1** right), which divides the Laga Basin into two zones. The more elevated zone is the northern one, while the southern one is more subsident. Along this line, one of the main transverse feeding channels was filled with the turbidite formation of the Laga.

In the Lower Messinian, the foredeep moved further eastward; in the Laga Basin, the turbidite sedimentation began in the more depressed southern areas and then continued northward, towards the edges of the ridges, until it filled the depressions[8]. In the middle Messinian, an evaporitic environment was established with the deposition of the gypsum-sulfur formation, related to the Mediterranean salinity crisis. While the sedimentation of turbidites, siliciclastics, and gypsum continued in a restricted euxinic environment on the south side of the Fiastrone-Fiastrella line[9]. In the upper Messinian, the evolution of the relief took place with the first emergence, due to the effect of compressive tectonics. At the same time, sedimentation in the euxinic environment continued only in the southern part of the Laga Basin. Between the upper Messinian and the end of the lower Pliocene, Apennine tectogenesis reached its peak[10], giving rise to a complex thrust building often interrupted and separated by transverse lines. The chain now extends to the entire Marche Region.

Only starting from the lower Pliocene was the basin affected by a sedimentation of blue-gray clays due to a bathyal environment, which now appears superimposed with a paraconcordant discordance with the Colombacci Clays of the Messinian. The foredeep is extended on the front of the entire Apennine chain. The northern and central areas of the Marche Region rose and emerged in the upper Pliocene as the compressive activity continued, while sedimentation continued in the southern areas. In the easternmost areas, the deposition of marine succession lasted until the end of the lower Pleistocene.

The foreland Marche area was affected by a new extensional tectonic phase coming from the west in the Pleistocene, displacing the pre-existing compressive structures. Subsequently, differentiated vertical movements developed along transverse faults with a tiered arrangement, where the northern area constitutes the highest element and the southern area the lowest. In particular, alternatively within the latter, it is possible to identify raised and lowered blocks with an anti-Apennine trend[11]. Even these areas emerged completely as a result of a general uplift phenomenon that involved all of Central Italy at the end of the Lower Pleistocene. In the innermost parts, they overlapped the positive motifs of a prevalently isostatic nature that had already affected the apennine chain[7]. The persistence over time of this activity of the transversal elements has suggested the existence of crustal discontinuities in depth, which seem to be able to manifest their effects on the surface, whatever the structural tectonic evolution of the sedimentary cover[12].

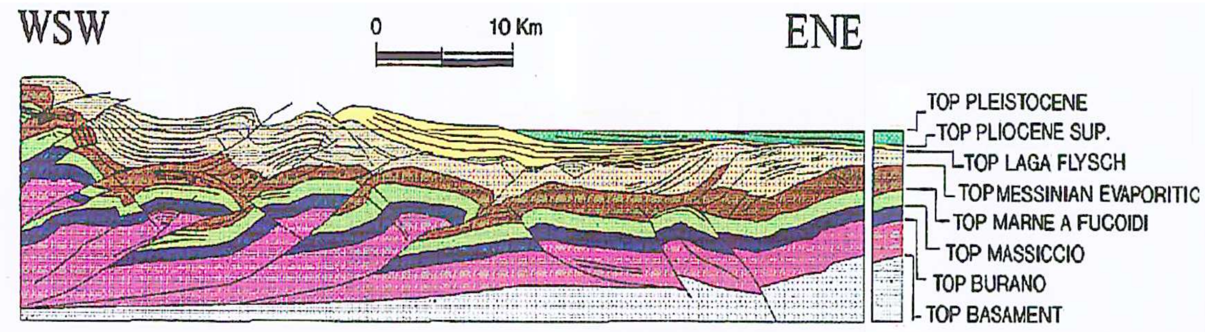

Figure 3. Structural stratigraphic framing of the area under study, obtained from the reprocessing of the seismic lines by ENI S.P.A.[13].

The area evidences various geomorphological aspects linked to the lithostructural characteristics (see **Figure 3**) of the soils and to the Quaternary evolutionary history[14]. In the westernmost portion, where the terrains of the Laga Formation emerge, the greater energy of the relief and the lithostructural and hydrogeological characteristics seem to have favored a more intense action of gravity[15,16]. Additionally, the deep incisions were favored by the greater elevation of this area, close to the Apennine chain, where erosive phenomena are still ongoing and mainly linked to anthropic activities that have profoundly changed the river beds and floodplains over time. Not secondary are the gully morphologies present in the clayey soils, arranged, above all, in the hillock support. The structure of the hydrographic network is strongly influenced by both the recent activity of transverse faults and the differential lifting of anti-Apennine morphostructures[12].

Quaternary (Pleistocene) tectonic activity, in addition to being documented through seismicity over many areas of the Quaternary basin, is also highlighted by surface manifestations such as salt springs and mud volcanoes linked to deep water circulation in fractured areas[17] and connected with the upwelling of salty waters present in the Pliocene sediments. River courses of a minor order are generally influenced by the last phases of tectonic activity and, on average, are more recent, have less deeply engraved beds, and are therefore more free to vary their courses. While the higher hierarchical auctions generally provide evidence following fractures of more ancient genesis[18]. The alluvial plains are not often very developed, except in the stretches closest to the mouth[7].

3. Previous and new results

Previous results regarding the circular landform in the Marche Region were based mainly on geophysical, hydrographic, and morphologic data[6]. Specifically, geophysical data concerning stress, along with magnetic and gravity fields, were considered. The contraction of the Mid-Adriatic Ridge presumably reflects a combination of far-field compressional stresses induced by the Africa-Europe convergence[19]. Thus, the compressional deformation of the central sector of the Adriatic foreland is retained to have reactivated preexisting normal faults that characterize the area under study[10]. Subsequently, the thrust axis in the area of the landform is along the direction SW-NE. For what concerns the geomagnetic anomaly at the position of the landform, it is around 15–25 nT, and a promontory shape in geomagnetic intensity is observed that coincides with the circular landform[20]. The geomagnetic anomaly variations, moving from the outside towards the center of the circular morphology, appear to have increased between 5 and 10 nT. Regarding the gravimetric anomaly at the landform site, this resulted in a negative with a 60–70 mGal intensity and a profile descending to the southeast[21], with no concentrated anomalies.

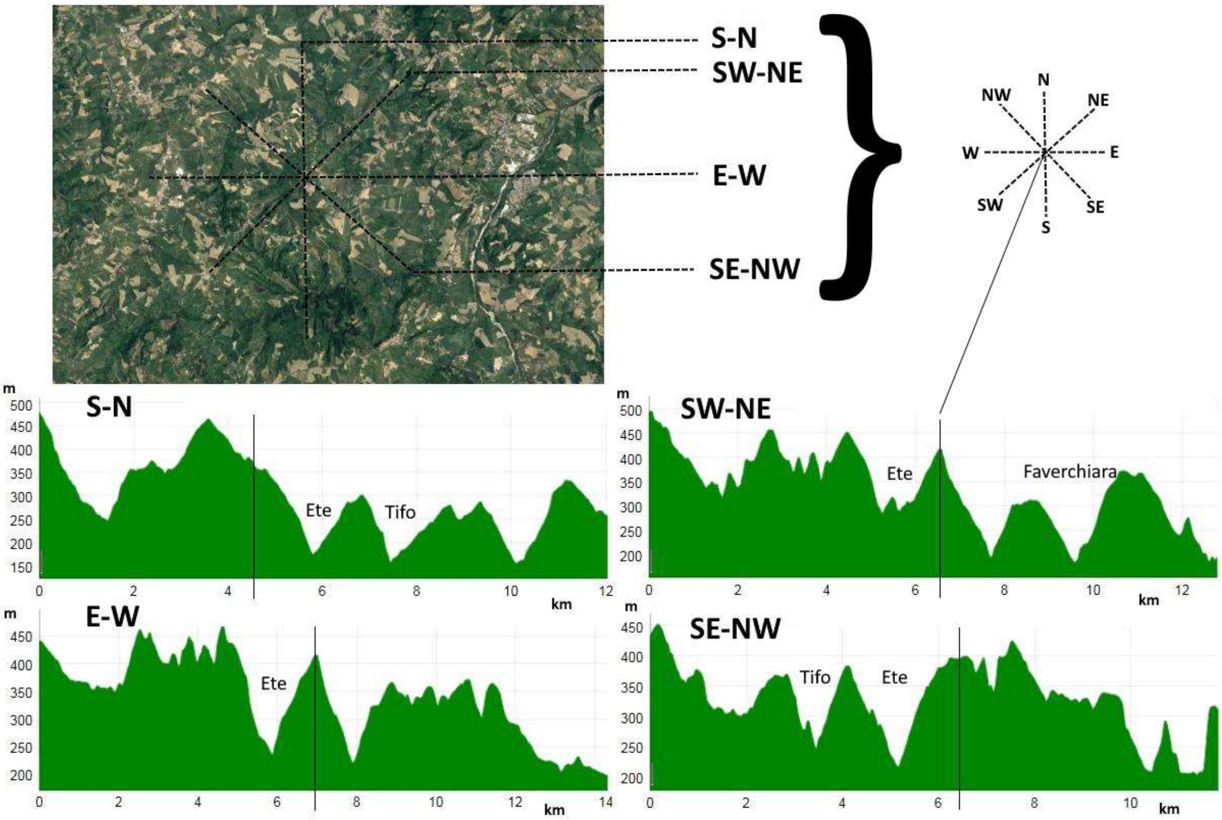

Figure 4. Altitude profiles amplified by a factor of 3 for the four sections S-N, E-W, SW-NE and SE-NW, vertical black lines on profiles indicate the crossing of the sections.

The hydrographic network inside the landform is circular and is made up of two concentric branches of the Ete Morto Valley; profile sections are shown in **Figure 4**. Hydrographic data is concerned with the length, mutual distance, and overall shape of the branches in the hydrological lattice. Internal branches appear as a circle of around 1.8 km (Ete Morto branches), while the external branches are a semi-circle of around 5.4 km (Tifo and Faverchiara branches); see **Figure 4**. The basin area of internal branches was calculated to be S_b = 11.9 km^2, and its perimeter was P_b = 14.2 km. The mainstream length of the Ete Morto basin inside the circular structure was calculated to be L_b = 4.27 km. These values deviate significantly from the Hack Law[22].

$$L_b = 1.5\ S_b^{0.6} = 6.63 \text{ km} \quad (1)$$

The basin area and perimeter define a low Gravelius Index[23],

$$I_g = P_b/(4\pi S_b)^{1/2} = 1.16 \quad (2)$$

and an elongation ratio[24].

$$R_a = 2(S_b/\pi)^{1/2}/L_b = 0.91 \quad (3)$$

consistent with a nearly circular morphology.

Topographic data were obtained on the most accurate DEM covering Italy, provided by applying heterogeneous elevation data sets obtained from existing digital cartography[25], table w47585_s10. A shaded-colored elevation map was calculated and is shown in **Figure 5**. The altitude of the landform center is about 418 m, and it merges with the southern part of the rim in the S-N profile section; see also **Figure 4**, which has a height of 467 m. The maximum diameter between ridges is D_{major} = 4.4 km with a direction of 76°, whereas the minimum diameter is D_{minor} = 3.1 km. The total internal area has been calculated as S = 10.5 km^2. The highest altitude of the internal rim reaches 507 m asl, while the lowest altitude is 159 m asl. The total perimeter is P = 13.1 km, with a morphology evidencing erosive features, corresponding to a deepening of the Ete Morto Creek into the clays. A low-angle "V"-shaped profile at the lowest altitude has been created with a strike angle of 123°. The depth within the major axis is d = 308 m, with an average diameter of D = 3.75 km, both defining a depth-to-diameter ratio.

$$dd = d/D = 0.08 \tag{4}$$

whereas the aspect ratio,

$$AR = D_{minor}/D_{major} = 0.70 \tag{5}$$

and the elongation

$$EL = S/[\pi(D_{major}/2)^2] = 0.69 \tag{6}$$

suggesting that the morphology is symmetric. The index expressing the relationship between the surface S of the morphology and the area of a circle with a perimeter P equal to that of the morphology, is the isoperimetric circularity.

$$IC = 4\pi S/P^2 = 0.77 \tag{7}$$

For what concerns an astrobleme interpretation of this landform, the amount of structural uplift hsu is usually related to the final crater diameter D, and a comparison of terrestrial craters evidenced that[26],

$$hsu = 0.06\ D^{1.1} = 257\ \text{m} \tag{8}$$

above the minimum depth, which corresponds to 416 m asl, about the same as the central uplift altitude which was equal to 418 m. While, the diameter of the uplift resulted to be much less than that characterizing Earth's craters. The transient crater D_t diameter was also calculated to be

$$D = 1.17\ D_t^{1.13}/D_{s\text{-}c}^{0.13} = 3.75\ \text{km} \tag{9}$$

$D_t = 3.2$ km, with the transition diameter from simple to complex for craters on the Earth $D_{s\text{-}c} = 3.2$ km. The investigated elliptical crater could have resulted from either low-velocity (0.5–10 km s^{-1}) and moderately oblique impacts with incidence angles of 30° to 60°. Moreover, scaling laws require that there might have been an impactor having a 100–300 m diameter[27].

Finally, the presence of mud extrusions in the area provided evidence of a clayey diapiric origin for the landform, as the overlying clay layers might have been fractured in a graben and erupted[6].

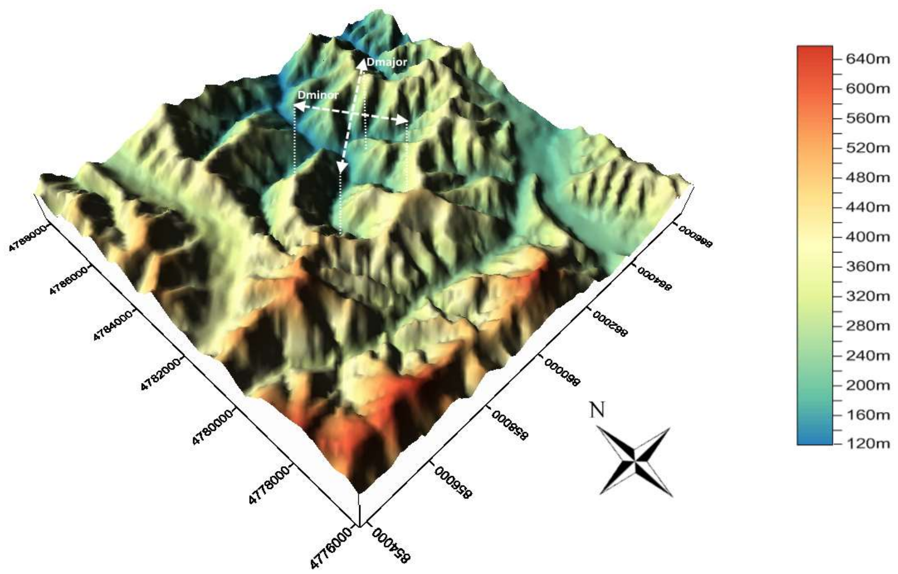

Figure 5. The circular landform is shown starting from DEM with the topography indicated by the color scale on the left; axes D_{minor} and D_{major} are shown in white above the landform.

Additional data was collected on the outer annular ridge, which is partially visible along the northern and western parts of the morphology and has a curvature radius of about 3.7 km with an average diameter of 7.4 km. The relief initially extends in a north-south direction from an altitude of 482.9 m asl at the fraction of Santa Lucia near Sant'Angelo in Pontano Village, continuing up until Borgo San Lorenzo, where at an altitude of 439.5 m asl it changes towards SW-NE, ending near the fraction of Il Castelluccio at an altitude of 351.2 m asl.

In this area, the Fiastra torrent at Passo Sant'Angelo deviates to the north. This phenomenon has been attributed to neotectonic movements that have produced terraces towards the Chienti River, probably starting in the final Lower Pleistocene[12,28]. The phenomenon of river bed deviation had previously been attributed more to tectonic reasons[29,30]. To the east of Passo Sant'Angelo, a saddle shape is present on the watershed, which can be interpreted as a surface of erosion. This could be the old straight path of the Fiastra Torrent, which continued east towards the Ete Morto stream[28], See **Figure 6**.

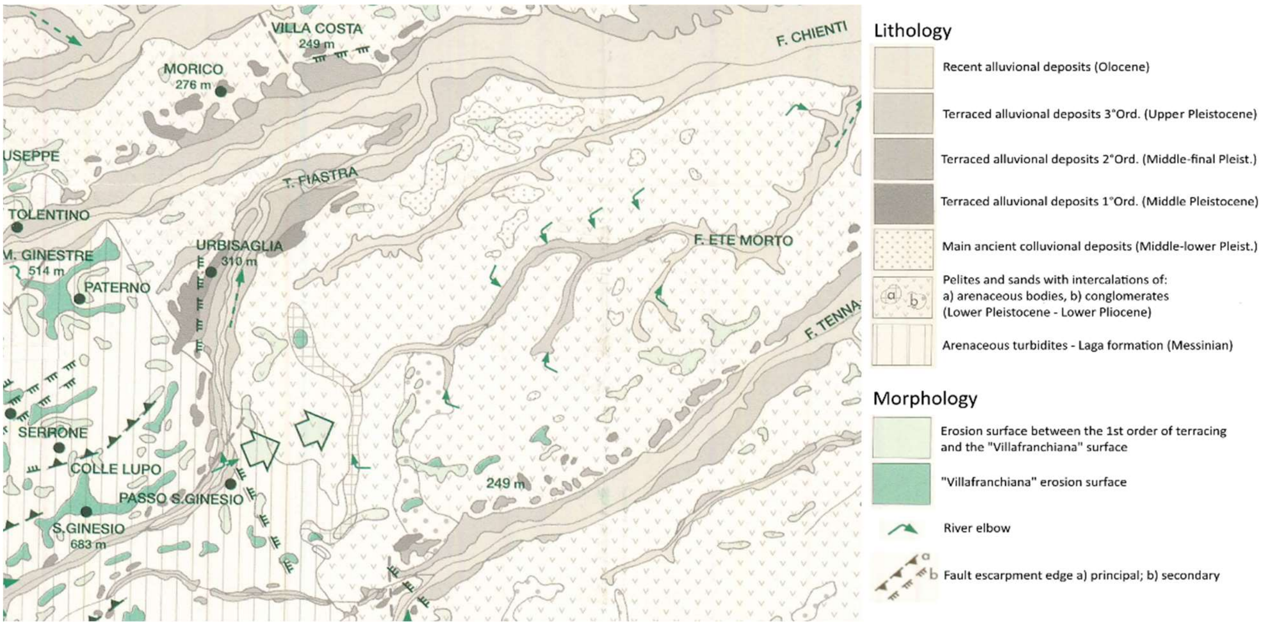

Figure 6. The hypotetical right path of the Fiastra Torrent indicated by green arrows that continues along the Ete Valley, from the map of Dramis et al.[28].

The distribution of the floods was not homogeneous in the basins, being well represented on the hydrographic left, while on the right, these floods are incomplete, as after their deposition, the progressive southward migration of the Marche rivers would have occurred[31,32]. This might be attributed to either a lack of terracing of the southern slopes or a gradual migration to the right of the riverbeds, leading to significant erosion and dismantling of previous alluvial deposits[32]. Alluvial deposits have been accumulated in the plains of the Tenna, Aso Rivers, and Fiastra Torrent. Along the Tenna River, all of the terraced orders reported in literature from the Middle and Upper Pleistocene are found[31]. The differing altitudes among the terraced deposits suggest the interspersing, at the depositional phases, of erosive phases that occurred at different rates of depth during the Quaternary tectonic uplift[31].

Evidence of recent tectonics has also been observed in multiple basins. Regarding neotectonic dislocation, this was observed across the Tenna River in the ancient alluvial deposits of the Middle Pleistocene, where adjacent and extremely limited strips of floods, located at different altitudes, appear displaced, which might have been associated with a reactivation of faults in a north-south direction, recognized in the substrate. In the alluvial deposits of the Final Middle Pleistocene, these faults have been found at Passo San Ginesio in the basin of the Fiastra Torrent.

4. Discussion

One of the most intriguing aspects of the structure is its incomplete second ring, which lies outside the first (see **Figure 2).** It was this appearance of concentric rings that gave rise to the hypothesis of an astroblem. Therein, the impact crater hypothesis was the first to have been formulated and consequently the most investigated[6]. However, multi-ring craters have been reported to have dimensions of hundreds km[27]. For example, on Earth, seismic reflection data have revealed Chicxulub to be a multi-ring basin[33], having a 180-kilometer-diameter ring. Numerical models suggest that all lunar basins larger than Schrödinger (320 km in diameter) should be capable of forming multiple rings as their transient cavities penetrate into the asthenosphere for both thermal profiles[34]. In light of the incompatibility of a multi-ring with a small crater, the incomplete ring of this landform was investigated through further hydrographic observations.

The morphology of the structure is characterised by a hydrographic network that develops radially, diverging from the flanks at higher altitudes. Inside the landform, the collectors develop on the slopes and flow into the Tifo, Ete Morto, and Faverchiara branches. The main aspect that stands out is the presence of two torrents close to the morphology that have deviations: the Fiastra Torrent, a Chienti emissary in the NW quadrant, diverges to the north, and the Salino Torrent turns southward, feeding the River Tenna. These deviations appear as a divergence from the straight path towards the Adriatic Sea, which occurs shortly before the landform (see **Figure 7).** It supports the hypothesis that the landform's origin might very well have been due to a concomitance of the effects of the tectonics occurring in the investigated area, resulting in the lifting of an obstacle.

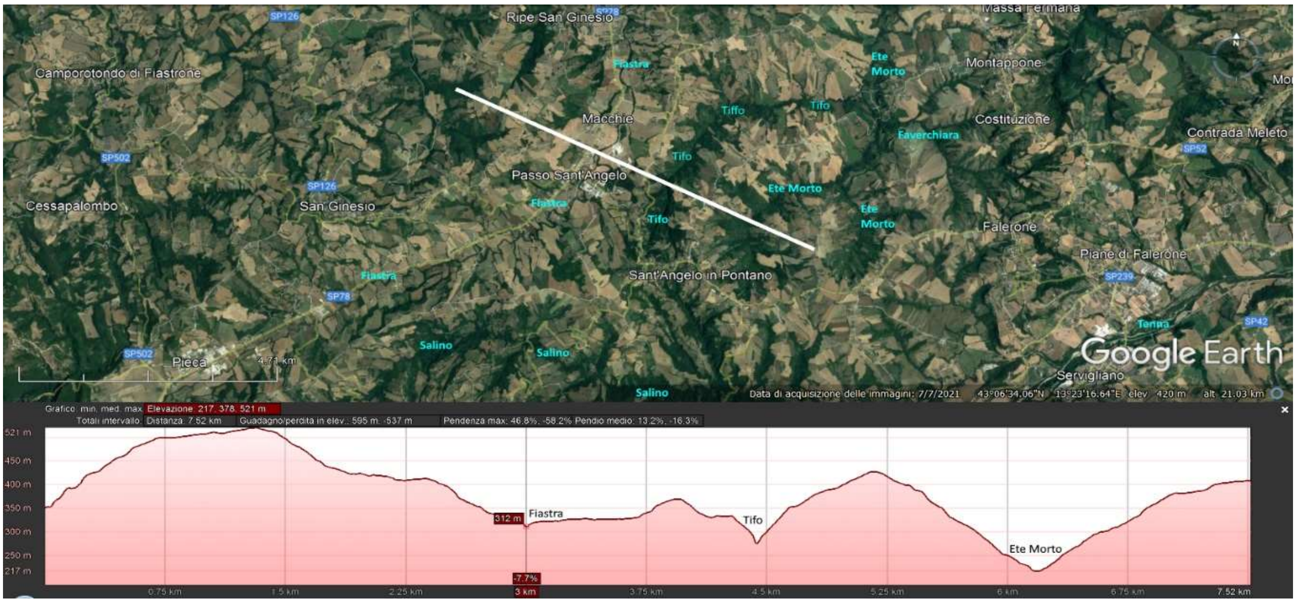

Figure 7. A section of the landform and its surrondings evidence alveos of different shapes and altitudes for the Fiastra Torrent, as well as the Tifo, and Ete Morto moats. The names of the waterways on the map are indicated in light blue.

The Fiastra Torrent is a relic of the previous hydrographic network, as up until the end of the Middle Upper Pleistocene it was a branch of the Fiastrone River[35]. Subsequently, due to a tectonic uplift, the Fiastrone River deviated, moving northwards, leaving the Fiastra valley, which was then fed by another stream. Currently, near San Ginesio, the Fiastra Torrent runs in a north-east direction, while near Passo Sant'Angelo, it gradually deviates northwards. The section in **Figure 7** shows that the valley of the Fiastra Torrent is asymmetrical, with a wide opening, and the height of the riverbed (312 m asl) is higher than both the Tifo ditch's riverbed (277 m asl) with a V-profile and that of the Ete Morto ditch (218 m asl) also with a V-profile. These differentiations may have originated due to:

1) The lithological diversity of the erosive background, in fact, passes from the formation of the Laga to the Colombacci clays up until the gray-blue clays; therein, from lithologies with greater consistency to lithologies with less consistency.
2) There are probable faults present on the outside and in the center of the structure; in fact, there is an edge of a secondary fault escarpment near Passo San Ginesio, as well as probable faults in the center of the structure.
3) Distensive and uplifted tectonics in the Plio-Pleistocene, which led to greater linear and superficial erosion.

The shape of the riverbed depends on its evolutionary stage. In our case, the uppermost valley of the Fiastra Torrent is narrower and widens at the point of the curve where meanders are formed, showing a decrease in the degree of the slope before the curve. Furthermore, the presence of all the orders of the river terraces suggests that the current route of the river had already been set in the Middle Pleistocene. Finally, on the west side of the landform, at the point of the curve, there is a very evident saddle-shaped formation in the fraction of Cappella dell'Immacolata (361 m asl). As shown in **Figure 8**, it is plausible that the Fiastra Torrent was at once connected with the Ete Morto ditch[28].

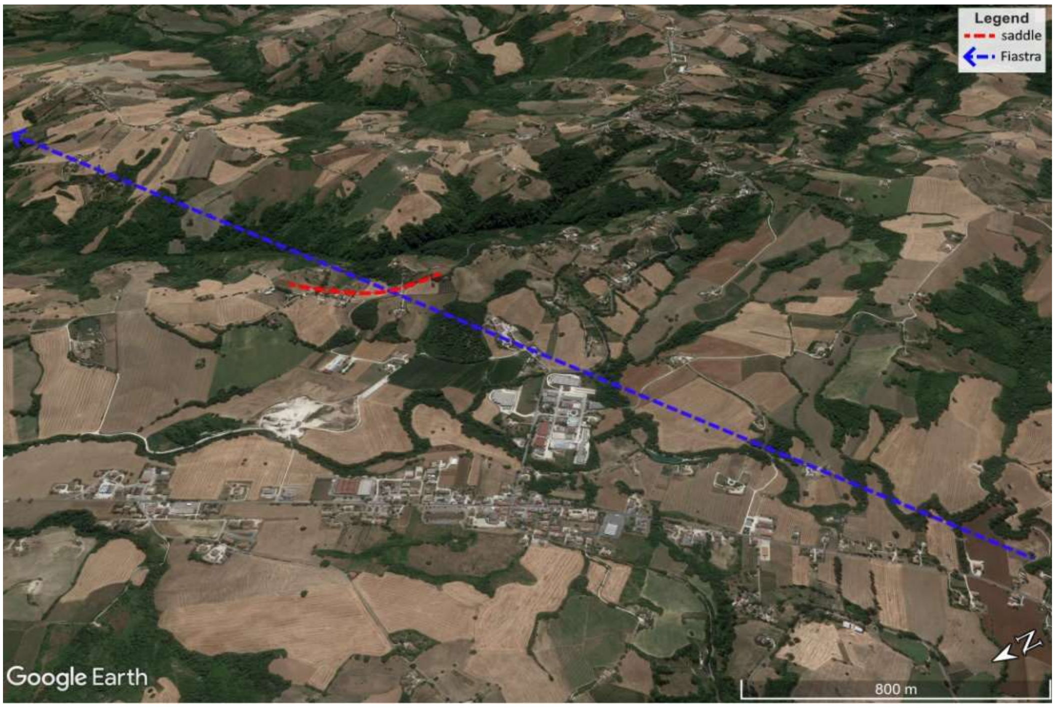

Figure 8. The saddle shape is in red and the originary path of the Fiastra Torrent is in blue; the Tifo ditch in center left, whereas the Ete Morto ditch is on top left.

In the Early Pliocene, up to the Pleistocene, there was a distensive tectonic and a subsequent uplift, which led, in addition to longitudinal and transverse fragmentation in the Umbrian-Marche area, to the formation of transversal dislocations placed in tiers from south to north, identifying different sectors. Wide valleys were produced on the Mio-Plio-Pleistocene terrigenous materials, whose interfluvi were rapidly eroded with consequent continuous lowering of the topographical surface[7]. In the context of the above-mentioned uplift, the upward thrusts of a diapir in its depth might have created a dome morphology on the surface. If so, the Fiastra Torrent was no longer connected to the Ete Morto, and its deviation might have occurred in two stages (see **Figure 9**).

Stage 1: The uprising due to the deep thrust led to the creation of a dome-shaped morphology. Subsequently, the Fiastra would have undergone a displacement of the water flow directly connected to Ete

Morto, thereby adopting the trajectory of the present-day Tifo ditch. This would have outlined a circular pattern around the lifting.

Stage 2: A continuation of the uplift might have led the Fiastra Torrent to leave the Tifo ditch, isolating Ete Morto and then diverting to the north, therein creating its current course.

Then, as already observed in a previous work[6], fracturing induced by an ascent of diapir mud produced the internal braches of the Ete Morto. The uplift of the Plio-Pleistocene led to a greater deepening of the Mio-Plio-Pleistocene formations, that is, in this case of the Tifo and the Ete Morto ditches. Greater erosion of the area made the reliefs of the structure topographically lower and the slopes superficially softer.

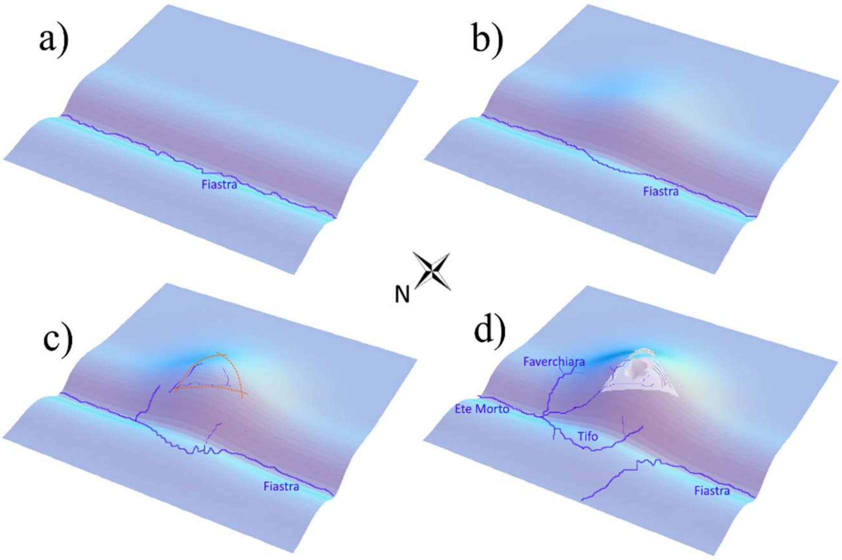

Figure 9. These proposed two stages are represented by four steps; **a)** the Fiastra Torrent flowing straight prior to the diapir ascent; **b)** diapir rising starts and the Fiastra Torrent begins to deviate in an arc shape; **c)** diapir rising increases, the curve of the stream increases, meanders are formed, and the graben (in red) opens on the top of the diapir; **d)** diapir rising increases, the Fiastra Torrent deviates north and the curve of the Fiastra becomes a ditch currently called Tifo, the latter forms a part of the concentric ring around the other one which is formed in the internal graben.

5. Conclusions

Google Earth images of an area located in the southernmost part of the Marche Region in Central Italy have revealed a circular landform consisting of a pair of concentric rings with a shared central elevation composed of gently rolling hills and valleys. Due to this double ring appearance, it was initially thought to be an astrobleme, although a preliminary morphological analysis suggested an endogenous origin[6]. Results from a previous work[28] suggested the hypothesis that the original path of the Fiastra Torrent was straight, continuing along the Ete Morto valley. Then, a hydrographic investigation suggests the origin of the external ring of the landform: based on the riverbed altitudes, shapes, and depositions, different soil consistency, and presence of meanders, the Tifo branch could have been a curved sector of the Fiastra stream. During the compressive phase, a circular lift at the landform site might have gradually bent the Fiastra stream until it definitively abandoned the Tifo Valley and diverted to the north. If so, the external ring might have had a non-extraterrestrial origin, thus supporting the presence of a clayey diapir.

Author contributions

Conceptualization, SC and CF; methodology, SC and CF; software, SC and CF; validation, SC and CF; formal analysis, SC and CF; geological investigation, SC; data curation, CF; writing—original draft preparation, CF; writing—review and editing, SC and CF; supervision, SC and CF. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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