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Key Points:
- Cittanova fault caused five M_w 7.0 earthquakes in the past 13 kyr
- Return times (~3.2 kyr) match low slip rate of the fault (0.6 mm/yr)
- Fault extension reflects residual Tyrrhenian back-arc opening

Supporting Information:
- Supporting Information S1
- Table S1
- Figure S1
- Figure S2
- Figure S3

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Low slip rates and multimillennial return times for M_w 7 earthquake faults in southern Calabria (Italy)

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Abstract The Calabrian Arc is the epicentral region of one third of the strongest earthquakes of Italy ($M_w \geq 7.0$). These are confined within a narrow peninsula which is the emerging portion of a slab-related accretionary wedge, and all occurred in the past four centuries. Therefore, here more than anywhere in Italy, historical seismicity alone is not sufficient for seismic hazard assessment. We carried out geological and paleoseismological studies in southern Calabria that allowed characterizing the seismogenic behavior of the Cittanova fault which was responsible for one of the most catastrophic earthquakes to ever occur in Europe, the M_w 7.0 5 February 1783 event. We have found out conclusive evidence for four Holocene earthquakes prior to 1783, with a recurrence time longer (~3.2 kyr) than the other Apennine faults (0.3–2.4 kyr). We have also estimated a robust slip rate for the late Upper Pleistocene (0.6 mm/yr) and an extension rate (0.4 mm/yr) that could reflect the residual back-arc opening of the Tyrrhenian Basin.

1. Introduction

The Calabria peninsula, which extends 200 km at the toe of the Italian boot, is the narrow, emerging portion of a wide, slab-related accretionary wedge (Calabrian Arc: CA from here on). CA formed during the Neogene as a consequence of NW subduction and SE trench rollback of a remnant of the Ionian lithosphere beneath Eurasia [*Malinverno and Ryan*, 1986; *Patacca et al.*, 1990], and it is currently migrating relative to Ionian lithosphere with ~2 mm/yr of convergence absorbed in the Ionian wedge (Figure 1, inset A) [*D'Agostino et al.*, 2011]. The subducting Ionian slab in the southern Tyrrhenian Sea is well depicted by both a Benjoff plain [*Peterschmitt*, 1956; *Chiarabba et al.*, 2008] and by seismic tomography [*Piromallo and Morelli*, 2003]. *Minelli and Faccenna* [2010] hypothesize that the strong Quaternary uplift of the CA, as shown by impressive staircases of marine terraces [*Miyauchi et al.*, 1994], is due to underplating of Ionian sediments in the last 2 Myr when, contemporary to the outward migration of the arc, the back-arc opening of the Marsili basin and the frontal bulk deformation of the outer Ionian wedge took place. During historical times, Calabria was struck by approximately 20 $M_w \geq 6.0$ crustal earthquakes, six of which had $M_w \geq 6.9$ [*CPTI11*, 2011]. Most of these events occurred in the last four centuries, accounting for 95% of the total seismic energy released in the CA during the past millennium [*Galli and Scionti*, 2006], and all were generated by different seismogenic structures, mainly extensional faults aligned along the Tyrrhenian side of the region [*Ghisetti*, 1981; *Tortorici et al.*, 1995; *Galli et al.*, 2007, 2010]. This suggests that return times for these structures are much longer than the historical completeness of seismic catalogs—currently rated at around six centuries for the largest magnitude classes in southern Italy (*Stucchi et al.* [2004]; or even less: *Camassi and Castelli* [2005]). Moreover, this implies that our knowledge of the seismogenic behavior of the Calabrian structures and of the resulting regional seismic hazard is still poor.

It is not clear whether this temporal cluster of seismicity is real or an artifact of the historical sources that were either episodically produced during the Middle Age in this crossroads of conquerors (Byzantines, Goths, Longobardes, Muslims, Normans, Angevines, and Aragoneses) or lost in later earthquake devastations (and the 1943 bombing of the Naples Archive)—probably all.

Here we present new data on the Late Pleistocene activity, paleoseismology, and seismogenic behavior of the Cittanova fault that was responsible for one of the most catastrophic earthquakes of the Mediterranean: the M_w 7.0 earthquake of 5 February 1783. That epochal event—even more than the 1755 Lisbon earthquake—attracted dozen of scientists, philosophers, and travelers from the European Enlightenment. As demonstrated worldwide—and not only for historically quiescent faults—paleoseismic data provide the majority of

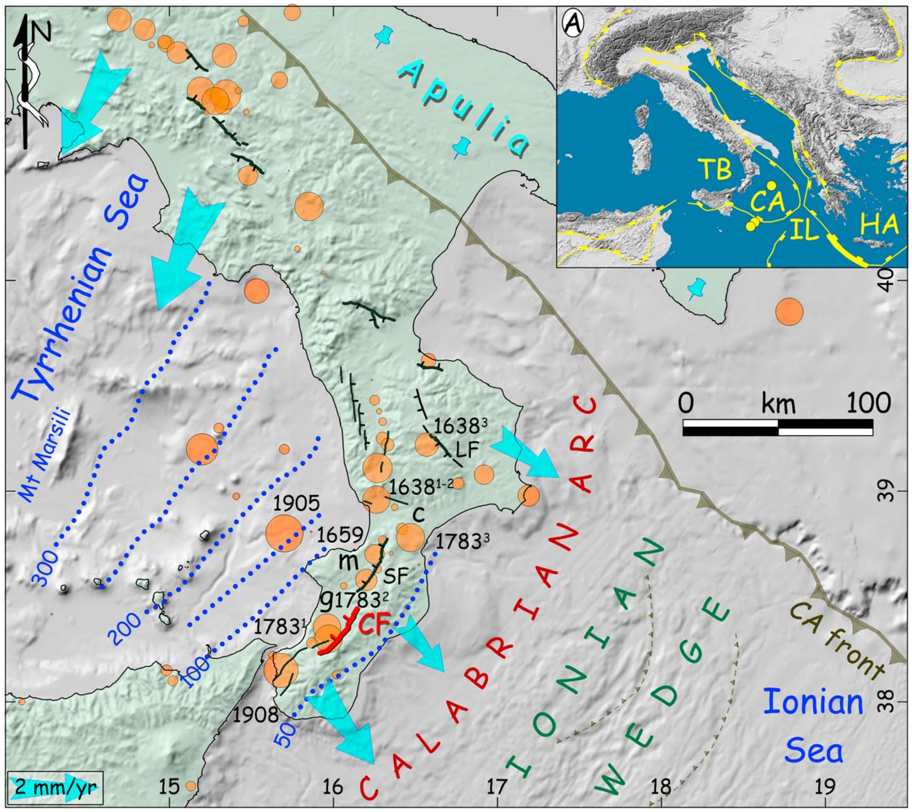

Figure 1. Geodynamic sketch of the Calabrian Arc. Blue dotted lines suggest the top of the Ionian slab (isobaths in kilometers [*Chiarabba et al.*, 2008]). Cyan arrows, GPS velocity field in Apulia reference frame (i.e., pushpins [*D'Agostino et al.*, 2011]). Bold lines, active faults [*Galli et al.*, 2008]: LF, Lakes fault; SF, Serre fault; CF, Cittanova fault. Orange circles, historical epicenters (radius proportional to magnitude; $5.6 < M_w \leq 7.5$; modified from *CPTI11* [2011]); 1783^{1-3}, 5 and 7 February and 28 March shocks; 1638^{1-3}, 27–28 March and 9 June shocks. c, Catanzaro Straits; m, Mesima Valley; g, Gioia Tauro Plain. Inset A: TB, Tyrrhenian Basin; CA, Calabrian Arc; HA, Hellenic Arc; IL, Ionian lithosphere. Circles, boreholes studied by *Polonia et al.* [2013, 2015]; bold line, supposed 365 A.D. megathrust source [*Galli and Galadini*, 2001].

information on the location, size, and recurrence of large earthquakes that is critical for seismic source characterization and Seismic Hazard Assessment [*McCalpin*, 2009].

2. Hints on the Historical Earthquakes of Southern Calabria

Beyond sparse and uncertain reports from the sixteenth century, our knowledge of the regional seismicity starts with the onset of the seventeenth century, when several $5.5 \leq M_w \leq 6.8$ events struck central and southern Calabria [*CPTI11*, 2011; *Scionti et al.*, 2006] marking the onset of a southward migrating sequence ended by the Messina 1908 event. These earthquakes include some of the strongest to ever occur in the Italian Peninsula (27–28 March 1638: M_w 6.8–6.6; 9 June 1638: M_w 6.7) [*Galli and Bosi*, 2003] (5 November 1659: M_w 6.6) [*Guidoboni et al.*, 2007] (Figure 1). After a century of seismic calm, the 1743 M_w 5.9 event hit southern Calabria [*Scionti et al.*, 2006], preceding by 40 years one of the most catastrophic sequence in Europe. This started on 5 February 1783 with a M_w 7.0 earthquake that razed all the villages of the Gioia Tauro Plain (g in Figure 1 and Figure 2), followed 2 days later by a M_w 6.6 shock in the neighboring Mesima Valley (m in Figure 1), and another M_w 7.0 event that struck the Catanzaro Strait (c in Figure 1) on 28 March [*ENEL*, 1986]. This sequence killed around 35,000 people, destroying more than 150 villages, and caused hundreds of colossal landslides [*Cotecchia et al.*, 1986]. Following another century of silence, in 1894 a M_w 6.1 event again hit the Gioia Tauro Plain, preceding by few years the two strongest events of the twentieth century: the M_s 7.5, 1905, and the M_s 7.3, 1908 earthquakes [*Margottini et al.*, 1993], occurred in the western Tyrrhenian coast and in the southern Messina Strait, respectively [*Galli and Molin*, 2009; *Guidoboni et al.*, 2007].

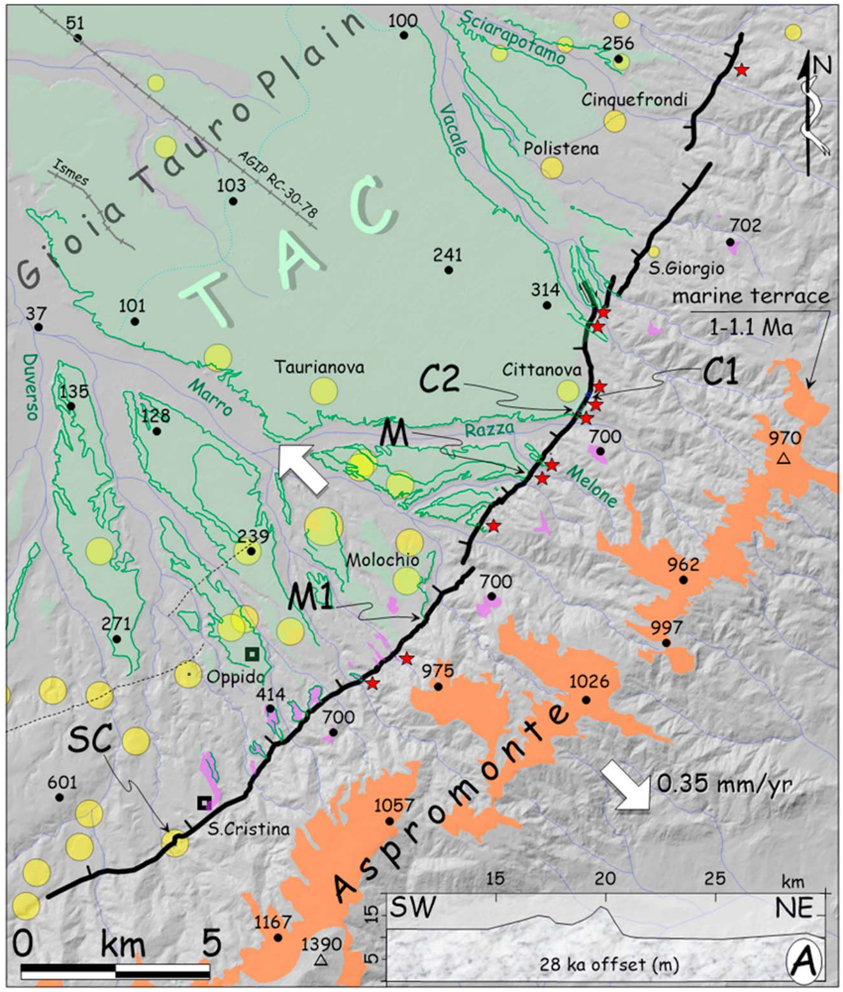

Figure 2. Trace of the Cittanova fault (tics on downthrown block). Yellow circle, 5 February 1783 intensity distribution (proportional to 9–12 Mercalli-Cancani-Sieberg (MCS) degree). TAC, Cittanova-Taurianova alluvial terrace (~28 ka); SC, faulted ruins of old Santa Cristina village; M1, site with faulted, dated colluvia; M, Melone trench; C1–C2, Cittanova trenches. Red stars, sites with measured TAC offset. Orange, remnant of marine terrace attributed to 1–1.1 Ma [*Miyauchi et al.*, 1994]; purple, remnant of faulted, Middle Pleistocene continental paleosurface. White arrows, Late Pleistocene fault extension. Inset A, along-fault projection of TAC offset.

Some of these earthquakes have been paleoseismologically associated with known or newly identified faults (Figure 1: June 1638 event to Lakes fault, LF; and the 5–7 February 1783 events to Cittanova and Serre faults, CF and SF, respectively) [*Galli and Bosi*, 2003; 2002; *Galli et al.*, 2007]. However, most of the faults involved in remain unknown or only tentatively related to proposed active faults [*Monaco and Tortorici*, 2000; *Galli et al.*, 2007; *Cucci and Tertulliani*, 2010; *Argnani*, 2011]. The 5 February 1783 earthquake resulted in major surface rupture along the Cittanova fault (CF), documented by eyewitness accounts and pictures [see *Galli and Bosi*, 2002, Appendix 1] at least between the 23 km distant villages of Santa Cristina (SC in Figure 2) and Cinquefrondi.

3. Late Pleistocene Activity of the Cittanova Fault

This N220° striking, 30 km long normal fault downthrows the crystalline-metamorphic basement of the Aspromonte massif from approximately 1000 m above sea level (asl) (elevation of Early Pleistocene marine terrace carved at the top of the rocky ridge; Figure 2) [*Miyauchi et al.*, 1994] to approximately 500–800 m below sea level (bsl) in the Gioia Tauro Plain ([*ISMES*, 1999] AGIP seismic line RC-306-78; Figure 2), where the Hercynian basement is buried by a thousand meters of Plio-Pleistocene marine deposits. Here at the foot of the 400–600 m high CF scarp, submarine dunes—made by sands, silico-bioclastic arenites, and gravels—passing to clayey silts and blue clays (Siderno-Gioia Tauro paleo-Strait infilling) [*Longhitano et al.*, 2012] are dragged

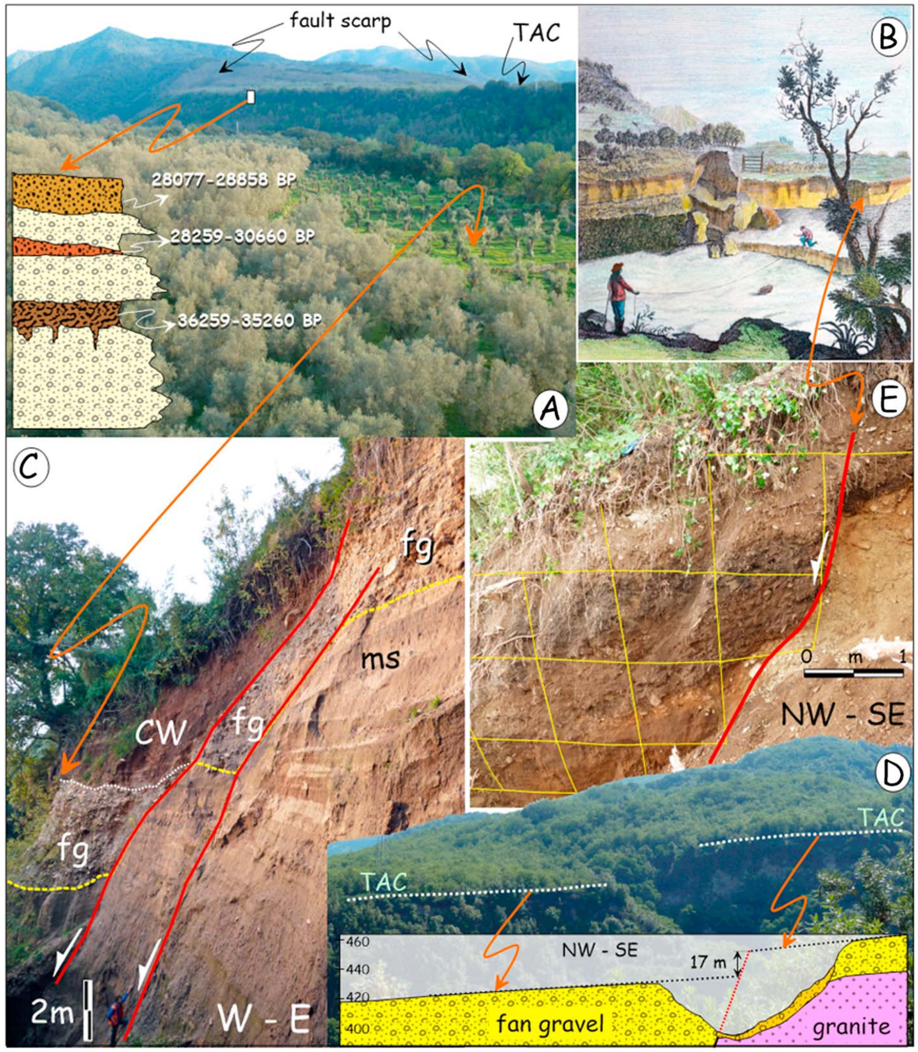

Figure 3. (a) View looking south of the fiumara Vacale, dissecting both the TAC (see stratigraphic column with ^{14}C age), and a later, lower terrace; note CF scarp in background. (B) Engraving from an original drawing by Pompeo Schiantarelli with the 1783 surface faulting near Cittanova (in *Sarconi* [1784]). (c) View looking north of the late glacial fluvial gravels faulting (fg) carved on Early Pleistocene marine sands (ms) in the fiumara Vacale (see corresponding terrace in Figure 3a). (d) View looking NE of the faulted TAC along the fiumara Melone, and geological profile showing the vertical offset. (e) Oblique view of the northern wall of trench C2; note the alluvial TAC gravels (footwall) faulted against sands and colluvia (hanging wall).

against the Aspromonte granodiorites and gneisses along the ~60° dipping CF plane. Most importantly, the CF cuts also through terraced Late Pleistocene alluvial deposits, colluvia, and paleosols (dated here through ^{14}C analyses; see Table S1 in the supporting information), juxtaposing these against both the marine succession and the basement (Figure 3) and providing conclusive clues on the CF activity. The top of the hanging wall is characterized by the Cittanova-Taurianova alluvial terrace (from here on: TAC), descending from the fault scarp foot toward the 20 km far coast (from approximately 400 m to 25 m asl; Figures 2 and 3). Its flat surface has been deeply incised and further terraced by the “fiumare,” seasonal torrents exiting the Aspromonte massif. To date, the TAC age was supposed to be Eutyrrhenian (MIS 5e, 125 ka) [*Miyauchi et al.*, 1994] or Middle-Late Pleistocene [*Tortorici et al.*, 1995]. Now thanks to ^{14}C dating of paleosols and colluvia interbedded in the uppermost gravel layers, we can constrain the age of the last alluvial fan to the late last glacial period. The uppermost, 1–2 m thick paleosol below the TAC was buried after 36,259–35,260 B.P. (^{14}C calibrated age) by the ultimate fan deposits which, in turn, are interfingered upward with soil colluvia dated 30,660–28,259 B.P. and 28,858–28,077 B.P. (Figure 3a). The paleosol age fits the Greenland Interstadial 7 (GI-7; 35,430–34,830 B.P.) [*Rasmussen et al.*, 2014], a period characterized by oceanic and atmospheric mild-warm conditions in the Northern Hemisphere (i.e., favorable to soil development; see coeval paleosols embedded in Apennine alluvial

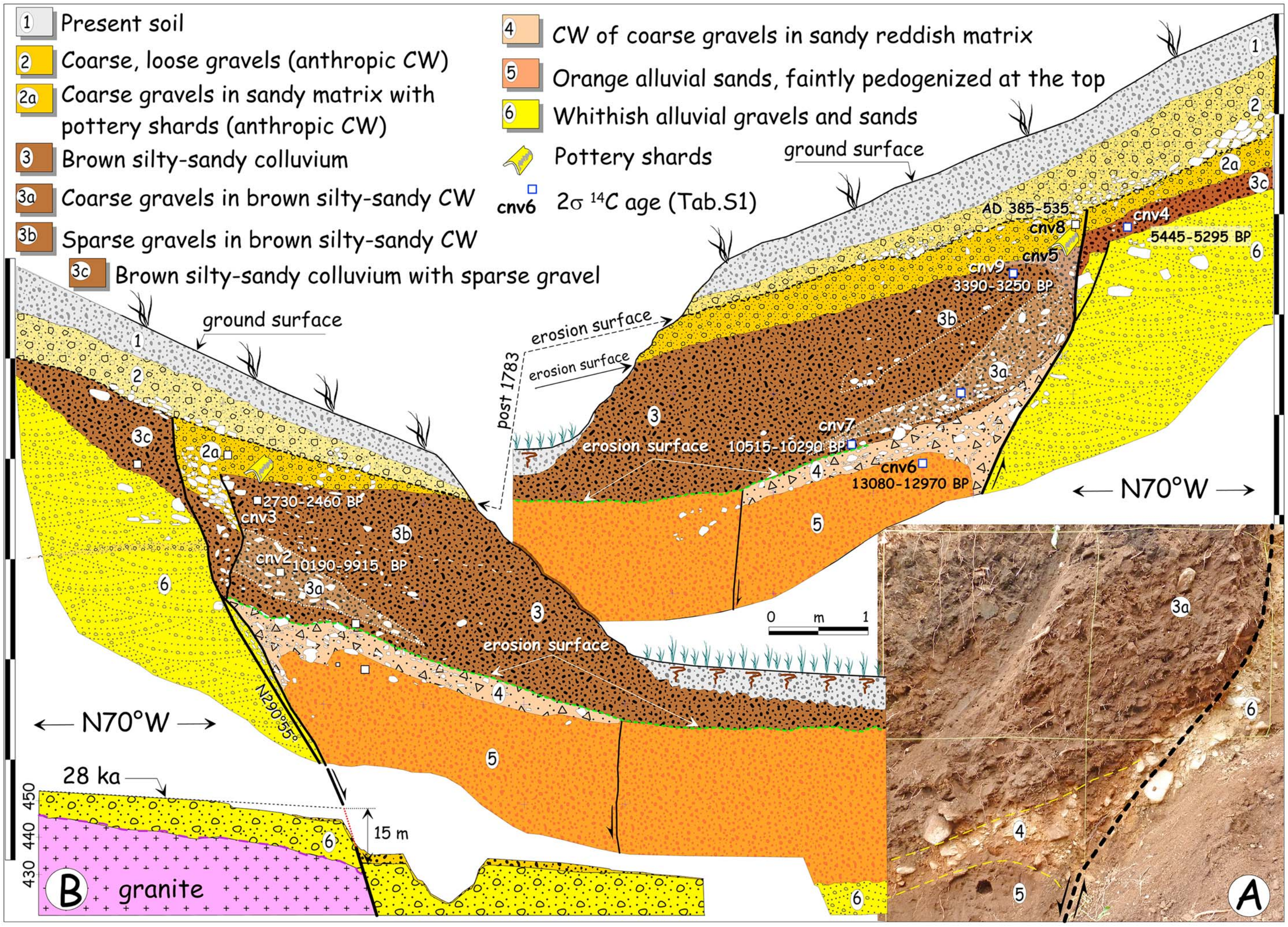

Figure 4. Logs of trench-C2 walls in Cittanova. (a) A detail of the colluvial wedge 4 (early Holocene). (b) The topographic leveling and the geological section across the fault scarp.

fans) [*Frezzotti and Giraudi*, 1992; *Giraudi and Frezzotti*, 1997; *Galli et al.*, 2005]. Therefore, we can approximate the fossilization age of the TAC to circa 28 ka—contemporary and due to the rapid (1–2 kyr) 40 m falling of the sea level down to 125 bsl [*Lambeck et al.*, 2011, 2014] at the onset of the Last Glacial Maximum (circa 30 kyr ago)—when the fiumare deepened quickly their beds, abandoning the TAC level down to $>$ 60 m.

This issue is very important, because where the TAC enters the CF footwall, it is offset by an amount that we measured via topographic leveling and 1 m lidar analyses along several transects (stars in Figure 2; Figures 2a, 3d, and 4b). The vertical separation ranges between 12 and 17 m, which represents the minimum offset, as the total vertical separation on the abandoned fan surface is greater due to 2–3 m of hanging wall burial, and to contemporary footwall erosion. Therefore, for the first time, here we estimate a reliable vertical slip rate of 0.6 ± 0.1 mm/yr for the past 28 ka.

4. Paleoseismology of the Cittanova Fault

Trenches across the CF [*Galli and Bosi*, 2002] provided clues for four earthquakes before the 1783 rupture. The last one was constrained within the fourth century A.D., whereas the others were indistinctly distributed in the Holocene, because of the lack of certain paleoseismic indicators (i.e., colluvial wedges: from here on CW. Figures S2 and S3). In April 2014 we opened a 20 m long trench across the fault scarp engraved in the Atlas of *Sarconi* [1784] inside Cittanova (Figures 3b, 3e, and 4); here we have exhumed the fault plane and

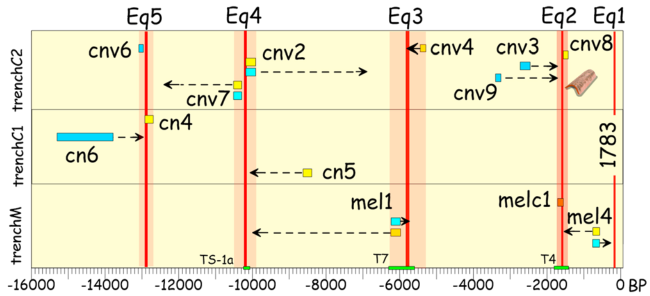

Figure 5. Chronogram of the surface rupture events identified from within the trenches; each radiocarbon sample is reported with its 2σ calibrated interval (yellow, ante quem term; cyan, post quem term; orange, ad quem term; tile, archeological shard). Red bars indicate the most likely age of paleoearthquakes (pink bars suggest uncertainties). Green bars TS-1a, T7, T4, age of seismoturbidites in the Ionian Calabria offshore [*Polonia et al.*, 2013, 2015].

a sequence of alluvial and scarp-related deposits. Due to secular human activities, the uppermost layers and the scarp profile have been reworked, especially because of the presence of State Route 111 crossing today—as in 1783—the CF. Nevertheless, even if the 1783 free face has been erased, the indication of previous surface ruptures were buried and preserved, allowing reliable econstruction of the Holocene faulting sequence.

The footwall in both trench walls is made up of loose, layered rounded gravels in sandy matrix, matching the uppermost layers of the alluvial fan dated 28 ka (unit 6 in Figure 4). This unit, which is gently back tilted, is capped by a dark colluvium (unit 3c), i.e., a reworked paleosol containing an age of 5445–5295 B.P., followed by loose slope gravel in sandy matrix, with sparse modern pottery shards (unit 2). The hanging wall is made up of fine, silty, orange alluvial sands (unit 5), slightly pedogenized at the top, passing bottomward to fan gravels, likely matching the uppermost, eroded layers of unit 6 in the footwall. The organic material at the top of this unit, dated 13,080–12,970 B.P., is buried by a wedge-shaped colluvium (unit 4; Figure 4a) which is made up of coarse gravels in reddish sandy matrix (CW of unit 6 gravels). This wedge is truncated by an erosional surface continuing westward over unit 5, and it is buried by brownish fine sands (unit 3), dated 10,515–10,290 B.P. at the bottom. These contain a second CW (unit 3a; again, unit 6 gravels in abundant brownish sandy matrix) dated 10,190–9915 B.P. Upward, unit 3 includes another level with abundant pebbles (unit 3b), deposited before 3390–3250 B.P. After 2730–2460 B.P., this unit was abruptly buried by a gravelly CW (unit 2a) containing Roman tile shards (Imperial age) and charcoals dated 385–535 A.D. The hanging wall units are faulted against unit 6 alluvial fan gravels, whereas they are sealed by units 2–1, which are post-1783 anthropogenic colluvia. In short, there are at least three CWs (units 4, 3a, and 2a), all mostly made at the expense of unit 6, with material falling from the free face formed at the time of each surface faulting event. They can be related to surface ruptures of events that occurred before the 1783 faulting, while unit 3b is only a faint and nonconclusive indication for a fourth event here. In turn, unit 3c, which unconformably lays over unit 6 in the footwall, postdates an episode of footwall erosion and scarp retreat likely related to a surface faulting episode.

By comparing and cross matching these results with the radiocarbon dating of the faulting evidence in the previous trenches [*Galli and Bosi*, 2002], we can obtain a more robust framework of paleoseismic indication along the CF. Figure 5 contains the dated elements that constrain each single faulting event in the present trench (trench C2), the old excavations in Cittanova (trench C1), and across the Melone torrent site (trench M). Prior to the 1783 faulting (Eq1), the penultimate event (Eq2) occurred between 235–405 A.D. and 385–535 A.D. This time span also fits the age of an epigraph mentioning a *TERREMOTVS* [*Putorti*, 1913] that damaged Rhegium few years before 374 A.D., as well as many other settlements of the region [*Galli and Bosi*, 2002]. As the modern Reggio Calabria was also struck by the 1783 earthquake (8–9 MCS degree), it is likely that the two events have been caused by the same fault in the third quarter of the fourth century A.D. The third to last event (Eq3) was also evident in trench M, even if dated only by a post quem term (c in Figure S2 in the supporting information). Thanks to the new indication in trench C2 (Figure 5, ante quem term provided by sample cnv4 in unit 3), we can now constrain its age between 6276–5248 B.P. and 5445–5295 B.P. The fourth from the last event (Eq4) was also only generically dated in trench M, whereas here it is constrained between 10,515–10,290 B.P. and 10,190–9915 B.P. Finally, the fifth from last event (Eq5) was preliminarily dated in trench C1 (Figure S3 in the supporting information), and now its age is robustly placed between 13,080–12,970 B.P. and 12,935–12,681 B.P. (Figure 5).

5. Discussion and Conclusions

Our study on the recent activity of the CF completes and extends the results of *Galli and Bosi* [2002], revealing that the 1783 earthquake is not the only M_w 7.0 event generated in historical times by this structure, as the CF ruptured in Roman times and repeatedly during the Holocene and in the Late Pleistocene. By cross matching the paleoseismological indication from the different trenches, we have narrowed the confidence interval for four consecutive paleoearthquakes prior to 1783 (Eq1) to: 385 ± 150 A.D. (Eq2; likely few years before 374 A.D.); 5785 ± 490 B.P. (Eq3); 10,215 ± 300 BP (Eq4); and 12,880 ± 200 B.P. (Eq5).

To find out alternative age constraints, we compared our findings with the results of *Polonia et al*. [2013, 2015] from three boreholes drilled in the Calabrian offshore. These authors hypothesize that several seismically induced turbidite beds interrupt both the sapropel S1 deposition (10.8–6.1 ka) [*De Lange et al*., 2008] and the Holocene pelagic sedimentation in the distal CA. According to this hypothesis, we observe a net overlap among the ages of our paleoearthquakes and those measured or modeled for some turbidites (Figure 5). In detail, our Eq4 matches seismoturbidite TS-1a (10,150 B.P. in *Polonia et al*. [2015]); Eq3 matches T7 (between 6278–5625 B.P. and 5292–4997 B.P.; *Polonia et al*. [2013, 2015]). Finally, Eq2 matches T4 (just before 215–547 A.D.), even though *Polonia et al*. [2013] attribute this huge mass flow to the 365 A.D. earthquake, which was generated by the 700 km far megathrust in the Hellenic Arc (Figure 1a) [*Pirazzoli et al*., 1996].

Thus, return times for M_w 7.0 earthquakes on the CF are irregularly spaced, ranging from ~1.4 kyr (between 1783 and the Roman event) to ~4.4 kyr, with an average value in the Holocene of ~3.2 kyr. This is a long recurrence time for southern Apennine faults, where large surface rupturing earthquakes are usually spaced a few centuries apart (0.3–1.6 kyr) [*Galli and Peronace*, 2014], or less than a couple of millennia apart [*Galli et al*., 2008, 2011], except for those on central Apennine dormant faults (~2.4 kyr) [*Galli et al*., 2015]. Nevertheless, this return time is consistent with the low slip rate of the fault (0.6 mm/yr) in the past 28 kyr. By multiplying slip rate and return time, the average vertical slip per event is 1.9 ± 0.3 m, an offset recalling the *Galanti* [1792] account of “several palms” (1 palm = 26 cm), and the CF engraving [*Sarconi*, 1784], where the 1783 free face is at the height of a person (Figure 3b).

Because on average the CF dips 60°, the NW-SE extension rate in the late Upper Pleistocene is 0.35 ± 0.05 mm/yr. This matches well the ~N132° extension imaged by GPS data [*Serpelloni et al*., 2010; *D'Agostino et al*., 2011] that account for 0.55 ± 0.1 mm/yr of extension in a wide, coast-to-coast polygon surrounding the CF (see GPS stations c-g-p-m in Figure S1 in the supporting information). This deformation, although much lower than in central-southern Apennine (2–3 mm/yr; Figure S1), documents that this portion of the CA is not migrating rigidly relative to Ionian lithosphere (i.e., at 2 mm/yr) [*D'Agostino et al*., 2011] but deforms internally. Moreover, here the extension driven by the CF parallels the regional dip direction of the Ionian slab and of the trenchward motion (Figures 1 and S1), a situation differing from the northern CA where the extension is oblique [*Galli and Bosi*, 2003; *D'Agostino et al*., 2011] (LF in Figures 1 and S1). Therefore, a possible geodynamic explanation for the crustal extension accommodated by the southern Calabria faults (CF and SF in Figures 1 and S1) and to the associated earthquakes is the still active eastward rollback of the Ionian lithosphere, with the measured geologic extension rate partly reflecting the present-day, residual Tyrrhenian back-arc opening.

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