Earth and Planetary Science Letters 444 (2016) 192–204

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

# Quantification of tsunami-induced flows on a Mediterranean carbonate ramp reveals catastrophic evolution

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ARTICLE INFO

*Article history:*
Received 26 August 2015
Received in revised form 31 March 2016
Accepted 31 March 2016
Editor: M. Frank

*Keywords:*
carbonate ramp
Mediterranean
tsunami
storm
supercritical flow
catastrophic evolution

ABSTRACT

Cool-water carbonates are the dominant limestones in the Mediterranean Basin since the Early Pliocene. Their deposition typically resulted in ramp morphologies due to high rates of resedimentation. Several such fossil carbonate ramps are characterised by a bimodal facies stacking pattern, where background deposition of subaqueous dune and/or tempestite deposits is repeatedly interrupted by anomalously thick sedimentary units, dominated by backset-stratification formed by supercritical flows. A multitude of exceptional triggers (e.g. storms, floods, tsunamis) have been invoked to explain the origin of these supercritical flows, which, in the absence of a quantitative analysis, remains speculative as yet. Here, for the first time, the catastrophic evolution of one such Mediterranean carbonate ramp, on Favignana Island (Italy), is quantified by combining $^{87}Sr/^{86}Sr$ dating, outcrop-based palaeoflow reconstructions and hydraulic calculations. We demonstrate that rare tsunami-induced flows, occurring on average once every 14 to 35 kyr, lasting a few hours only, deposited the anomalously thick backset-bedded units that form half of the sedimentary record. In between such events, cumulative two years of storm-induced flows deposited the remaining half of the succession by the stacking of subaqueous dunes. The two to four orders of magnitude difference in average recurrence period between the two flow types, and their associated sedimentation rates, emphasises the genetic differences between the two styles of deposition. In terms of sediment transport, the studied carbonate ramp was inactive for at least 99% of the time with gradual progradation during decennial to centennial storm activity. Carbonate ramp evolution attained a catastrophic signature by the contribution of rare tsunamis, producing short-lived, high-energy sediment gravity flows.



## 1. Introduction

Cool-water carbonates in shallow, temperate seas are characterised by the Heterozoan Association of James (1997), consisting largely of the remains of red algae, bivalves, bryozoans, echinoids and larger foraminifera, in the general absence of non-skeletal grains. They lack the major bioconstructions and early cementation typical of their tropical counterparts (Ahr, 1973; Carannante and Simone, 1988). The skeletal debris-covered sea floors thus formed are prone to remobilisation and hence have a reduced capacity to accumulate above storm wave base (Pomar and Tropeano, 2001), which may lead to the development of distally steepened ramp profiles (Pomar et al., 2002; Pedley and Carannante, 2006) (Fig. 1B). Skeletal sand and gravel produced on the ramp top in the unprotected carbonate factory are transported downramp by incidental currents, sweeping sediment below wave base. This results in the occasional deposition of bioclastic material on the ramp slope, leading to carbonate ramp progradation through the formation of large-scale clinoform units up to tens of metres high.

The sedimentary record of the Mediterranean Basin contains numerous examples of clinoform successions created in this way (e.g. Hansen, 1999; Pomar and Tropeano, 2001; Pomar et al., 2002; Puga-Bernabéu et al., 2010; Massari and D'Alessandro, 2012), forming up to six-storey vertical stacks where carbonate ramps originated in tectonically active areas, such as the Lower Pleistocene foreland and satellite basins of Sicily (e.g. Catalano et al., 1998; Massari and D'Alessandro, 2012). These clinoform successions, which prograded up to 1–2 km with a maximum height of several tens of metres, were suggested to correlate with the 41-kyr orbital obliquity-forced oscillation of global sea level related to the

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http://dx.doi.org/10.1016/j.epsl.2016.03.052
0012-821X/

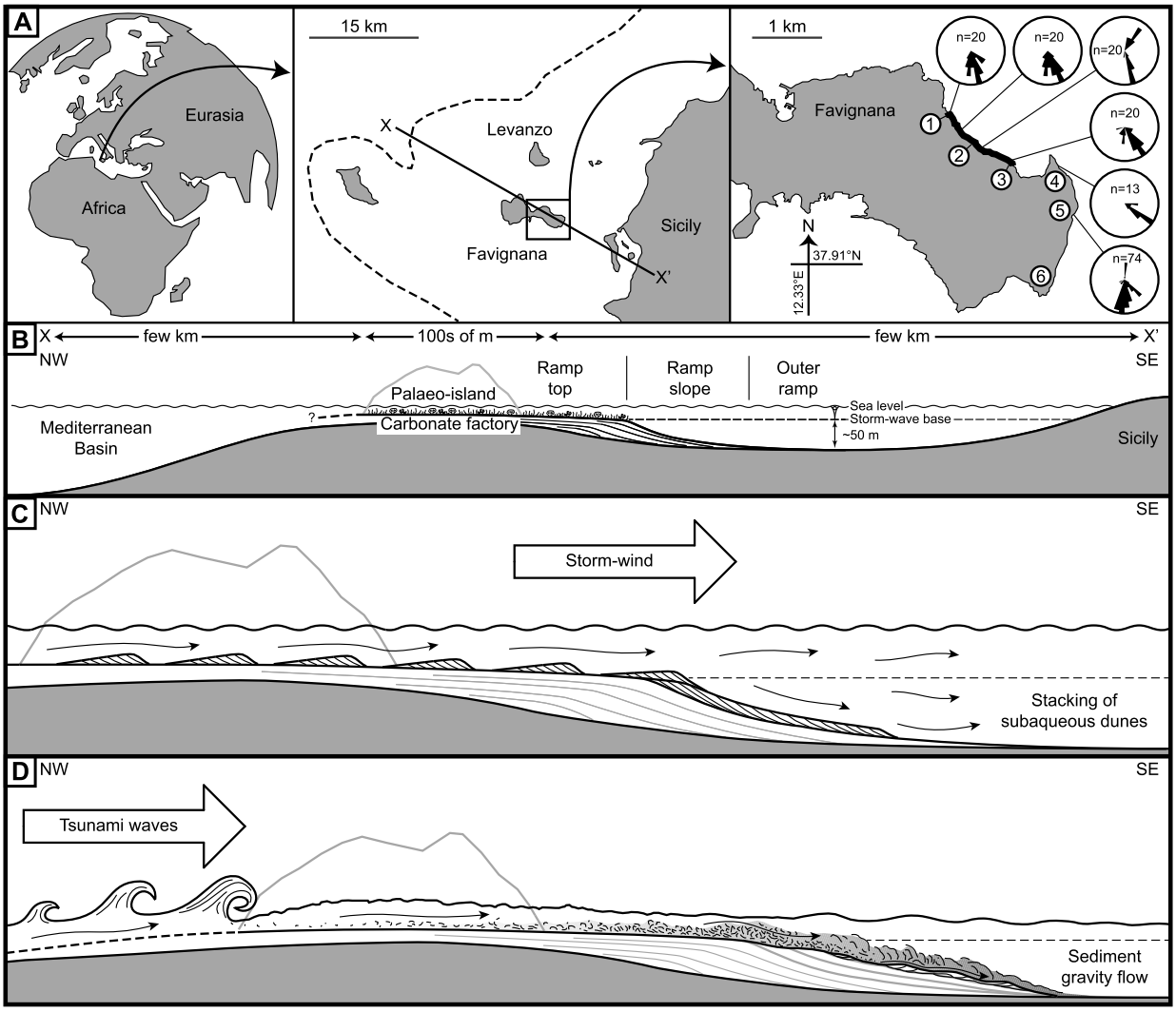


**Fig. 1.** Geography and conceptual cross-section of Favignana Island. (A) The study area (framed) is located offshore western Sicily in the central Mediterranean Basin. Dashed line indicates the present-day shelf (200 m isobath). The large sea cliff (Fig. 2) is highlighted by the thick line on the NE coast of the island. Rose diagrams each represent *n* measurements of the palaeoflow direction of subaqueous dune deposits in two dune cross-bedded clinoform units. Palaeoflow direction suggests that the clinoform succession of the Favignana carbonate ramp prograded approximately towards SE, away from and sourced by a palaeocarbonate factory between the islands of Favignana and Levanzo. Encircled numbers show strontium isotope stratigraphy sample locations; see also Table S1 in Supplementary Material. (B) Schematic cross-section displaying sub-environments on the carbonate ramp and the location of the palaeo-island (projected). (C) Depositional model for dune cross-bedded clinoform units, formed by the migration of subaqueous dunes during storm-driven, wind-induced currents. (D) Depositional model for backset-bedded clinoform units, deposited by tsunami-induced sediment gravity flows.

waxing and waning of Early Pleistocene northern hemisphere ice sheets (Catalano et al., 1998).

Individual clinoform units, which thus encompass the key architectural elements of carbonate ramp clinoform successions, typically consist of bioturbated tempestite and/or cross-bedded deposits (e.g. Hansen, 1999; Puga-Bernabéu et al., 2010; Massari and D'Alessandro, 2012), the latter formed by the downramp migration of subaqueous dunes (*sensu* Ashley, 1990). In addition, several Neogene–Quaternary carbonate ramp successions in the Mediterranean Basin comprise various proportions of clinoform units of anomalously thick, erosion-based sets displaying a poorly pronounced, upslope-dipping stratification in concave-up scours (e.g. Hansen, 1999; Pomar et al., 2002; Andreetta et al., 2008; Massari and D'Alessandro, 2012). Such sedimentary structures are commonly interpreted as backset-beds resulting from hydraulic jumps in submerged particulate gravity flows at the transition from erosive, Froude-supercritical flow to depositional, subcritical flow (Massari, 1996; Cartigny et al., 2014). A number of extreme events were proposed to have triggered such flows, including exceptional storms, strong floods and tsunamis.

This paper aims to provide a quantitative analysis of the origin of (1) backset-bedded deposits and (2) subaqueous dune cross-bedded/tempestite deposits on Mediterranean carbonate ramps, to clarify the relationship between the anomalous backset-bedded units and their background sediments. Using strontium isotope stratigraphy, outcrop-based palaeoflow reconstructions and hydraulic relations, we estimate the average recurrence periods and flow durations of the events linked to both types of deposits in the ramp succession of Favignana Island. On the basis of original data presented here, deposition of the studied succession is constrained within several hundred kyr. Furthermore, over an average period of 14–35 kyr half of the deposits formed during a cumulative two years of storm-induced currents, while the remaining half was deposited in less than six hours by a single, high-energy flow.