Romanian Reports in Physics **72**, 703 (2020)

SOUND SPEED CHARACTERISTICS AND IMPULSIVE NOISE HOTSPOTS ASSESSMENT IN THE NORTH-WESTERN BLACK SEA

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Received August 31, 2019

Abstract. The anthropogenic noise has become a major pollution source concern in the European seas. The Descriptor 11 of the Marine Strategy Framework Directive (MSFD) deals with the introduction of energy in the marine environment by human activities. The indicators that describe Descriptor 11, cover low and mid frequency impulsive sound (*e.g.* seismic airguns, sonars, pile driving and explosives) and the frequencies of ambient noise (that are dominated by shipping sound). This study is focused on some key aspects of the existing knowledge on the sound speed features in the Romanian Black Sea shelf. Information gathered for temporal and spatial record of activities that produced low to mid frequency (10 Hz to 10 kHz) impulsive noise in the North-Western Black Sea shelf are also described.

Key words: impulsive noise, sound speed, Black Sea.

1. INTRODUCTION

Water is an ideal environment for sound: acoustic waves travel four times faster in water than in the air [1] and underwater attenuation is much lower than in air. Human activities introduce a broad spectrum of anthropogenic energy into the marine environment including: electromagnetic, sound, light, heat and radioactive fields. Of these, the underwater sound is the most prevalent.

The oceans are not uniform water bodies as a result of the circulation system (currents). This dynamic allows the mixing of water masses with significant variations in temperature and salinity. The seawater sound speed is highly dependent on the state properties. The propagation of the sound wave speed is directly proportional to pressure. At the interface of the thermocline, lies a region of minimal speed of sound that prevail the transmission of low-frequency sound over long distance – SOFAR (*SOund Fixing And Ranging*) channel.

The sound waves propagation through the SOFAR channel is deflected toward a region of lower velocity as a result of refraction. Therefore, the waves travelling upward toward the surface deflect downward and those travelling toward deeper water are deflected upward.

Anthropogenic noise sources can be classified as impulsive (short burst of high intensity sound) or continuous. Each classification is associated with particular effects on marine life and each requires a particular management approach to mitigate potential impacts. Impulsive noise consists of short sound, discrete, with a sudden onset, such as acoustic pulses from explosions or seismic prospecting activities. Such sources may cause acute effects on marine ecosystem that interfere with auditory detection and directly affects the marine mammals / fish or indirectly through predators or by pray [2], including permanent or temporary hearing damage, physiological stress, and changing individual behaviour and / or social and antipredator responses [3]. Recent research suggests that seismic surveys cause significant mortality to zooplankton populations, a single air gun causes significant damages for a range up to 1.2 km [4].

An impulsive noise is defined as short and fast pulse spikes (intermittent or infrequent noises) that affects the marine ecosystem, between 10 to 300 Hz. Activities that generate short impulsive noise are: pile driving, geophysical surveys (seismic, sub bottom profiling and multibeam echosounders), explosives, sonars and military activities. For oil and gas exploration and seabed mapping, seismic exploration devices (air guns) are used for geological surveys and geophysical studies.

In response to the possible impact of anthropogenic noise on marine life, the policy makers developed management approaches to assess and mitigate this risk through frameworks such as the *Marine Strategy Framework Directive European* (MSFD). Adopted in June 2008, the MSFD (2008/56/CE) – through the 11 descriptors – requires the European Union member states to implement an ecosystem-based approach, to protect the resource, to achieve, maintain, and guarantee the Good Environmental Status (GES) by 2020 [5] in their waters. MSFD defines GES as "*the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive*" [6].

The GES comprise the introduction of energy, through the *Descriptor 11 – Introduction of energy (including underwater noise) does not adversely affect the ecosystem*. The aim of this Descriptor is to ensure that both impulse and continuous sounds from anthropogenic sources do not exceed levels that adversely affect marine ecosystem.

In Romania, the MSFD is transposed into the national legislation by the Regulation on the Protection of the Environment in Marine Waters, through the Emergency Governmental Ordinance 71/2010 and adopted by Law 6/2011 with later changes in law 205/2013 [7].

Until the risen concern of the underwater noise impact on marine ecosystem and *Marine Strategy Framework Directive European (MSFD)* implementation, in the Western Black Sea shelf the topic was covered by the Romanian Navy Research Centre for military purposes. After the MSFD implementation in Romania, as European Union member state, the ecosystem-based approach was scientifically transferred to NIMRD. As preamble to modelling the noise propagation, is necessary to state the base on main Black Sea waters physical features (*e.g.* sound speed, SOFAR channel) in the Romanian Black Sea continental shelf.

The paper aims to establish and analyse the energy parameters and the underwater noise sources from anthropogenic sources with a special emphasis on the assessment of activities that can generate underwater impulsive noise in the North-Western Black Sea. Also, the sound speed computation based on field observations of temperature, salinity and pressure in the Romanian Black Sea shelf are presented.

2. METHODOLOGY

In this study the sea pressure, temperature, salinity and sound speed were computed by the CTD probe, using the international standard UNESCO equation – the Chen and Miller algorithm [8].

For EXO Multiparameter probe, a simplified formula [9] in water depths of 1000 m or less, the following equation (1) is used to calculate the sound speed:

$$c = 1449.2 + 4.6 \cdot T - 0.055 \cdot T^2 + 0.0029 \cdot T^3 + (1.34 - 0.01 \cdot T) \cdot (S - 35) + 0.016 \cdot z \quad (1)$$

where c = sound speed [m/s]; T = temperature [°C]; S = salinity [Practical Salinity Units, or PSU] and z = depth [m].

The seasonal cruises, organized by NIMRD in the frame of Monitoring Program, were carried out in the NW Black Sea inner shelf on-board RV/*Steaua de Mare 1* (Fig. 1) during three seasons: early spring (in March), summer (July–August) and autumn (November).

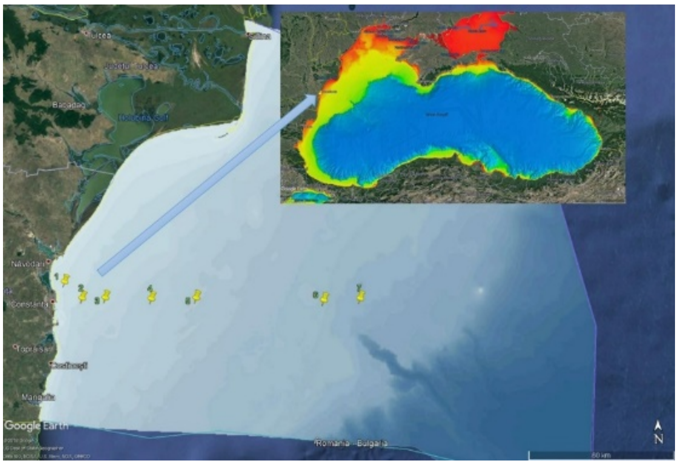

Fig. 1 – Seasonal cruises stations along East Constanta transect (44°10’N) in the Western Black Sea in 2017.

The information's used for the index activities that generated underwater impulsive noise during 2002–2018 in the North-Western Black Sea were collected from the *National Agency for Environmental Protection* [10], *Romanian National Agency for Mineral Resources* [11] and from internal reports of *National Institute for Marine Research and Development "Grigore Antipa" Constanta* [12].

Data analysis and graphical representation of sound speed are performed using Golden Software – Surfer and Grapher [13]. Black Sea bathymetry was retrieved from *Emodnet Bathymetry Portal* [14]. Representation of bathymetry and impulsive noise index for the Romanian Black Sea shelf is realized using gridded file Golden Software – Surfer and visualized with Google Earth platform [15].

3. RESULTS AND DISCUSSIONS

3.1. SEAWATER SOUND SPEED

The sound is represented by the mechanical disturbance through a fluid and the basic features of the sound field structure are strongly related to the regional hydrological conditions. Depending on temperature, salinity and pressure, the speed of sound in seawater is not a constant value. It varies seasonally, temporally and by depth with and major effect on how the sound travels in seawater.

The average sound speed of the Black Sea basin is equal to 1487.0 m/s. In the layer 0–300 m is about 1469.8 m/s and in the layer 400–2000 m records the value of 1490.2 m/s [16].

The paper focuses on the oxic layer between 0 and 80 m as the acoustic wave undergoes a near-surface upward refraction in the upper mixed layer while due to the Black Sea strong stratification, in the deeper layers the sound speed is practically constant.

Seasonally, at Constanta offshore (about 70 nautical miles distance from the coast) in the benthic layer, the sound speed reaches 1465 m/s in spring (March), 1467 m/s in summer (July–August) and 1466 m/s during autumn (November). The seasonal variability of sound speed is limited by the layer 0–80 m and corresponds qualitatively to seasonal variability of sea temperature (Fig. 2, Fig. 3d).

The cold-water masses on the Romanian Black Sea shelf are formed as a part of the oxic layer [17, 18]. Processes of winter convection lead to steady increasing of sound speed with depth providing positive refraction and favourable conditions of sound propagation. In March 2017 the lower limit of the cold layer can still be perceived at the bottom in the shallow waters (Fig. 2a). At the surface, the calculated sound speed has the value of 1458.06 m/s in the near-shore Black Sea waters (Constanta1 station) and 1472.66 m/s in offshore waters (at Constanta 7).

The maximum negative gradient of sound speed (∇c): in spring is observed at the surface down to 10 m depth: ~1.8 m/s (Fig. 3a), in summer ~30 m/s (Fig. 3b) in thermocline (10–20 m water depth) and in autumn ~15 m/s (Fig. 3c) in deep waters (40–50 m).

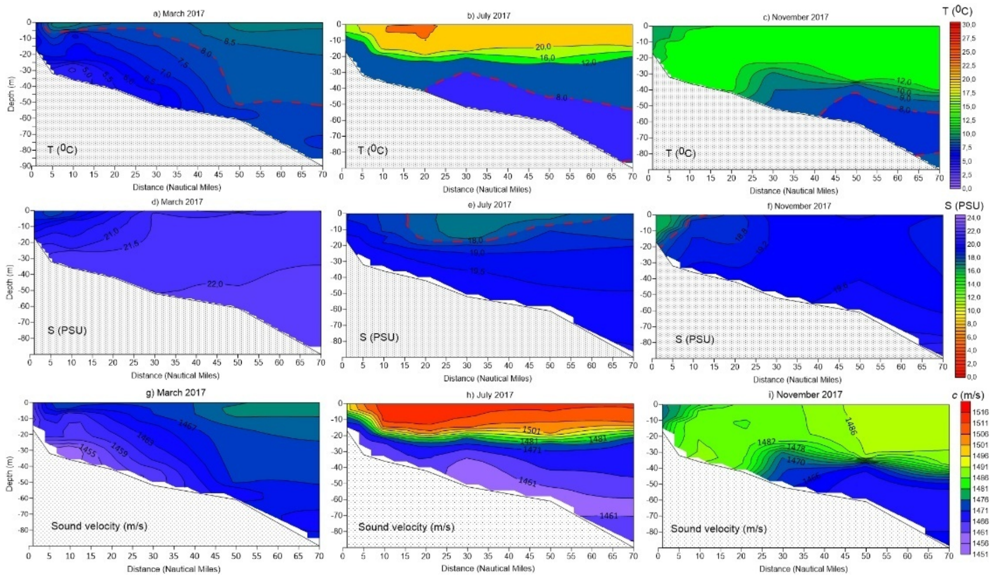

Fig. 2 – Main physical parameters vertical profiles along East Constanta transect (44°10'N) during spring, summer and autumn seasons: i) sea temperature (a, b, c); ii) salinity (d, e, f) and iii) sound speed (g, h, i).

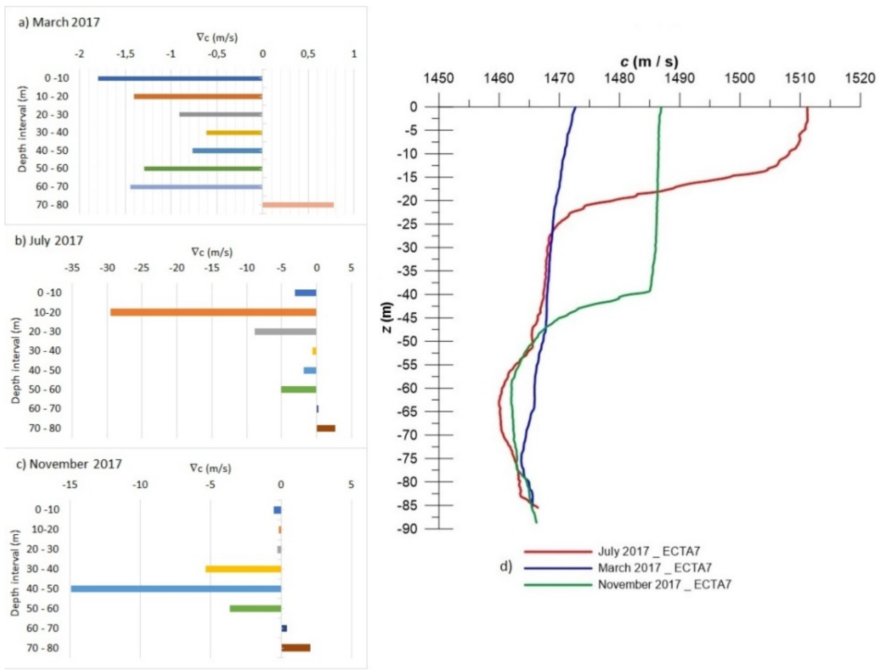

Fig. 3 – Offshore Constanta (ECTA7) sound speed velocity (*c*) during spring, summer and autumn – a, b, c) 10 m sound speed gradient, and d) sound speed per depth *c*(*z*) profiles.

The distribution of the sound speed in the sea water influences the acoustic phenomena. The propagation of acoustic signals is distorted by ecosystem features, sea currents fronts and eddies, sea waves and the local bathymetry.

In the offshore station (90 m below the sea surface), the lowest sound speeds observed in spring (March, c = 1463.6 m/s) at the 75.6 m water depth, at 63.5 m in summer (July, c = 1459.9 m/s) and in autumn (November, c = 1462.0 m/s) at 62.3 m (Fig. 3d). The minimum is determined at the bottom of the thermocline (Fig. 3d, red line – summer). Therefore, below the thermocline the sea temperature bide constant and as a consequence, the speed of sound increases because of the pressure increment (SOFAR channel).

Seasonally, the sound propagation predominant conditions can be described as follows: winter – positive refraction; summer – negative refraction and SOFAR propagation; autumn: a surface channel and SOFAR propagation (Fig. 2, Fig. 3d).

3.2. AN ANALYSIS OF UNDERWATER NOISE SOURCES FROM ANTHROPOGENIC SOURCES

In the oldest oil-producing countries in the world, Romania, the first recordings on seismic activities for oil and gas resources in the national Black Sea continental shelf, were placed first in the years 1967 to 1969. The first offshore oil platform – *Gloria Platform* was launched in 1975 with the first oil production in 1987 [19]. *OMV Petrom* extracted up to 2019, hydrocarbons from the offshore Romanian Black Sea.

For the construction of the regional geological model, regional seismic profiles (*Trident EX-29 Rhapsody* and *EX-30 Blocks*) were performed in 1984, as well as individual profiles in the years 1982–1986 and reassessed by new seismic profiles in 2012 [20]. For *Neptun Block XIX*, regional seismic 2D profiles were realized during 1993, 1994, 2001 and 2008 and to improve the resolution were re-evaluated in 2009 and 2013 by *OMV Petrom S.A.* and *ExxonMobil Exploration*.

New seismic acquisitions, using 3D and 2D high-resolution technical data, obtained in the geophysical prospection allowed detailed and accurate interpretation of the marine substrate layers necessary for well drilling sites.

The main oil and gas operators with concession agreements for Exploration-Development-Exploitation in the Western Black Sea (Fig. 4) authorized by the *Romanian National Agency for Mineral Resources* [11]: OMV Petrom S.A. and ExxonMobil Exploration & Production Romania Ltd. (*XIX Neptun 2*), Lukoil Overseas Atash B.V. and SNGN ROMGAZ S.A. (*EX – 30 Trident*), S.C. Petromar Resources B.V. and S.C. Petromar Resources S.A. (*EX – 28 Est Cobalcescu*, *EX – 29 EST Rapsodia*, *EX – 27 Muridava*), Black Sea Oil & Gas S.R.L. and PetroVentures Resources S.R.L. and Gas Plus International (*XIII Pelican + XV Midia*), OMV Petrom S.A. (*XVIII Istria, XIX Neptun1*), Petro Ventures Europe B.V. and Black Sea Oil & Gas S.R.L. (*EX – 25 Luceafarul*).

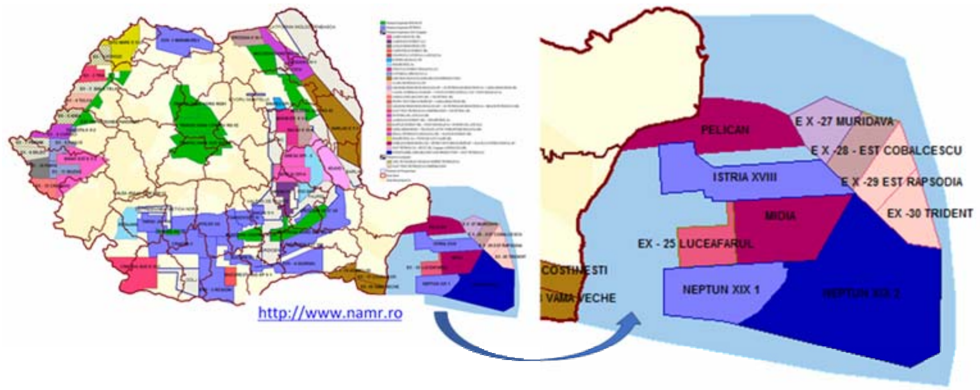

Fig. 4 – Romanian Perimeters for prospecting, exploration, development and exploitation [21].

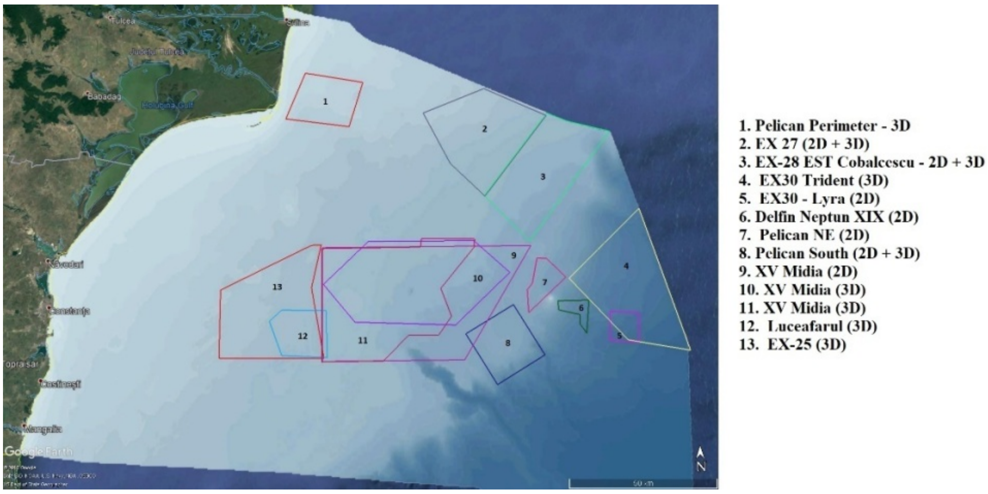

Fig. 5 – 2D and 3D geophysical investigations in the EEZ Romania –
North-Western Black Sea shelf.

The purpose of MSFD-D11C1 indicator is to assess the quantity and distribution of impulsive sound sources in the European Seas (*e.g.* Black Sea). The Marine Strategy Framework Directive (MSFD) requires reporting impulsive noise sources: a) have a lower frequency of 10 kHz and b) adversely affect marine ecosystem [5]. Selection and classification impulsive noise sources in Romanian waters were conducted in accordance with guidelines laid down in [22].

So far, 13 activities generating impulsive noise – 2D and 3D seismic surveys – which were conducted on the Romanian Black Sea shelf during 2009–2017 periods are identified (Fig. 5).

The broad bands of frequencies generated by the array airguns during the seismic activities form a pulse with peak-to-peak amplitude correspond to

220–240 dB re 1 µPa @ 1 m (values reported by the operators for EIA – Environmental Impact Assessment permits). According to [22], the reported source level (zero-to-peak pressure) can be classified as very low and low magnitude (Table 1).

Table 1

Classification of seismic surveys by the sound source level [22]

Magnitude	Source level (zero-to-peak)
Very low	209–233 dB re 1 µPa·m
Low	234–243 dB re 1 µPa·m
Medium	244–253 dB re 1 µPa·m
High	> 253 dB re 1 µPa·m

The major source type in marine exploration is the air-gun array. An air-gun array is composed of multiple units [23]. In the North-Western Black Sea were used 1 up to 2 arrays (information's that Oil and gas companies reported for the EIA permits) and each array consists of 24 to 36 air-guns for the perimeters as shown in Fig. 5. The air-gun array volume is the sum of the volumes of each gun and range, depending on seismic acquisition type, from 500 to 3590 $inch^3$. During 2009–2017 a total of 719 days of seismic surveys activity were recorded (Fig. 6) with a maximum in 2012 and 2013 years (180 and 240 days).

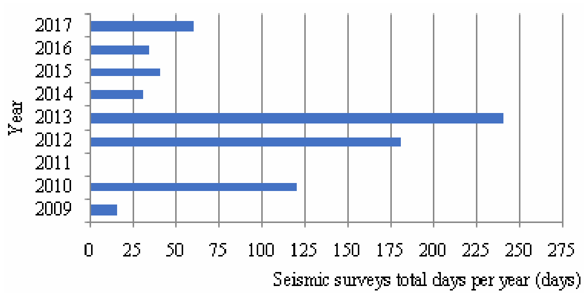

Fig. 6 – Total days per year for activities generating impulsive noise – 2D and 3D seismic surveys (Fig. 5) in the NW Black Sea shelf.

Stakeholder concern often focuses locally on high-intensity noise potential generated by seismic geo-surveys and not on long-term injuring or disturbing marine mammals. Significant numbers of studies on marine species and [24] published the first general exposure criteria regarding injury for marine mammals and [25] detailed about 37 species to be affected by seismic air-gun noise.

Cannot be presumed that on marine mammals or fishes, no biological reactions, habitat disturbance and displacement consequences result from exposure to impulsive noises, when no behavioural response is measured during or after seismic surveys.

4. CONCLUSIONS

The Black Sea is one of the largest enclosed seas characterized by less saline waters, a permanent halocline, an average sound speed of 1487.0 m/s and deep anoxic waters (rich in hydrogen sulphide). The sound speed presents seasonally significant differences with a maximum negative gradient in summer, due to the strong Black Sea stratification. Below the thermocline is found the Cold Intermediate Layer (CIL) outlined by 8ºC isotherm. The behaviour of sound propagation in the sea water is determined by the sound velocity. The propagation features in the north-western Black Sea shelf shows a positive refraction in winter and a negative refraction in summer. The depth corresponding to the sound speed minimum is known as sound channel axis. The *SOund Fixing And Ranging* (SOFAR) channel lies at the interface of the thermocline and its propagation is observed in warm and in intermediate season below 30 m water depth offshore Romanian Black Sea coast. In SOFAR channel sound waves propagate to long ranges with low or no attenuation.

For Descriptor 11 – MSFD, the reporting and monitoring of impulsive underwater noise sources is a requirement in national and regional monitoring program. In the Romanian Black Sea continental shelf during 2009–2016 were identified 13 seismic surveys (2D and 3D) generating impulsive noise, which represent the first national register on impulsive noise D11C1. The airguns maximum intensity sound pressure level, during the seismic activities, varied from 220dB re 1 µPa @ 1 m to 240 dB re 1 µPa @ 1 m. No additional public information's are available for seismic surveys (*e.g.* seismic impulse-block days) or other impulsive noise sources, like: underwater explosions or military sonars.

The specific conditions within the Black Sea investigated over the last years allow us to customize a standard noise assessment model. The measured data is consistent and provides a solid base but future assessment is required for a better understanding of the noise pollution within Back Sea waters.

Although global knowledge of the impacts of underwater noise is increasing, there is a need for further research in the area: continuous measurements and modelling noise propagation in the Black Sea basin or at regional scale. The author aims to include in further works *in-situ* measurements and regional scale underwater noise modelling results.

Acknowledgments. This study has been carried out with financial support from the Monitoring Study Contract – Romanian Ministry of Water and Forests no.55/2018.

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